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Weirs as a Mitigation Measure in Regulated Rivers—

The Norwegian Experience

John E. Brittain[1]

ABSTRACT

Hydropower has been extensively developed in Norway and mitigation measures are one of the major elements in the planning and licensing procedure. Measures include flow management, weirs, substrate improvement, fish ladders and fish stocking. Many of these measures have been developed and evaluated in two major R&D programmes, "The Weir Project" and "The Biotope Adjustment Programme" spanning the period 1973–97. Weirs have been widely used in Norwegian rivers. They lessen the effects of river regulation, can improve fish recruitment, stabilise groundwater levels and concentrate flows. They can also function as sediment traps in rivers with high sediment loading. Many weirs have been in place for over a decade, providing valuable experience regarding ecological function as well as maintenance. Weirs may be constructed of concrete, wood or moraine material (rocks and boulders). Their forms may vary, both in relation to the material, purpose and environmental context. Stream gradient must also be taken into account. Weirs are usually positive with regard to landscape and aesthetic considerations, fish survival during winter and increased biodiversity. Negative effects may include increased sedimentation, fish community changes, migration barriers and excess macrophyte growth. However, these detrimental effects can be reduced by active planning and management.

RÉSUMÉ

La mise en œuvre des mesures d'atténuation des impacts associés au développement hydro–électrique norvégien est une partie intégrante du processus de planification et d'obtention des permis. Ces mesures incluent la gestion du débit, l'amélioration du substrat, la construction de seuils et de passes migratoires de même que l'ensemencement. Parmi ces techniques, plusieurs ont été évaluées dans le cadre de deux importants programmes de recherche et développement : Le « Projet Seuil » et le « Programme d'ajustement des Biotopes » qui se sont déroulés entre 1973 et 1997. Les seuils sont utilisés fréquemment dans les rivières norvégiennes. Ils permettent d'atténuer les effets du débit régularisé, peuvent améliorer le recrutement de poissons

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et stabilisent le niveau de l'eau souterraine de même que permettre de concentrer le débit. Ils peuvent aussi servir de trappes à sédiments dans les cours d'eau à charge sédimentaire élevée. Plusieurs seuils sont en place depuis plus de dix ans, ce qui a permis de récolter beaucoup d'information sur leur rôle écologique et sur les besoins d'entretien de ces ouvrages. Les seuils peuvent être construits en béton, en bois ou avec des matériaux alluviaux (roches et graviers). Leur forme peut varier selon le contexte environnemental, l'objectif à atteindre et les matériaux utilisés. La pente du cours d'eau doit aussi être prise en compte dans la conception des seuils. Généralement, ces outils d'atténuation ont un impact positif sur la biodiversité, la survie des poissons en hiver et pour les considérations esthétiques du cours d'eau. Par contre, ces ouvrages peuvent avoir certains effets négatifs, comme une augmentation de la sédimentation, des modifications des communautés ichtyennes, une croissance excessive des macrophytes et la constitution d'une barrière à la migration. Cependant, ces impacts négatifs peuvent être minimisés par une planification et une gestion dynamique.

HYDROPOWER IN NORWAY

Norway is ideally suited for hydropower because of high relief combined with high precipitation and runoff, especially in the western parts of the country. Almost all of the country's power supply comes from electricity generated by hydropower. The majority of developments involve mountain or high level reservoirs, the stored water usually being directly transferred via tunnels to lowland power stations. There are also a number of run–of–the–river power stations mainly along the major rivers in eastern Norway. In most cases winter flows are increased, while the spring spate driven by snowmelt is reduced. Norway has a long history of hydropower development, but the main developments took place during the period 1955–85. Today there are few new large developments, but several old schemes are due for revision and renewal of their licenses.

LICENSING CONDITIONS

The licensing procedure in Norway is rather complex, especially for large schemes. This is necessary in order ensure democratic processes and to take account all user interests as well as environmental needs (Eie and Brittain, 1994; Brittain and L'Abée–Lund, 1995; www.nve.no/water/water licensing/hydropower). In addition to the technical conditions, licenses are granted only on specific environmental conditions, to counteract or eliminate damages and disadvantages for public and private interests. Such conditions usually apply to natural resources; fishing, game and conservation measures; site clearance and landscaping; weirs and erosion prevention; pollution; protection of cultural heritage sites; discharge patterns and minimum flows.

