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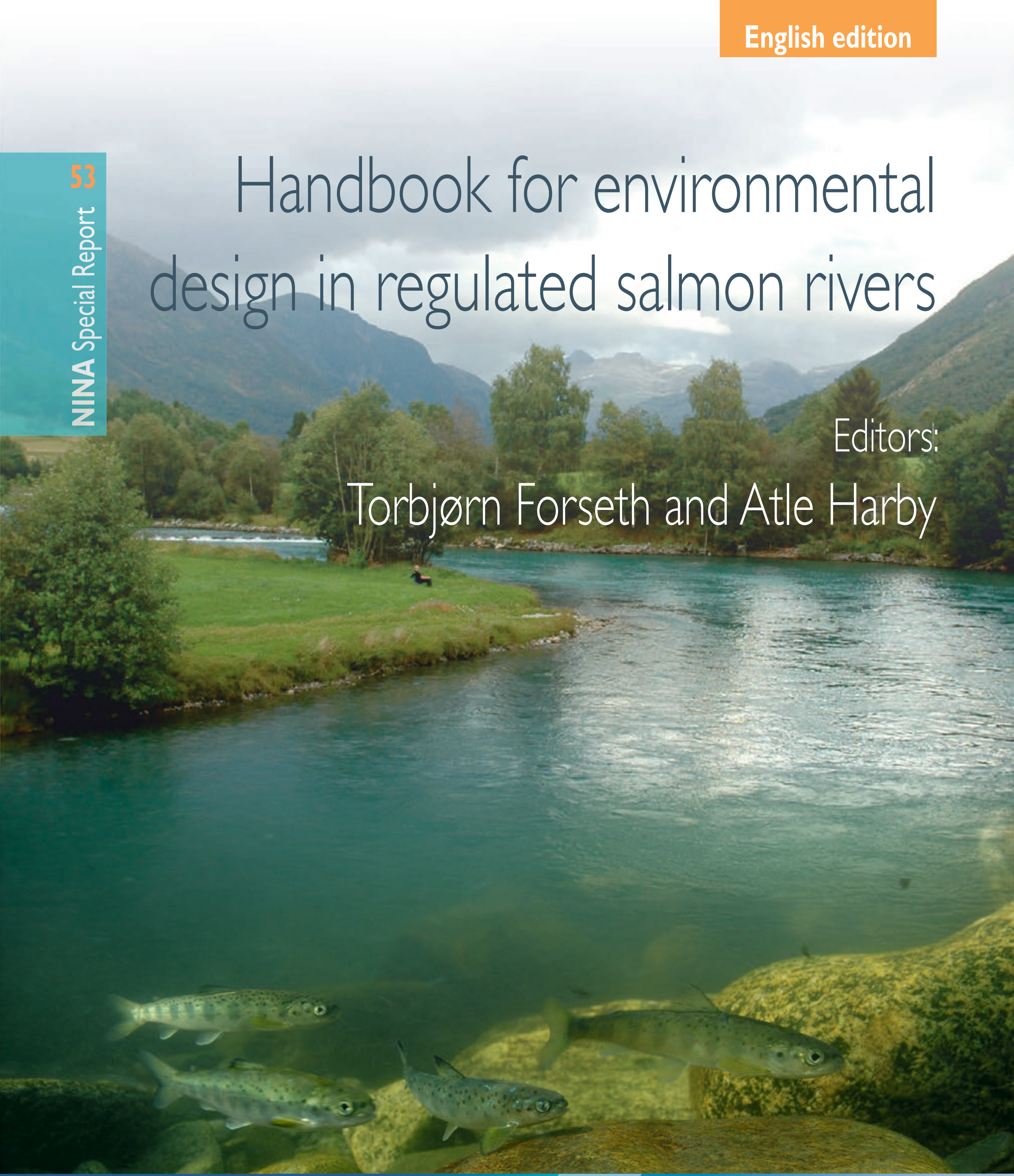
Handbook for environmental design in regulated salmon rivers

Editors:

Torbjørn Forseth and Atle Harby



CEDREN
Centre for Environmental Design of Renewable Energy

FME
CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Handbook for environmental design in regulated salmon rivers

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CEDREN – Centre for Environmental Design of Renewable Energy Interdisciplinary research centre for the technical and environmental development of hydropower, wind power, transmission cables, and the implementation of environmental and energy policy.

SINTEF Energy Research, the Norwegian Institute for Nature Research (NINA) and the Norwegian University of Science and Technology (NTNU) are our major research partners. A number of energy companies, as well as Norwegian and international R&D institutes and universities, are also partners in the project.

The centre is funded by the Research Council of Norway and energy companies, and is administered as part of the CEER programme (CEntres for Environmentally-friendly Energy Research). The CEER programme consists of time-limited research centres which carry out focused and long-term research of high international quality with the aim of addressing specific challenges in the fields of renewable energy and the environment.

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Preface

This "Handbook for environmental design in regulated salmon rivers" is the most important result of the project "EnviDORR" (Environmentally Designed Operation of Regulated Rivers), popularly referred to as "more salmon, more power". Cross-disciplinary research has allowed us to explore the opportunities for combining the interests of salmon production and power production, demonstrated with this handbook. Involved researchers have contributed with bold and innovative efforts. We have highly specialised research teams in the fields of salmonid biology, hydrology and engineering working with hydropower in Norway. However, there is still much to learn about the complex relationships between power production, environmental factors and salmonid population dynamics. At the same time, the public authorities and the industry are facing important decisions in the coming years involving balancing environmental and power production considerations in several river systems. For this reason, the research group has had to make some hard choices based on the best of our current knowledge. We hope that this in itself will provide motivation for further development of our knowledge base, and that this handbook will be a dynamic tool which can be updated when new knowledge comes to light.

The EnviDORR project has been funded by the "RENERGI" programme of the Research Council of Norway, and became part of the portfolio of the CEDREN research centre when it was established in 2009. The project has received considerable funds from the hydropower industry and the public authorities, and I wish to take the opportunity to thank the following partner organisations for their financial and technical contributions: Statkraft, Agder Energi, BKK, E-CO Vannkraft, Sira-Kvina kraftselskap, TrønderEnergi, Energi Norge (involving many of its member companies), the Norwegian Water Resources and Energy Directorate, and the Norwegian Environment Agency (formerly the Norwegian Directorate for Nature Management). Moreover, industry partners such as Hydro, Statnett and Eidsiva have also contributed funds to the CEDREN centre.

In addition to the cited co-authors, many others have contributed to the preparation of this handbook. In particular I wish to extend my thanks to Maxim Teichert (a Ph.D. student working on the project), Lena S. Tøfte, Arne J. Jensen, Nils-Arne Hvidsten, Sven Erik Gabrielsen and Julie Charmasson, all of whom in their different ways aided the project and the development of this handbook. I am also grateful to those of our partners who contributed with their constructive comments to earlier drafts. As the project progressed we presented the concept to CEDREN's scientific committee and received many useful comments, in particular from Klaus Jorde and Daniel Boisclair. Jostein Skurdal has been an diligent proof-reader in the later stages.

Lillehammer, September 2013

Torbjørn Forseth
Project Manager

Photo: Ulrich Pulg

About the handbook

This "Handbook for environmental design in regulated salmon rivers" describes how to evaluate, develop and implement measures to improve living conditions for salmon populations in regulated rivers, while taking hydropower production into account. The concept of environmental design for salmon in regulated rivers involves the special adaptation of environmental conditions that is beneficial to the salmon population. The handbook is intended primarily for those intending to carry out analyses and assessments of issues linked to salmon populations in regulated rivers. However, we also provide a thorough overview of methods, tools and solutions available to hydropower utility companies, the public authorities and other stakeholders. The public authorities may also find the handbook useful as a basis for planning environmental impact assessments, while hydropower utility companies may use it in connection with commissioning of their own surveys. Hopefully, this handbook will also provide better insight into the scope of possibilities linked to improving living conditions for salmon populations, while at the same time ensuring that power production is maintained or increased whenever possible.