Compensatory flows are intended to preserve both aquatic life and the character of the landscape. Priority is often given to preserving fish stocks, especially Atlantic salmon *(Salmo salar)* and brown trout *(Salmo trutta)*. Pollution is not a problem in most Norwegian rivers, but may in some cases be a factor when deciding the volume and variation of the residual flows. A number of different user interests may also be considered, such as irrigation, recreational activities and timber floating. Aesthetics, such as the appearance of waterfalls in tourist or urban areas, are also important. In addition, the role of the river as a barrier for livestock may be considered. The rules of operation also include flood events. In several of the more recent developments, the first five years of operation have been used as a trial period in order to optimise the rules of operation. To reduce the negative effects of reduced flows different mitigation measures have been considered, such as weirs, substrate improvement and fish stocking (Hey, 1994; Brittain and L'Abée-Lund, 1995; Eie *et al.,* 1997).

WEIRS AS MITIGATION MEASURES

In Norway, weirs have been constructed as a remedial measure for more than 25 years, and more than 1,000 have been built. Their main purpose has been to create a suitable habitat for fish and maintain a certain water level in the river for aesthetic reasons (Hillestad, 1982). They have also been used as an erosion prevention measure.

When the terms of the license have been fixed, a group appointed to produce a plan for weirs and other biotope adjustment measures with representatives from the Norwegian Water Resources and Energy Directorate and the Directorate for Nature Management, the licensee, and any other people who might be affected by the project. By direct field observation of the affected reach, appropriate localities for weir construction are selected, keeping in mind a set of criteria: (1) the weir must not represent a physical barrier to fish migration, both locally and throughout the whole river system; (2) if necessary, a fishway is included in the weir; (3) the weir basin must have sufficient water depth for fish during winter; (4) the weir should not destroy original spawning areas, especially for salmonids; (5) landscape and aesthetic aspects; (6) cost–benefit considerations; (7) groundwater levels will remain at pre–encroachment levels; (8) other potential mitigation measures (e.g. deployment of large boulders, deepening of existing pools).

Weirs built in Norway can be categorized according to construction material: wood, concrete or moraine material (boulders, rocks and gravel) (Figures 1 and 2). The material is chosen on the basis of the river morphology, distance to access roads, available moraine material, necessity of maintenance and the main purpose of the weir (e.g. aesthetical or biological reasons).

Wooden Weirs

The lifetime of wooden weirs decreases when the weir crest is dry compared to when it is completely submerged and needs to be checked annually. Ice jams may