Power generation and regulation alter the physical characteristics of a river system and thus also the environmental conditions under which salmon populations live. On the other hand, regulation also creates opportunities to implement environmental design solutions favourable to salmon. Some Norwegian hydropower projects have had major negative impacts on salmon populations, while others have resulted in moderate or virtually no reductions in salmon production. In a few cases it has been shown that salmon production has probably increased following regulation. There are many socio-political considerations calling for efforts to reduce the number of regulations having a negative environmental impact on salmon populations. At the same time, there is an obvious need for higher renewable energy production in the light of climate change. For this reason it is important that improvements in local environmental conditions take place while minimizing loss in power production. The public authorities are currently focusing on developing opportunities for power production expansions linked to measures to improve environmental conditions. Environmental conditions for salmon populations are now a priority consideration in relation to concessions and licences. This handbook describes approaches used to arrive at satisfactory solutions for both salmon production and power production interests. Even though this handbook is considered for salmon, many of the topics covered will apply to other fish species, most notably brown trout.

To a major extent, the handbook is based on work carried out as part of the "EnviDORR" project (Environmentally Designed Operation of Regulated Rivers) at the CEDREN research

Photo: Helge Skoglund

centre (Centre for Environmental Design of Renewable Energy). EnviDORR is funded by the "RENERGI" programme of the Research Council of Norway, backed up by considerable funding from the hydropower industry and the public authorities. The project has enabled us to fill many important gaps in our knowledge regarding environmental design. In some river systems we have demonstrated that with sufficient knowledge and interdisciplinary collaboration in the fields of ecology, hydrology and power production operations, it is possible to arrive at satisfactory solutions. The handbook also builds on existing knowledge of salmon ecology and population dynamics from Norwegian and international sources. Norway has been conducting research on salmon for a century, and our established specialists are in the research front in this field. During the last 50 years, research institutions have carried out innumerable studies and projects focused on salmon populations in regulated river systems. As a result of its investment in hydropower, Norway has established highly specialised research institutions in the fields of hydrology and engineering linked to hydropower. Traditionally, these institutions have worked separately, but in recent years interdisciplinary initiatives have been established which have laid an important foundation for the concept of environmental design, which has now been organised to form the distinct research entity we call CEDREN.

We still do not know everything about the highly complex relationships between environmental conditions and salmon population dynamics, leaving a need for greater knowledge about many aspects. However, lack of knowledge should not prevent researchers from providing our best advice at this time when the public authorities and the industry are facing important decisions involving balancing environmental impacts and power production in several river systems. Re-licensing of concession terms, the EU Water Framework Directive, and new legislation all tell us that "now is the time". This is why the research group has decided to prepare this handbook based on the best of our current knowledge. This process means that we have had to provide our best estimates of some of the eco-hydrological relationships to identify the most critical bottlenecks to salmon production. Thus the handbook also builds on non-published research seminars organised as part of the EnviDORR project, and many discussions which have taken place among the various specialist groups involved.

The concept of "Environmental design in regulated salmon rivers" represents a process of innovation. The ideas and the concept have been developed, and to some extent assessed, in a few river systems. Only when solutions have been implemented and tested over time will we have a fully developed "innovation product". This handbook thus represents a first version. We plan to revise it as new research and applications of the concept are published.

In order to make it more readable and compact, and not to appear too much like a textbook, we have opted to exclude detailed scientific arguments and references from the handbook.

Basic knowledge can be found in the primary literature and in literature summaries in the form of reports and books. Selected and particularly relevant articles, books and reports are listed at the end of the handbook. As an introduction we also provide some new and important information on salmon populations which is of particular relevance to the topics in this handbook.

The handbook is organised into two main sections. The first describes how to make a diagnosis, and the second the types of design solutions available. Both sections include specific descriptions of the methods used.

Overall, the handbook provides a comprehensive scheme aimed at evaluating the current basis, and arriving at recommendations for solutions designed optimally to address the welfare of salmon populations and effective power production in regulated river systems. The scheme is based on an interdisciplinary approach and requires expertise from the fields of salmon ecology, hydrology, hydraulics and power plant operation.

The EnviDORR project has also carried out comprehensive research into two-way migration of salmon passing power plant installations, but we have chosen not to include this topic in the handbook. There are plans for a major increase in research into this issue. If we succeed in obtaining funds from the Research Council of Norway, the hydropower industry and the public authorities, a separate handbook addressing design solutions for fish migration in regulated river systems will be published. In the present handbook we assume that systems facilitating the upstream migration of adult salmon and the downstream out-migration of smolts and overwintering kelts have been or will be developed.

CEDREN is also focusing on research linked to rapid and frequent fluctuations in water level and flow resulting from hydropeaking and hydro operations, and the impact on salmon populations (the EnviPEAK project). The results and recommendations in relation to power plant operations linked to hydropeaking and fluctuations in water level and flow will be presented in a separate report to be issued by the EnviPEAK project. For this reason we will not describe impacts or mitigation measures for rapid and frequent water level fluctuations in this handbook.

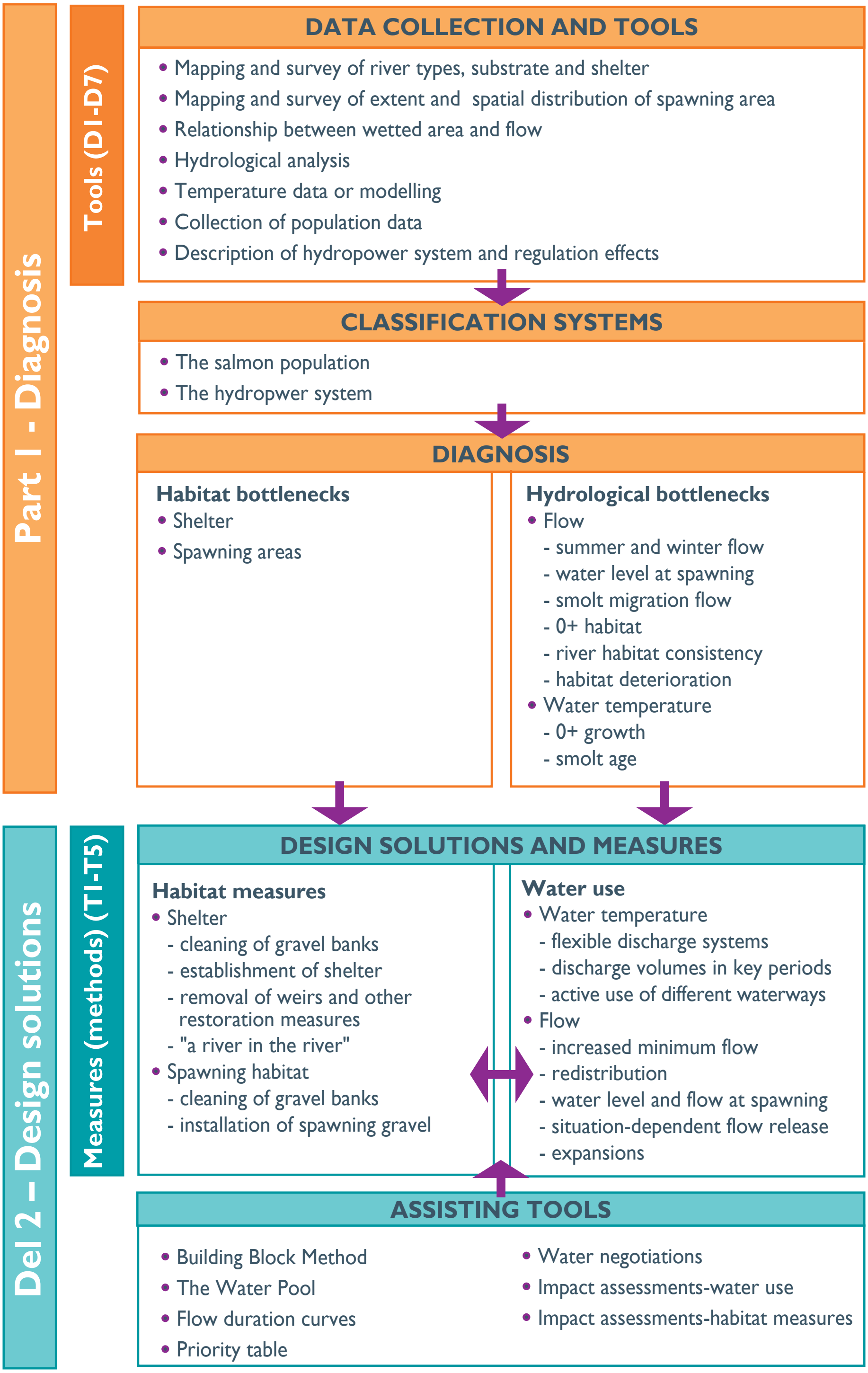
To the reader

Figure 1 provides a description of the overall structure of the environmental design concept, and is designed to help the reader better understand the processes towards effective mitigation measures in regulated rivers. The handbook is organised into two main parts. Part 1 describes how to arrive at a diagnosis, while part 2 describes how effective design solutions can be developed and implemented.