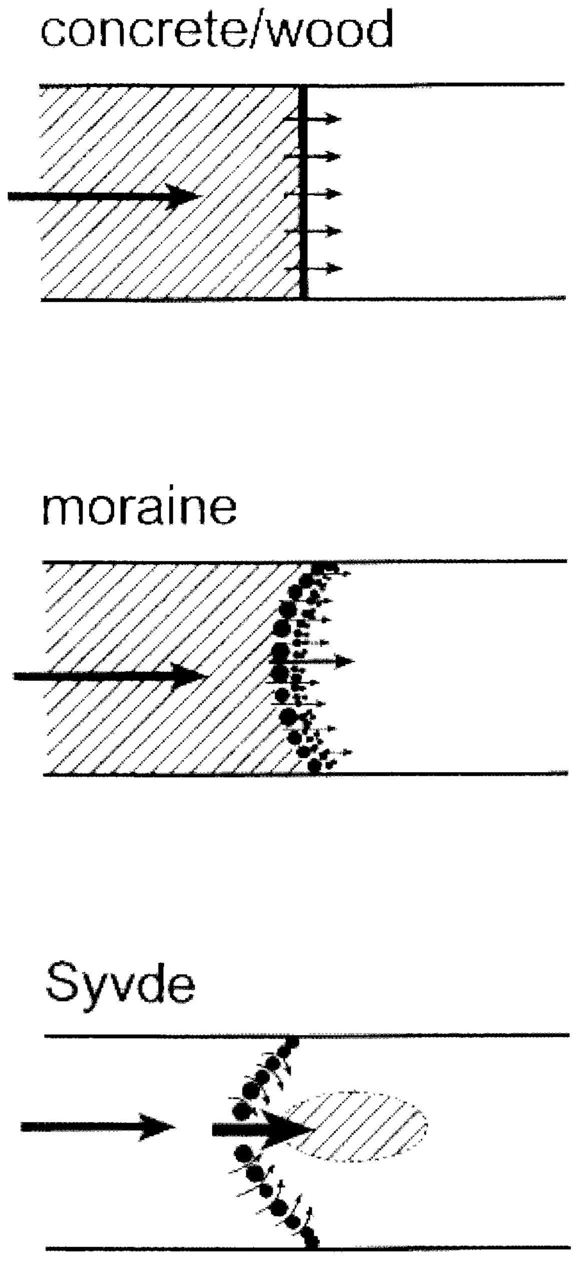

Figure 1. Schematic Drawing of Three Types of Weir Construction. Shaded Areas Indicate an Increase of Water Depth. Arrows Indicate Major Water Flows.

be damaging to the construction. The weir produces a significant upstream basin (L'Abée-Lund and Brittain, 1997). The downstream side of the weir is more or less perpendicular to the river bed, making it difficult for fish passage. However, this weir type is often built in localities where small waterfalls already make fish migration impossible, and there is usually no need for modifications to facilitate fish migration over the weir. However, if fish migration is of serious concern, a fishway may be constructed in the bedrock alongside the weir. Localities chosen for wooden weirs are often the same as for those built of concrete, but the construction costs are lower for wooden weirs. Moreover, transport is easier and the damage to the area caused by construction is lessened with a wooden weir.

Concrete Weirs

Weirs of concrete affect the river environment in a similar way as wooden weirs (L'Abée-Lund and Brittain, 1997) in that the weir may affect fish migration, but contrary to wooden weirs, fishways are easily incorporated into the construction (Figure 2A). This weir type is commonly used where the bedrock is close to the surface or forms the river bed itself. Concrete may also be used in combination with moraine material where the river bank is composed of large boulders or bedrock. The concrete must be anchored to the river bank, to prevent erosion. Another problem with concrete in combination with moraine material is the possibility of erosion on the downstream face of the weir. If the substrate is small in size, the water flowing over the weir will cause erosion and eventually undermine the whole construction. Thus, concrete should be used only in combination with moraine material when the substrate consists of large rocks, or when the downstream face of the weir can be stabilized with boulders. The construction cost of weirs made of concrete is high, but the need for maintenance is limited.

Weirs of Moraine Material– Embankment Weirs

Compared to the other types, this weir type is the most common type in Norway due to aesthetic and economic advantages (L'Abée-Lund and Brittain, 1997). The weir will not be significantly different from the original river environment as material from the area is used. The construction costs will also be low if sufficient material is available in the vicinity. Moreover, a variety of construction designs are used for this weir type, varying from a restricted elevation of the river bed to small waterfalls 0.5–1 m in height (Figure 2C). The moraine weir is susceptible to erosion as significant increases in water flow may occur annually or in certain years. Thus, the construction and use of boulders in critical parts of the weir is essential. Knowledge of hydraulic conditions and experience is vital in this context. Several measures can be used to enhance fish migration through weirs of moraine material, and fishways constructed of concrete have been used with success.