The process leading to a diagnosis is described in part 1 "Diagnosis". This begins with a description of data collection for habitat conditions, hydrology, salmon populations and the power production system. It then moves on to describe how we use a series of classification systems as the basis for a summary table (representing the diagnosis) used to identify and rank the habitat-related and hydrological bottlenecks for salmon production. This table, in combination with a corresponding table for power production and regulation impacts, provides the principal basis for an assessment of measures employed as part of the design solutions. Data acquisition and analytical methods are described in separate chapters (**D1** to **D7**) at the end of part 1. These sections are written mainly for those intending to carry out mapping and surveys, and are of course also useful to those commissioning or issuing directives regarding impact assessments.

When a diagnosis has been reached, the work to develop design solutions can begin. The process used to find effective solutions, and the methods employed to implement these, are described in part 2 of the handbook (Design solutions). As a starting point habitat bottlenecks are addressed using habitat-related measures, and hydrologic bottlenecks using so-called "water use" initiatives (modifications to flow and water temperature). However, the best solutions commonly involve a combination of measures, where the costs linked to water use initiatives are weighed up against the benefits to the salmon population. In this way water is made available where it is most needed. In some cases, costly water use initiatives can be replaced by habitat measures, while in others expansions of the power production system may provide better opportunities for environmentally-designed water use. There are several tools available which can help us to achieve optimal water use design solutions. Such tools assist us in making balanced decisions – the right solution at the right time in the right place – and make it possible to estimate the impacts of different design solution scenarios. In cases where a package of measures has been reached at, habitat measures can be carried out according to established methodologies. These are described in chapters **T1** to **T5** at the back of part 2.

Figure 1. *The structure of an environmental design concept as presented in this handbook. Reference is made to the book's main sections. Note that the colour codes used in the diagram are the same as those used in the book.*



Part 1 - Diagnosis

Tools (D1-D7)

DATA COLLECTION AND TOOLS

- Mapping and survey of river types, substrate and shelter
- Mapping and survey of extent and spatial distribution of spawning area
- Relationship between wetted area and flow
- Hydrological analysis
- Temperature data or modelling
- Collection of population data
- Description of hydropower system and regulation effects

CLASSIFICATION SYSTEMS

- The salmon population
- The hydropwer system

DIAGNOSIS

Habitat bottlenecks

- Shelter
- Spawning areas

Hydrological bottlenecks

- Flow
  - summer and winter flow
  - water level at spawning
  - smolt migration flow
  - 0+ habitat
  - river habitat consistency
  - habitat deterioration
- Water temperature
  - 0+ growth
  - smolt age

Del 2 – Design solutions

Measures (methods) (T1-T5)

DESIGN SOLUTIONS AND MEASURES

Habitat measures

- Shelter
  - cleaning of gravel banks
  - establishment of shelter
  - removal of weirs and other restoration measures
  - "a river in the river"
- Spawning habitat
  - cleaning of gravel banks
  - installation of spawning gravel

Water use

- Water temperature
  - flexible discharge systems
  - discharge volumes in key periods
  - active use of different waterways
- Flow
  - increased minimum flow
  - redistribution
  - water level and flow at spawning
  - situation-dependent flow release
  - expansions

ASSISTING TOOLS

- Building Block Method
- The Water Pool
- Flow duration curves
- Priority table
- Water negotiations
- Impact assessments-water use
- Impact assessments-habitat measures

Some terms and definitions

The following is a list of terms used in this handbook. Usage is tailored to the handbook, and will not always comply fully with more general definitions and usages of the terms in question.

River reach: *A part of a river system which has a uniform impact from regulation, and thus similar flow and water temperature regimes.*

River segment: *A part of a river reach (usually between about 500 and 1000 metres in length) which has relatively uniform habitat conditions and no barriers to any fish movements.*

Habitat: *The physical factors prevailing in the river and river bed.*

Residual flow reach: *A river reach where flow is withdrawn, and where there is no flow release requirements.*

Minimum flow reach: *A river reach where flow is reduced or withdrawn, but where a flow release is required.*

Downstream reach: *A river reach located downstream of a power plant outlet where flow depends on operations of reservoirs and river regulation, and where flow is a) approximately natural or b) seasonally redistributed or c) both increased and seasonally redestributed.*

Spawning water level ratio: *The ratio between average water levels (in cm) recorded during the spawning period and the lowest weekly average (or in some cases daily average) levels recorded during the following winter.*

Winter: *The period from when average temperature drops below six degrees in autumn until it exceeds six degrees the following spring.*

Smolt migration period: *A four-week period in spring during which the vast majority of smolt migrate from the river. The start of this period may vary from year to year.*

Growth period: *A four-six week period following swim-up (for first-year fry) or following temperature increase in spring (for parr) during which most growth takes place.*

(Population) bottlenecks: *A broad term used to describe environmental factors within a river system which contribute towards reducing salmon population sizes. The term encompasses both density-dependent bottlenecks (which during certain periods result in major reductions in population size), and more or less density-independent environmental factors (also called "limiting factors"), which also contribute to population size reductions.*

Salmon fry: *First-year fry (0+) during their first summer in the river.*

Salmon parr: *A collective term for juvenile salmon older than fry.*

Pre-smolt: *Parr which are large enough in autumn to most likely be able to migrate from the river as smolt the following spring.*

Photo: Helge Skoglund

Important aspects of salmon production

Vital mechanisms in salmon smolt production are population regulation processes resulting from density-dependent growth and survival. Our knowledge of these mechanisms, which has increased considerably in recent years, is key to the selection of approaches and classification systems included in this handbook. The term population regulation encompasses mechanisms which prevent the uncontrolled fluctuation of population sizes in response to environmental factors, and it is these mechanisms that allows the definition the salmon carrying capacity in a river. Fish growth and survival are on the one hand dependent on the number of fish present in a given area (population density) and, on the other, access to resources in the form of habitat and food. If densities are high in relation to resource access, growth and survival rates may be reduced and population sizes will adapt to the environment's carrying capacity. In such cases, a population will experience a density-dependent bottleneck. Such bottlenecks may arise at different stages of the fish life cycle (during spawning, during the first summer after hatching, or as parr). Every population and river are unique, and it is essential to identify the so-called "population regulation stages" (the life cycle stages during which population regulation takes place) and the limiting resources linked to each river system and each river reach

Recent research has demonstrated that population regulation mechanisms act primarily at scales much smaller than the river scale. The distribution of spawning areas has a major influence on fish production because fry have only limited mobility. Local population densities, and thus also density-dependent mortality among fry, can be high in the vicinity of spawning areas, while sites some distance away produce few or no fry.

It has been shown that in the case of salmon parr, access to shelter in the form of interstitial spaces between rocks or among twigs, roots and vegetation is crucial in providing protection from predation and reducing energy expenditure. Even though the mobility of juvenile salmon increases as they develop, it is not only the extent, but also the spatial distribution, of shelter available to parr which influences smolt production. Thus also the case of parr, much population regulation takes place at a spatial scale much smaller than the river scale, because the fish commonly fail to fully exploit the shelter available. Thus in some places, especially in the vicinity of spawning areas, parr density becomes particularly high, resulting in reduced growth and high mortality rates, while other sites exhibit densities below carrying capacity. The reason for this limited mobility is probably related to the costs and risks associated with longer distance movements. Also, difficulties and constraints on movement (due to limited swimming capacity) may result in fragmentation of the juvenile fish population. An ideal salmon river thus offers sufficiently large and well-distributed spawning areas combined with easy access to adequate shelter. In both cases, the populations have experienced bottlenecks in which the presence and distribution of spawning areas and shelter represent the respective limiting factors. These are referred to as habitat bottlenecks.

Since density-dependent growth and survival rates are so crucial to salmon populations, and because hydrologic factors are in turn crucial to fish density, we can introduce the term "hydrological bottleneck". Since it determines the extent of water-covered area, it is clear that flow will influence fish density along a given river reach. When flow is high, resulting in a large water-covered area, fish distribute themselves over a large area at low densities. As flow decreases and water-covered area is reduced, fish densities increase (provided that all other factors remain unaltered). Low-flow periods in winter and summer may thus generate bottlenecks which, by promoting density-dependent mortality, reduce population sizes to levels lower than prevailing habitat factors would otherwise indicate.

Even if other environmental parameters (frequently termed density-independent or limiting factors) are not as equally clearly linked to fish density as those factors described above, the distinction between density-dependent factors and independent factors is seldom clearly defined. Many factors which intuitively appear to be density-independent (such as flooding events which may result in mortality among recently-hatched fry), may also have density-related components (such as access to shelter indicating that mortality is dependent on fish density prior to the flood). A guiding principle here is that variation (such as from year to year) in environmental factors such as water temperature, flow regime and nutrient supply, results in variation in river carrying capacity. The action of density-dependent processes ensures that population sizes will follow this variation. In this handbook, we describe all the factors which limit salmon production in their various ways in the form of bottlenecks.

Part I – Diagnosis

During the diagnosis phase, evaluations of the salmon population and power plant system are carried out separately. The main goal is to identify salmon population bottlenecks and the limitations and opportunities in the power production system. During this phase we evaluate the individual factors favourable for salmon populations and power production, respectively. In this handbook a given river system is subdivided into "*reaches*" , each of which exhibits uniform hydrologic conditions. Each reach is in turn subdivided into "*segments*", defined on the basis of habitat (**figure 2**). When we use the term "habitat", we are referring to the physical conditions in the river and river bed.

A *river reach* is defined as a length of river with uniform impact of regulation, and thus similar flow and water temperature regimes. Thus there should be no power plant outlets or intakes, dam structures, or major tributaries within a reach. Depending on its overall magnitude and length, it is recommended to subdivide a reach into segments approximately 500 to 1000 metres in length. Small rivers will have shorter segments than larger rivers, and segments do not have to be of uniform length. They may also be shorter or longer than described above. The following criteria are used to subdivide a reach into segments:

1. A segment shall contain no barriers to the migration of juvenile fish, such as powerful rapids or minor waterfalls which can be passed by adult fish, but which are difficult for juvenile fish
2. Habitat conditions, in the form of substrate size and access to shelter (see **D2**), must be as uniform as possible. For example, within a single segment there shall be no major transitions from areas containing large boulders and good access to shelter, to larger areas dominated by sand or bare rock.

The subdivision of a river into reaches and segments can be sketched from aerial photographs (orthophotos) and then finally determined during habitat mapping and the assignment of river classes. The subdivision will apply to all biological, habitat-related and hydrological data acquisition and analyses described in this handbook.

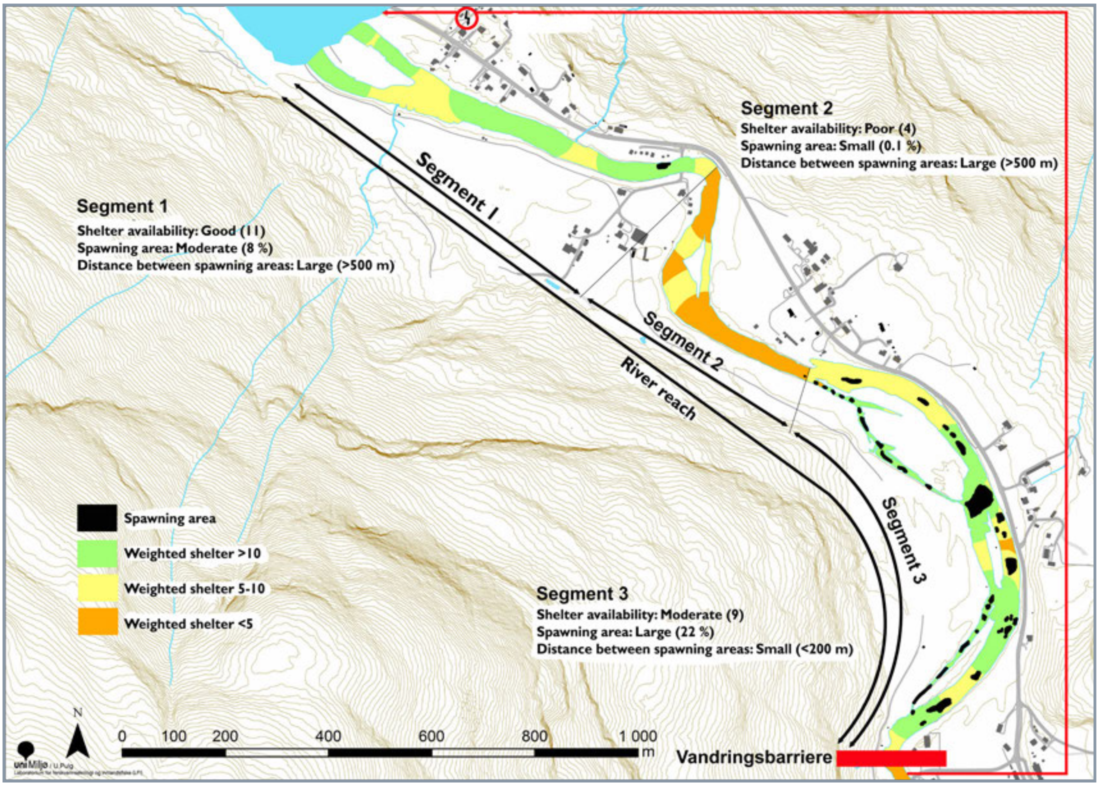
In the following chapters we will describe how salmon populations and the power production system should be mapped, surveyed and evaluated.

Photo: Anders G. Finstad

The salmon population

The main purpose of the diagnosis is to identify habitat-related and hydrologic bottlenecks affecting salmon production, together with bottlenecks which result from the interaction between habitat-related and hydrologic factors. To achieve this, we must identify the main population regulation stage or stages. This can be done by mapping habitat-related conditions and by carrying out hydrologic analyses, supported by survey of population data. Density-dependent bottlenecks can arise during spawning, during the first summer after hatching, or later during the development of juvenile fish. Every population and river are unique, and it is thus essential to identify the population regulation stages and the limiting factors acting in the river system in question. The population regulation stage may also vary from one part of a river system to another.

Figure 2. Illustration of the subdivision of a river into reaches and segments, together with an example of how shelter and spawning areas can be plotted on a map.



Habitat-related bottlenecks

The population regulation stage, and thus also the resulting habitat-related bottlenecks, can be determined by habitat mapping. Additional information can be obtained by acquiring data on age distributions within the juvenile fish population (see Information from population data). The two most important habitat-related factors (resources) which must be mapped in the field are the extent of shelter available to the fish (**D1**) and spawning habitat (**D2**). Both the total extent and the spatial distribution (spread) for both factors must be surveyed along the river reaches in question. It may be useful to plot the distribution of these resources on a map as a basis for evaluation at both reach and segment levels (see illustration in **figure 2**.

The distribution of spawning areas has a major influence on fish production. Because fry exhibit limited mobility, local population densities (and thus density-dependent mortality among fry) may be high close to spawning areas, while areas some distance away may have few or no fry. **Table 1** shows a system in which both the size of spawning areas and their distribution (distance between areas) are combined to form a classification system applicable to each river segment.

Photo: Ulrich Pulg

Table 1. A system for an overall classification of spawning habitat based on size of spawning area (within each segment) and spatial distribution (average distance between spawning habitat across all segments). The limiting values for "small, moderate and large" extent of spawning habitat are provisional, and may be adjusted as and when more empirical data are obtained from Norwegian river systems.

		Extent of spawning habitat as a percentage of river area.		
		Small (<1%)	**Moderate (1-10%)**	**Large (>10%)**
Distance between spawning habitats (across all segments)	Large (>500 m)	Small	Small	Moderate
	Medium (200-500 m)	Small	Moderate	Large
	Small (<200 m)	Moderate	Large	Large

Shelter is measured directly in the field (**D1**) and classified on the basis of an average measure of access to shelter (**table 2**). Spatial distribution (spread) within reaches is based on the distribution of shelter in each segment within the reach.

*Table 2. A system for the classification of access to shelter based on field measurements (**D1**) and calculations of the depth-weighted average shelter values within each river segment.*

Access to shelter (depth-weighted value)		
Poor	**Moderate**	**Good**
<5	5-10	>10

Based on the mapping and classification of extent and spatial distribution of spawning habitat and shelter (**tables 1 and 2**), it is possible to identify the most probable population regulation stage (**table 3**). Using the same survey and classifications, it is also possible to estimate the probable productivity of the river system, and whether the bottlenecks are linked primarily to access to spawning habitat, access to shelter, neither, or both (**table 4**).