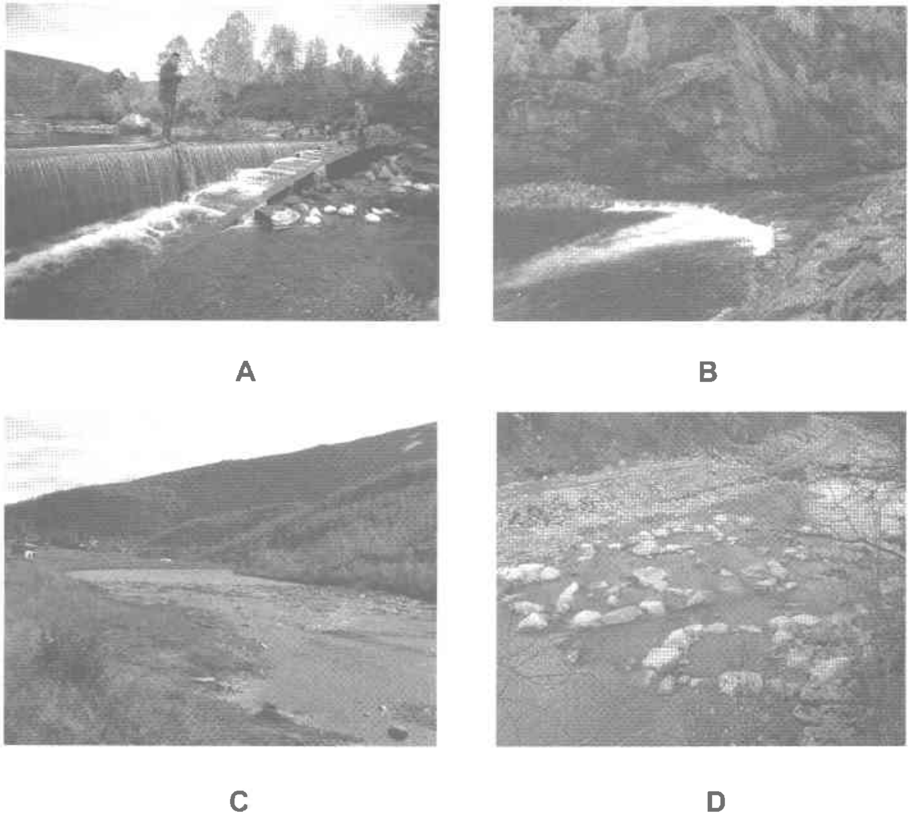

Figure 2. Different Types of Weir Construction. A: A Concrete Weir Incorporating a Fish Ladder; B: A "Syvde" Weir in a Salmon River; C: An Embankment Weir Built With Moraine Material; D: A Cell Weir Shortly After Construction. Photographs: NVE Archives, Jon Arne Eie and Jan Henning L'Abée-Lund.

The Syvde Weir

The Syvde weir is a special kind of weir constructed of wooden material or boulders. The central part of the weir faces upstream, and is lowered compared to the part that is attached to the river bank (Figure 2B). It gathers the water flow in the centre of the channel and thereby permits fish migration even at low discharges (L'Abée-Lund and Brittain, 1997). Contrary to the other types of weirs, the Syvde weir produces only a restricted weir basin upstream meaning that sedimentation of fine substrate or suspended matter is limited. The pool created downstream of the weir may be deep, is sustainable due to hydraulic conditions, and often creates a good fishing area. This weir type was originally constructed in a western Norwegian river to create suitable areas for recreational Atlantic salmon fishery, and has subsequently been constructed in several rivers with anadromous fish species. The functionality of the Syvde weir depends on the river gradient. In high gradient rivers (>1 m/s) the Syvde weir will have little or no effect, while in low gradient rivers (<0.3 m/s) it is not recommended.

Cell Weirs

A 'cell' weir is an alternative to a weir with a single sill or crest. This is similar to natural section of rapids, with a network of small weirs and pools upstream of a main sill. When viewed from above, it looks like a honeycomb, but is not similarly structured (Figure 2D). Cell weirs create greater habitat and hydraulic diversity than traditional weirs. Their appearance is also more natural which is important from an aesthetic point of view. They are a lesser barrier to fish movement than weirs with a single continuous sill. The hydraulic forces are also spread more widely, reducing erosion and making them more stable in the long-term. However, they are expensive to construct. The cell weir was first used in Central Europe with good results, and several have been built in Norway during recent years.

Retaining Weirs in Reservoirs

The substantial drawdown in hydropower reservoirs renders the regulation zone a barren, unproductive environment with unstable substrates, no macrophytes and low numbers and diversity of zoobenthos, providing an environment unsuitable for many fish species. The construction of a retaining weir in one or more of the arms of the reservoir provides a more stable littoral environment and acts as a refuge for reservoir fish populations (Eie *et al.*, 1997). This lessens the need for fish stocking, and has a positive effect on waterfowl populations (Reitan and Sandvik, 1996). By using a limited part of the potential regulation volume for this purpose, adjacent wetland areas may also be maintained.