Table 3. Identification of the probable population regulation stage based on the classification and extent of spawning habitat and access to shelter. Fry are defined as first-year fry (0+, first summer in the river), while parr is a collective term for older juvenile salmon. Population regulation also takes place in situations where there is good access to shelter and a large extent of spawning habitat, and the limiting factor is denoted as "Unknown".

		Spawning habitat		
		Small	**Moderate**	**Large**
Shelter	**Poor**	Fry +Parr	Parr +Fry	Parr
	Moderate	Fry	Fry +Parr	Parr
	Good	Fry	Fry	Unknown

Table 4. Classification of river segment productivity for salmon based on the occurrence and spatial distribution of spawning habitat and shelter (Blue, yellow and green indicate low, moderate and high productivity, respectively). Limiting habitat-related factors are Spawning= spawning habitat, Shelter=access to shelter and Both=both shelter and spawning habitat. "None" means that neither shelter nor spawning habitat represent important limiting factors.

		Spawning habitat		
		Small	**Moderate**	**Large**
Shelter	**Poor (<5)**	Both	Shelter	Shelter
	Moderate (5-10)	Spawning	Both	Shelter
	Good (>10)	Spawning	Spawning	None

It is not only the extent and spatial distribution of shelter and spawning habitat which are important for salmon production, but also whether there is adequate spatial connection between patches of shelter and spawning habitat. This is because both fry and parr exhibit limited mobility and move only short distances and quite gradually from their hatching site (especially in the case of fry during their first summer). Mobility increases with increasing size and age. Optimal fish production requires that both spawning areas and access to shelter occur in each segment. River systems or reaches with long distances between spawning areas and areas providing good access to shelter may exhibit lower levels of fish production. The **table 4** must therefore be completed for river segments. A segment-based presentation, as illustrated in **table 5** provides a description of productivity (colour code as in **table 4**) in different parts of the river system.

Table 5. An example of classification of productivity (blue=low, yellow=moderate and green=high) at river segment level (500-1000 metre lengths), summarising the most important habitat bottleneck in the segment in question.

Segment	**Productivity**	**Habitat bottleneck**
1	Low	Shelter
2	Low	Shelter
3	Moderate	Spawning habitat
4	Low	Shelter
5	High	Spawning habitat
6	High	None
7	High	None
8	High	None
etc.	High	None

Hydrologic bottlenecks

We have described how physical conditions in the river can result in habitat-related bottlenecks. In the same way, hydrologic conditions will result in bottlenecks in the sense that they determine the size of the living area (water-covered area) available to a population, and its quality in terms of temperature and water velocity. Whereas habitat-related bottlenecks must be described at segment scale (500-1000 metres long), many of the hydrologic bottlenecks may be described and classified at a larger (reach level) spatial scales, defined on the basis of uniform hydrologic conditions (flow and water temperature). The identification of hydrologic bottlenecks is based on; 1) analyses of water-covered area as a function of flow (**D3**), 2) analysis of hydrologic alteration (**D4**), 3) the modelling of temperature changes (**D5**) and 4) the modelling of biological responses to temperature changes (**D6**).

Flow

Water-covered area provides the basis for salmon production in a given river system. The extent of water-covered area varies with flow, but the shape of this relationship depends on the river bed profile and must thus be described at segment level. We assume a proportional relationship between water-covered area and salmon production, such that if water cover increases by 20%, production will also increase by 20%. This presupposes that new water-covered areas which may become available offer approximately the same habitat quality as existing ones. We assume that this is valid until flow becomes so high that the area in question is dominated by water velocities which exceed critical tolerance thresholds for newly-hatched fry (see below). When the relationship between water-covered area and flow has been established for representative segments, and overall for the reaches, it is possible to develop a classification based on the dependency of fish production on flow (from high to low flows) for the relevant area (**table 6**).

The classification can be aggregated from segment to reach level and thence for the entire river system. If the overall water-covered area varies dramatically with flow, flow rates will in themselves act as key limiting factor on salmon production in the river system or reach. However, if such variations are small, flow will be a less important factor.

Table 6. Classification based on the influence of flow on fish production, derived from how much water-covered area changes in response to changes in flow within a given interval.

Variation in water-covered area as a function of flow	Significance of flow and water-covered area
Weak relationship resulting in minor changes	Minor
Moderate to steep relationship	Moderate
Steep relationship resulting in major changes	Major

However, both flow and the extent of water-covered area vary seasonally and from year to year. To identify hydrologic bottlenecks we must therefore identify both the periods of the year when they occure and their duration. This is carried out by analysis of hydrologic alteration (**D4**). Salmon production analyses focus on low-water periods during the summer and winter, and the ratio between water levels during spawning and during low-water periods the following winter (*spawning water level ratio*). Depending on the correlation with flow, low-water periods in summer and winter will result in reduced water-covered area and increases in fish density, which in turn may lead to reduced summer growth rates and/or lower summer and winter survival rates. High flow during spawning followed by low flow in winter can lead to stranding and egg mortality. It is assumed that for these three factors, one week's duration is sufficient to produce a negative impact, and for this reason analyses are usually based on average weekly flow data (weekly averages). Since it is assumed that the salmon population is adapted to conditions prior to regulation, a comparison is made of the lowest weekly average flow in summer and winter before and after regulation (an example is given in **figure 3)**. If the reach under investigation is subject to hydropeaking, or in any other way exposed to short periods of significantly reduced flow during the period in question, it must be analysed separately. Groundwater inflow in spawning gravel may improve egg survival during periods of low flow during winter, and must be surveyed in rivers where groundwater influx is likely to be high.

Hydrologic analyses determine to what extent low-water periods *resulting from regulation* represent bottlenecks (**table 7**). Low-water periods may represent bottlenecks even if regulation has not altered their occurrence. In river systems which usually exhibit low flow in winter (due to frost and low winter run-off), it is assumed that the resulting low-water periods

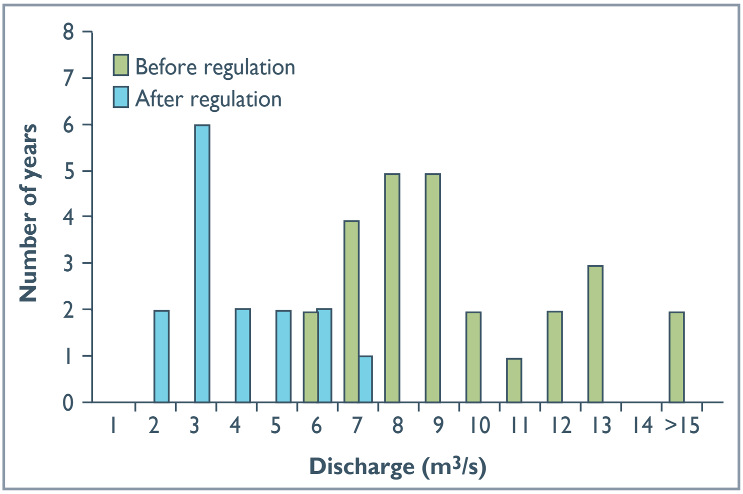


Figure 3. An example of a frequency distribution (no. of years) of lowest average weekly flow before (green columns) and after (blue columns) regulation. From Kvinavassdraget in Aust-Agder county, Norway. The column on the extreme left shows the number of years for which the lowest average weekly flow was less than 1.5 m^3/s (water flow 1) and the next, the number of years for which flow was between 1.5 and 2.5 m^3/s (water flow 2), and so on.

represent more severe bottlenecks than those occurring in summer. In river systems in warmer climates subject to relatively little frost and snow (such as in lowland coastal areas in southern and western Norway), low-water periods during summer may be more important.

Table 7. A system for the classification of, and to what extent changes in the lowest weekly average flow from unregulated to regulated state in summer and winter represent a salmon population bottleneck. (Based on the percentage change in median weekly average minimum flow). If regulation has resulted in an increase in minimum flow, this is assumed to have a positive impact on the salmon population. This table applies to river systems which exhibit naturally low flow values in winter and can be reversed (switching summer and winter) for lowland river systems in southern Norway where summer flow is a more critical factor.

Season	**Change in lowest weekly average**	**Impact on population**
Summer	Increase	Positive
	Reduction < 20%	No bottleneck
	Reduction 20-40%	Weak bottleneck
	Reduction 41-60%	Moderate bottleneck
	Reduction < 60%	Severe bottleneck
Winter	Increase	Positive
	Reduction < 10%	No bottleneck
	Reduction 10-30%	Weak bottleneck
	Reduction 31-50%	Moderate bottleneck
	Reduction < 50%	Severe bottleneck

We use the term "spawning water level ratio" to describe the relationship between water levels during spawning and those during low-water periods the following winter. Significant decrease in water levels after spawning may lead to high mortality among eggs and alevin concealed in the gravel. The impact of additional mortality of this type will depend on the extent to which access to, and distribution of, spawning habitat already represents a population bottleneck. Since egg survival is not directly linked to flow as such, but depends on whether the eggs are covered by water until hatching, we use water level values (in cm) during spawning and during the winter as the basis of the classification. Based on the change in water level from the average during the spawning period to the lowest weekly average in winter, it is possible to determine the extent to which egg mortality due to drying-up or freezing represents a major bottleneck (**table 8**). In some river systems, and especially in those where low water coincides with periods of extreme cold, shorter periods of low water may also result in mortality. In such cases, and in situations where the lowest daily average water depth is significantly less than the lowest weekly average, the lowest winter daily average value is used for the classification.

Table 8. A system for the classification of, and the extent to which, the relationship between flow during spawning and low flow the following winter represents a bottleneck for egg survival, based on the occurrence and distribution of spawning habitat. and reductions in water level from the spawning period average to the lowest weekly average during winter (averaged over a number of years).

		Spawning habitat		
		Small	**Moderate**	**Large**
Reduction in water level	**<30 cm**	Moderate bottleneck	Weak bottleneck	No bottleneck
	30-50 cm	Severe bottleneck	Moderate bottleneck	Weak bottleneck
	>50 cm	Severe bottleneck	Severe bottleneck	Moderate bottleneck

This classification can be modified in the light of data on spawning area depths under typical flow conditions during the spawning period (see **D2**). The classification is applied at segment level.

As noted above, flow during critical periods (with the exception of brief flooding events) may be so high that the river becomes dominated by water velocities exceeding those favourable to newly-hatched fry. This defines an upper limit on flow conditions favourable to salmon production. Fry recently emerged from the gravel grow well during their first month, when water velocities are between 0.2 and 0.4 m/s, whereas poor growth or weight loss may result from water velocities higher or lower than these values. Our assumption is that too high velocities is generally more likely to become a bottleneck. No straightforward method has been established for estimating the extent of areas exhibiting favourable water velocities for first-year fry. It is possible to conduct measurements or hydraulic modelling, but modelling of representative reaches is very time-consuming. For this reason we have opted to recommend a simpler classification addressing the extent to which access to suitable habitat for first-year fry represents a probable bottleneck, based on river gradient and dominating river classes under summer flow conditions (**table 9**). Assessments may be based on qualitative descriptions (from field observations or aerial photographs) and/or more quantitative descriptions of dominant river classes (**D1**). This classification enables the identification of reaches or rivers in which access to favourable water velocities for first year fry *may constitute a bottleneck.*

Table 9. A system for the classification of, and the extent to which, it is probable that the occurrence of sufficiently large areas exhibiting suitable water velocities (less than 0.4 m/s) constitutes a bottleneck for the growth and survival of newly-hatched fry (after emergence from the gravel). It is based either on a qualitative description of stream gradient and velocities along the reach, or the composition of river classes or mesohabitats in the reach (see **D1***).*

Description of the river reach	**Dominant river classes**	**Probability of bottleneck**
Low gradient with large areas of moderate to low water velocities	Pools and shallows (mesohabitats C and D only)	None
Moderate to steep gradient with a mix of rapids and slow-flowing areas	Glides, pools and shallows (mix of mesohabitats A, B1, B2, C and D)	Low
Steep gradient with many rapids and only few slow-flowing areas	Glides, rapids, riffles and pools (mesohabitats A, B1, B2, E, F and limited C)	Moderate
Very steep gradient dominated by powerful rapids and whitewater	Whitewater and rapids (mesohabitats E and F only)	High

Flow conditions can also influence salmon populations in ways other than their impact on smolt production. Flow conditions during smolt migration in spring may influence smolt survival both during migration through the river and after the fish have entered the fjord (in cases where the river in question flows into a fjord). Our assumption is that high and variable flow conditions during smolt migration promote rapid and synchronous migration activity (lasting relatively few days), resulting in higher survival rates than would be the case under low and stable flow conditions (which promote more uniform rates of migration over a longer period). In some river systems temperature increase is the principal environmental factor responsible for the timing and synchronisation of smolt migration. However, our assumption is that changes in temperature resulting from regulation only rarely represent a major problem for migration. Smolt migration is typically limited to a four-week period in spring and its timing must be determined on the basis of surveys of the river or estimated from regional patterns. Variations in average flow, expressed by the coefficient of variation (CV), for the four-week period (**D4**) are used as the basis for a classification addressing the extent to which changes in flow during out-migration following regulation may have an impact on smolt survival (**table 10**).

Table 10. A system for the classification of, and extent to which, changes in flow conditions during smolt out-migration influence smolt survival, based on an assessment of the percentage change in average flow conditions during the migration period (before and after regulation), and variation in flow conditions during the same period (expressed as the coefficient of variation, CV).

Change in flow conditions		**Variation in flow (CV)**		
		>60%	**10-60%**	**<10%**
	<10%	None	Minor	Moderate
	10-50%	Minor	Moderate	Major
	>50%	Moderate	Major	Major
	Increase	Positive	None	Minor

In the longer term, a reduced frequency of flooding events may result in a deterioration of habitat quality, both by the silting of spawning habitats and the clogging of sheltered habitats. Theses types of habitat deterioration can be assessed by habitat mapping (**D1** and **D2**). The occurrence of low-sheltered habitat values recorded in areas with coarse substrate (rocks and boulders), and areas exhibiting only limited spawning but otherwise suitable substrate size distributions (1-10 cm), indicate clogging of sheltered habitat and silting of spawning habitat, respectively. A hydrologic analysis of flooding events before and after regulation (**D4**) will also provide data to support the likelihood that reductions in flood frequencies have reduced, or may in the future reduce, long-term production by causing habitat deterioration (**table 11**).

Table 11. A system to determine the probability of changes in flood frequency contributing to habitat deterioration, based on changes in the frequency and magnitude of flooding events (from before to after regulation).

Reduction in flood magnitude		**Reduction in flood frequency**		
		Minor	**Moderate**	**Major**
	Minor	Low	Moderate	Moderate
	Moderate	Low	Moderate	High
	Major	Moderate	High	High

The river course

In combination with the landscape, flow conditions along a river course also influence habitat composition on a larger, spatial scale. There are links at several different spatial scales between the physical environment and the salmon population's living conditions. An individual salmon will at all times behave according to its immediate surroundings (*microhabitat)*. It is here it finds shelter and food. Throughout its life, a salmon also adapts to diurnal and seasonal fluctuations in its greater environment. Thus a salmon also adapts to river types (*mesohabitats*, such as the presence of rapids and deep pools; **D1**).

Even though our knowledge in this field is somewhat limited, it is probable that the distribution of river types such as rapids, pools and shallows (see **D1**) may influence productivity in a given reach. Reaches which fluctuate between pools, rapids and shallows are commonly regarded as being more suitable for salmon than more uniform reaches. This is because the conditions created within such reaches offers suitable habitat for both spawning fish, fry and parr of different sizes and seasons. Since regulated rivers may have lost some of their natural variation, especially in areas where flow has been reduced or the stream channelled or confined by artificial structures, river habitat composition at reach level may constitute a bottleneck. Reaches with reduced flow may lack deeper pools (exploited by overwintering fish and by adult fish as refuges) and be dominated by shallow and slow-flowing segments. On the other hand, in areas where flow has been increased, segments containing slow-flowing, shallow water may now be restricted in extent and too few to provide suitable habitat for newly-hatched fry, with currents too powerful to provide refuges in the event of flooding. Such changes can be recorded by mapping river types based on flow conditions representative of the those prevailing before and after regulation, or by applying more subjective approaches. At present, the degree of uniformity is assessed on the basis of qualitative descriptions of changes in the river course following regulation (**table 12**). **Table 12** can also be used if the annual mean flow remains the same, but with a different distribution such that typical flow conditions are changed. If typical flow levels are reduced, the system set out for "Reduced flow" in the table should be applied. If typical flow values have increased, the system entitled "Increased flow" in table 12 should be applied.