Advantages and Disadvantages of Weirs

Weirs have a positive effect on the landscape and aesthetics, reducing water velocities, increasing wetted area and water volume and creating improved conditions for fish and fish food organisms. They increase physical habitat diversity, leading to increased biodiversity and also stabilize groundwater levels. Weir basins may also function as a source of irrigation water, as a barrier for livestock in adjacent fields, as well as being a popular recreational area for bathing during summer and skating during winter. Ice conditions are often more stable and weirs can reduce the risk of ice jams. Weirs reduce scouring and erosion damage to bridges, roads, etc. is lessened, and function as sediment traps in rivers with high levels of sediment. In special cases weirs can be used to prevent fish entering power station turbines areas. Organic material will be trapped in the weir basin, thereby increasing overall retention in high gradient rivers. This will increase biological production, within the weir basin, but also for the reach as a whole due to increased retention time.

Weirs are a permanent, stable feature introduced into a river, tending to lock channel morphology dynamics in the same way that flood embankments prevent any change in channel form. This will hinder potential long–term changes in channel morphology. However, weirs are a mitigation measure and not a restoration to the pre–encroachment situation.

In the weir basin, as a result of reduced water velocities and accumulation of softer sediments there will be a change from lotic to lentic floral and faunal elements. This will generally increase biodiversity, but if too many weirs are built the proportion of lotic habitats will be reduced. For example, suitable spawning habitats for salmonids may be reduced, although there will be an improvement in the survival of juveniles and larger adult fish and more seriously, there may be a shift in the dominance of fish species, favouring cyprinids at the expense of salmonids for example. There are strong indications that the bird life in and around the watercourses has become more diverse and more productive since the weirs were built. This is ascribed to the marked increase in benthic production in the river (Eie *et al.,* 1997). Ducks may also be favoured at the expense of other water birds.

In rivers with low minimum flows, where the weir basins are long and shallow and feature finely–grained sediments, conditions will favour the type of vegetation associated with slow–flowing waters (Rørslett and Johansen, 1996). Increased growth of aquatic vegetation has taken place in several Norwegian watercourses regulated for hydropower. In certain rivers, mainly in the coastal areas of southern and western Norway there have been severe nuisance problems with the formation of thick vegetation mats, clogging waterways and rendering them unsuitable for recreational activities such as boating, fishing and bathing. However, factors other than low flows may have contributed to these changes.

BIOLOGICAL EFFECTS OF WEIRS

Research on weirs in Norway started under the auspices of the Weir Project in 1973 (Mellquist, 1986) and continued with studies of other mitigation measures in the Biotope Adjustment Programme (1985–95) (Eie *et al.,* 1997). The long–term biological effects of weirs have been well documented in a study in the River Ekso in Eksingedal, western Norway (Figure 2C).

Benthos Dynamics

Benthic communities in weir basins are dynamic, and mainly as a result of reduced water velocity, will lead to the sedimentation of particles (Fjellheim *et al.,* 1989). In the River Ekso, oligochaetes comprised the dominant group inside and outside the weir basin after the weir was built. The mayfly biomass was high in the lotic waters outside the weir basin, while the production of chironomids was largely the same inside and outside the basin. Subsequently, there was a strong increase in the production of chironomids and oligochaetes in the weir basin, and 12 years after the weir was built the chironomid biomass was nearly 30 times higher than prior to construction (Bækken *et al.,* 1984).

The benthic community changed from one consisting of species adapted to life in lotic waters to species adapted to lentic waters. For example, large, burrowing species of chironomids, mainly belonging to the genera *Stictochironomus* and *Micropsectra*, dominated the benthos, although there had been very few of them before the weir was built. Parallel to the changes in species, major changes took place in the total benthic biomass. Three years after the weir was built in Eksingedal, the total biomass decreased drastically in downstream riffles, at the same time as biomass in the weir basin increased strongly because the weir basin was acting as a sedimentation trap for organic matter.

Thirteen years after weir construction, the benthic community underwent another transformation (Fjellheim *et al.,* 1993; Fjellheim and Raddum, 1996). The winter of 1988–89 was particularly wet, and huge amounts of snow accumulated in the mountains of western Norway. At the same time, temperatures were mild in the lowlands, reducing the demand for power. Large volumes of water had to be discharged over the regulation dam into the Eksingedal watercourse, increasing water flow almost fivefold through the weir basin, compared with a normal year. The after–effects of the increased water flow appeared very quickly. The benthic biomass was reduced dramatically, and major interspecific changes occurred. The large, burrowing chironomids were flushed out, along with huge volumes of sediment, and the community quickly transformed to a more lotic benthos.

Fish in Weir Basins

Reduced flow in rivers and streams can have particularly strong adverse effects on larger fish. Weirs are an appropriate measure for increasing water volume, but have a number of other indirect effects. In the Nea River it was shown that while brown trout already colonized a new weir basin after just six months, the establishment of a stable, sizeable stock took longer (Arnekleiv, 1993). The condition factor of fish was also higher in mature weir basins than in new ones, suggesting that there was better access to food organisms in the older weir basins. Weirs had no adverse effects on fish migration in the Eksingedal watercourse, where the weirs allowed passage (Evensen, 1984).

Most investigators have found that weirs increase fish density, and that the population density in the weir basins is higher than in riffles outside the basins. There may be excess production of juvenile fish in weir basins that can be used to stock reservoirs within the same catchment (Fjellheim and Raddum, 1994). However, weir basins do not automatically generate an increase in fish density. Basins that have finely–grained sand bottoms with virtually no rocks may have a lower density of fish than what would be found in stretches of rapids, but if the banks of a weir basin are reinforced with large boulders, the fish density may be higher than in rapids. To promote increased fish density in weir basins, the basins must also be deep enough to ensure good winter survival rates. Interspecific interactions may, however, result in lower salmonids densities than one would expect, as Atlantic salmon and brown trout juveniles have similar habitat use (Heggenes and Saltveit, 1990).

It is well documented that fish often grow significantly more quickly in weir basins than in stretches of rapids for three reasons (e.g. Raddum *et al.*, 1989; Arnekleiv, 1993): water temperatures in lentic waters are higher with a positive effect on fish metabolism; fish also expend less energy in staying in lentic waters and salmon do not exhibit territorial behaviour; compared with regulated rivers with little water flow, weir basins with deep areas and a varied substrate furnish fish with better protection against predators such as mink.

It appears that the functional unit is not the weir basin alone, but also the lotic stretches above and below it. Rapids are also an important part of the food supply for fish. Many of the food organisms that drift into the basin come from rapids, and trout forage on them. The weir basins represent areas with stable environmental conditions that ensure survival during winter and dry periods.

OTHER MITIGATION MEASURES

It should be emphasized that weirs are only one of several mitigation measures employed in Norwegian regulated rivers. Frequently a combination of different measures is used. These include the following:

Groins, either as supplement to weirs or instead of weirs, have been used to enhance habitat diversity in canalised and regulated rivers and to reduce bankside erosion (Muhar, 1996).

Substrate improvement is used in canalised rivers where sand and other fine material dominate the bottom. Rocks and stones can be deployed in the river, providing improved conditions for fish, by creating greater diversity in substrate, flow conditions and water depth, as well as providing cover (Gore and Petts, 1989; Brittain *et al.,* 1993). Large boulders have also been placed in rivers to increase habitat heterogeneity, especially for larger fish.

Channel modification may be undertaken to accommodate changed flows after regulation. However, care must be taken not to increase the risk of flooding at high discharges. This can be solved by a double profile, in which a narrow channel is excavated within the original river channel for low flows, while the original wide channel is retained for high flows. This stepwise profile can be exploited to construct fishing paths along the new smaller channel.

Fish stocking has a long history in many regulation schemes. However, with the dangers inherent in the spread of fish diseases, the mixing of genetically distinct fish populations (Hansen *et al.*, 1991) and because stocking of juveniles gives low recapture rates (Cresswell, 1981; Fleming, 2001), increasing emphasis is now being given to physical measures aimed at improving natural recruitment reducing the need for stocking. These include the introduction of large rocks, provision of appropriate spawning substrate, concentration of water flow, creation of cover and the building of side channels for spawning and juvenile habitat (Näslund, 1989).

Fish ladders have been constructed in many Norwegian rivers, not only to ensure natural migration, but also to increase the areas for migratory populations. Fish ladders have extremely variable efficiency. Fish ladders are the most common mitigation method, but where space is available, by–pass channels may be more effective, especially for non–salmonids (Jungwirth, 1996).

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