Table 12. A system to determine the probability of whether the degree of uniformity along a river course resulting from regulation constitutes a fish production bottleneck, based on a qualitative description of changes in habitat components (a reduction or increase in flow) following regulation.

Reduced flow:		
Degree of uniformity	**Type of change**	**Probability of bottleneck**
Low	Shallower and smaller pools, no change in extent of shallows	Low
Moderate	Shallower pools and fewer and smaller rapids, moderate increase in extent of shallows	Moderate
High	Shallower pools, fewer and smaller rapids and a dominance of calm, slow-flowing shallows	High
Increased flow:		
Degree of uniformity	**Type of change**	**Probability of bottleneck**
Low	Moderate reduction in extent of shallows	Low
Moderate	Reduction in extent of shallow areas and rapids, increase in whitewater	Moderate
High	Dominance of rapids and deep rapids, limited extent of shallows and slow-flowing pools.	High

Water temperature

Water temperature influences egg-to-fry development rates and the growth rates of juvenile salmon. It thus also influences the duration of the period in which a salmon remains in freshwater prior to migration as a smolt. Since mortality in the river phase is high and density-dependent, low temperatures increasing smolt ages result in fewer smolts, while higher temperatures provide high numbers of younger smolt – provided that all other factors remain constant. Temperature is an environmental factor frequently modified following regulation, and it is important to describe these changes. In many cases, temperature data will be available from the periods before and after regulation. However, for rivers where such information is absent, temperature data must be obtained by means of modelling (**D5**). Our assumption is that the fish population is adapted to the temperature conditions prior to regulation, and thus we focus here on changes which have taken place subsequently. However, this does not mean that water temperature may also have been a salmon production bottleneck prior to regulation. In Norway water temperatures are generally low. Almost all problems related to water temperature for salmon production is caused by a reduction in water temperature. However, in some cases, reduced flow combined with high air and water temperatures may generate problems.

Water temperature may be a bottleneck for first-year fry if their growth rate becomes very low in their first and most vulnerable year in the river. This may result in increased mortality during the first growth season. Low growth rates may also result in small fry with low energy reserves as winter approaches, potentially increasing mortality. Production may also be influenced if growth rates decline to a level which leads to an increase in smolt age. On the basis of observed or modelled temperature data (**D5**), it is possible to estimate the timing of emergence from the gravel of the fry both before and after regulation, based on knowledge of spawning times and application of egg development models (**D6**). Our assumption here is that modelled changes in timing of fry emergence from the gravel will influence early survival rates if temperature conditions result in delayed initiation of growth and poor growth during the summer. The estimated timing (before and after regulation) of emergence from the gravel, when the fry start to eat and grow, is used to determine the starting date for growth modelling (**D6**). Growth modelling are used as a first assessment of the probability that a reduction in fry growth caused by regulation is so strong that survival during the first winter is affected. The actual size of first-year fry during the autumn, which must be determined by sampling (**D7**), is subsequently used to determine the extent to which reduced water temperatures *resulting from regulation* constitute a population bottleneck (**table 13**).

Table 13. A system for the classification of, and extent to which, reduced water temperatures resulting from regulation constitute a population bottleneck. The system is based on whether changes in growth (derived from modelling) have occurred, and on the size of first-year fry measured in the field in autumn..

		0+ length in winter (mm)		
		>45 mm	**40-45 mm**	**<40 mm**
Changes in growth	**No change**	No bottleneck	No bottleneck	No bottleneck
	Reduced	No bottleneck	Moderate bottleneck	Severe bottleneck

Growth models are also used to compare growth rates and smolt age both before and after regulation in order to determine to what extent smolt production is reduced, as a result of reduced water temperatures during the growing season, and reduced growth rates leading up to smoltification (**D6; table 14**). Analyses of scale samples (before and after regulation) and/or age determinations of juvenile fish or smolt may be carried out to supplement and verify the modelling.

Increases in water temperature in reaches downstream power plants during winter may lead to changes in ice conditions which in turn influence parr survival. This applies in particular to rivers in northern Norway when surface ice, which provided solid ice cover in winter prior to regulation, disappears, and in rivers where regulation promotes the formation of frazil and anchor ice. Frazil and surface ice formation may increase in minimum and residual flow reaches. A classification system for this potential bottleneck has yet to be developed, and these issues must be handled separately as and when required and incorporated into the design solution assessments.

*Table 14. A system for the classification of population impacts resulting from lower water temperatures following regulation, based on a modelled increase in average smolt age (**D6b**).*

Increase in smolt age	**Impact on population**
< 0.1 years	No reduction
0.1-0.25 years	Minor reduction
0.25-0.75 years	Moderate reduction
>0.75 years	Major reduction

Table 15. A system used to determine whether a salmon population in a river reach is primarily recruitment- or parr-limited based on the relative proportions of first-year fry (0+) and 1+ parr. The absence of a limiting stage indicates that there are no discrepancies between the occurrence of first-year fry and parr. In reaches which are clearly recruitment-limited, the density of juvenile fish will generally be low, and this is incorporated as an additional criterion.

Ratio of first-year fry/parr	**Limiting stage**
< 1 and low densities	Recruitment
1-2.5	None
>2.5	Parr

Information from population data

The sampling of juvenile salmon using electrofishing techniques carried out at several spatially distributed stations (**D7**) can be used; 1) to support habitat and hydrologic bottleneck assessments, 2) to provide more detailed information about population regulation stages, and 3) to provide important information about factors influencing growth. Given satisfactory sampling resolution, catch efficiency and fishing conditions, it is possible to extrapolate estimated fish densities by calculating average values either for individual reaches or the entire river system. A population containing a small proportion of first-year fry relative to older juvenile fish, is most probably limited by access to spawning areas, egg survival during the winter, or access to suitable habitat for fry immediately after they have emerged from the gravel. We refer to such a population as "recruitment limited". If the numbers of older juvenile salmon are low in relation to first-year fry, the population is most probably limited by access to sheltered habitat. Such populations are referred to as "parr-limited". As parr develop they are able to move from poorly to better sheltered areas. A useful classification must thus be based on averaged data at reach level (**table 15**).

Such a classification provides an indication as to whether the population in different reaches is primarily recruitment- or parr-limited. The limiting factors can be determined by applying the habitat and hydrologic bottleneck classification systems.

Furthermore, if water temperature is reduced following regulation, it is essential to obtain data on the size of the first-year fry in autumn (see **table 13**).

Aggregated assessment of factors influencing production and bottlenecks

Table 16 provides a pooled and systematic summary of the various classification systems. Habitat mapping, combined with population mapping using electrofishing techniques, provides an overall basis for identification of the population regulation stage. It also forms the basis for identification of the most important habitat bottleneck (the factor limiting for production). Classification of the occurrence of spawning areas and sheltered habitat enables determination of the river system's probable production capacity based on physical conditions. By controlling the extent of water-covered area, the river flow determines the total available living area for fish populations. It is thus fundamental to the diagnosis to evaluate the importance of the flow regime in determining the production capacity of the river. In this light, we can more closely examine the hydrologic bottlenecks which may limit smolt production at the level indicated by the habitat bottleneck. These factors are linked partly to fish concentrations densities, and partly directly to the extent to which physical factors such as temperature, water velocities, ice-related processes, etc. exceed toleration thresholds. Finally, we must consider factors which immediately or in the longer term reduce the number of migrating smolt population-reducing factors.

*Table 16. A summary of the various classification systems used to determine 1) the population regulation stage, 2) habitat bottlenecks and productivity, 3) the importance of flow for overall production (carrying capacity), 4) hydrologic bottlenecks and factors which reduce population size (smolt production and survival) and carrying capacity. The basis for this classification system is given in tables 1 to 14. Numerical rankings (0 to 3) are assigned to scaled factors, and these are applied in the overall diagnosis system (***table 17***). "+" indicates that regulation has had a positive impact.*

Population regulation	Regulation stage based on habitat mapping	Fry/parr/none
	Regulation stage based on population mapping	Fry/parr/none
	Regulation stage – overall assessment	Fry/parr/none
Habitat bottlenecks	Limiting habitat factor	None/spawning habitat/shelter/both
Productivity based on habitat		Low/moderate/high (1-3)
Flow and total salmon production	Significance of flow for salmon production	Minor/moderate/major (1-3)
Hydrologic bottlenecks	Flow in summer	Increased, none/weak/moderate/severe (+, 0-3)
	Flow in winter	Increased, none/weak/moderate/severe (+, 0-3)
	Spawning water level ratio	None/weak/moderate/severe (0-3)
	Probability of 0+ habitat as bottleneck	None/low/moderate/high (0-3)
	0+ growth as bottleneck due to low temperature	None/moderate/severe (0,2,3)
Combination bottlenecks	Probability of river habitat uniformity as bottleneck	None/low/moderate/high (0-3)
Population-reducing factors	Reduced smolt production due to temperature	None/minor/moderate/major (0-3)
	Reduced smolt survival during out-migration	Increased, none/minor/moderate/major (+, 0-3)
	Probability of habitat deterioration	None/low/moderate/high (0-3)

By assigning numerical rankings (0-3) to scaled factors it is possible to estimate an overview of the river system, subdivided into reaches and segments. This overview (**table 17**) represents the final diagnosis, presented at a suitable spatial scale, which provides the foundation for the development of mitigation measures.

Table 17. Salmon population diagnosis at appropriate spatial scale (reach and segment) for a conceptual river system. The diagnosis shows the following; 1) the most probable population regulation stage (Fry=first-year fry, Parr=older juvenile salmon), 2) habitat bottlenecks (Spawn=occurrence and distribution of spawning habitat, Shelter= occurrence of sheltered habitat), 3) an overall assessment of productivity based on habitat conditions, 4) the importance of flow for fish production (carrying capacity), and 5) the probability of existence, or severity, of hydrologic bottlenecks and population-reducing factors. T is temperature. An explanation of the numerical values is given in **table 16.**

Reach	Length (m)	Segment	Length (m)	Population regulation stage	Habitat bottleneck	Productivity (1-3)	Importance of flow (1-3)	Spawning water level ratio (0-3)	Flow conditions in summer (+, 0-3)	Flow conditions in winter (+, 0-3)	0+ growth (0, 2, 3)	0+ habitat (0-3)	T and smolt production (0-3)	Flow during smolt migration (+, 0-3)	Habitat deterioration (0-3)	River course uniformity (0-3)
1	4000	1	800	Fry	Spawn	1	3	2	0	2	2	0	3	0	0	1
		2	1000	Fry	Spawn	1	3	2								
		3	600	Fry	Spawn	1	3	3								
		4	900	Fry	Spawn	2	2	2								
		5	700	Fry/Parr	Both	1	2	3								
2	3500	6	500	Fry/Parr	Both	1	1	3	3	3	2	0	1	0	2	0
		7	600	Parr	Shelter	2	1	1								
		8	800	Parr	Shelter	2	1	1								
		9	500	Parr	Shelter	2	1	2								
		10	600	None	None	3	3	2								
		11	500	None	None	3	3	2								
3	2300	12	1000	Fry	Spawn	2	2	2	2	3	0	1	0	2	2	0
		13	800	Fry	Spawn	1	2	1								
		14	500	Fry	Spawn	2	3	2								
etc.		etc.														

The tabulated values can also be aggregated in order to examine the importance of the different factors at reach and river scale by applying length-or area-weighted averages (for factors with numerical values) or frequency distributions. For example, the weighted average productivity for the example shown in the table would be 1.66, which classifies the river system as having somewhere between low and moderate productivity, and the production is moderately (2.2) dependent on flow conditions. Winter flow conditions and the influence of water temperature on smolt production stand out as the most important bottlenecks.

Power Generation

In order to obtain an adequate basis for the diagnosis and evaluation of potential measures, it is essential to assemble all relevant information about the hydropwer system. Typically the plant operator can provide adequate information about the reservoir (volume and water levels masl), penstocks, tunnels, maps, and the plant itself (power output and capacity). An example is provided in **figure 4**. This and other information obtained from the utility companies must be systematic organised to determine which factors have direct or indirect relevance to the reaches where salmon production takes place. This applies not only to installations and the types of impact caused by regulation in actual reaches, but also to the opportunities that may exist to implement changes to or expansion of the power system.

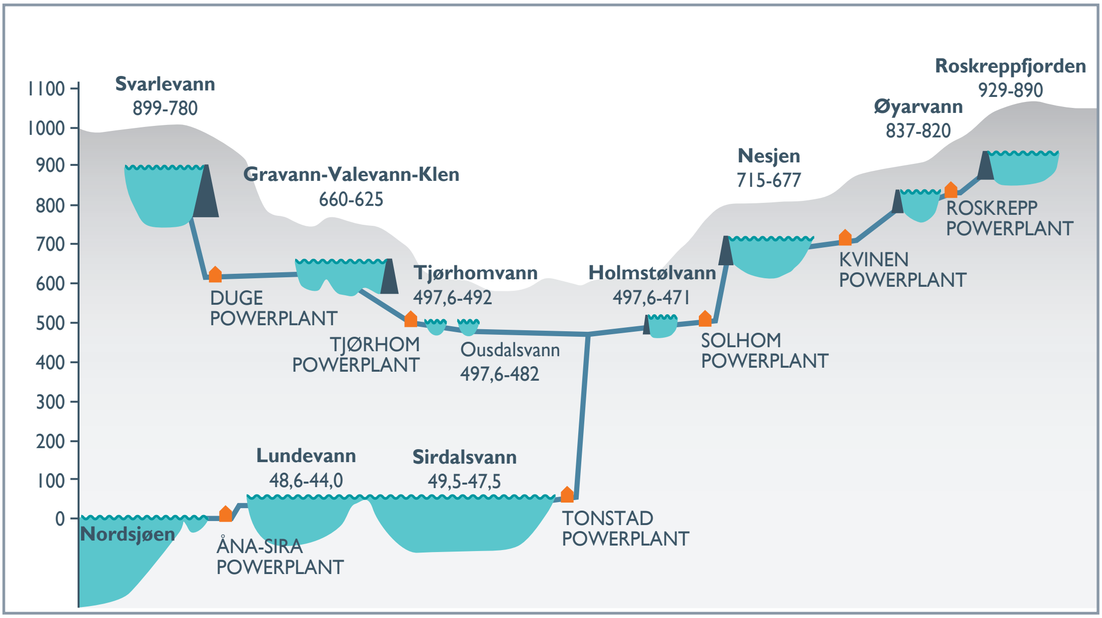
Photo:
Ånund Killingtveit

Installations

The following provides a detailed description of power plant installations both upstream of and within salmon-carrying reaches. Descriptions must be made of all reservoirs upstream of the salmon-carrying reach, including 1) information on typical operational strategies, 2) any restrictions in terms of the maximum and minimum regulated water levels, 3) whether bottom water is being drawn out and 4) whether or not alternative release mechanisms exist. Installations built along salmon-carrying reaches must be described at reach level and the descriptions must include the following;

- Power plant intake (supplementary information: Are mechanisms installed to prevent fish from entering the plant?)
- Power plant outlet (supplementary information: Are there by-pass gates, in the event of plant failure, or barriers installed at or near the spillway to prevent fish from entering via the outlet tunnel?)
- Dams, weirs, gates or other constructions linked to plant operation
- Fishways, fish ladders or other devices installed as environmental measures

Figure 4. Example of a description of a power production system, reservoirs (with lowest and highest regulated water level in masl), power plants and water ways. From the Sira-Kvina hydropower system in Vest-Agder county, Norway.



Restrictions on power production

Hydropower infrastructure is selected on the basis of achieving an optimal exploitation of water resources under the constraints given in the licence. Power generation will be optimally adjusted in relation to energy prices, which will vary both on a daily and seasonal basis. In general terms, licence restrictions, such as mandatory reservoir water levels or environmental flows, will always constrain electricity generation. Authorities may also require that reservoirs are operated reduce flood or drought risk. The greatest negative impact on power production results from those restrictions which impose minimum levels of flexibility, either in terms of time or scope. From a power production perspective it is desirable to;

1. minimise water discharge which by-passes the turbines and
2. exploit the reservoirs in such a way as to maximise economic return and minimise spill of water.

These two issues are linked because inefficient reservoir operation often results in increased spill. Runoff may vary considerably from year to year. This factor, combined with restrictions, and other regulatory or market considerations, may result in very different operational patterns from year to year.

Turbines, gates and other installations have physical limitations in operation relation to flow. A turbine has performance limits within which it can generate electricity. Outside these limits, water must either be retained within the reservoir or released, by-passing the turbine. The majority of turbines perform at maximum efficiency within an optimal range of flow values, and efficiency will be reduced if they have to operate outside this range. This will result in wear and tear which exacerbates efficiency losses, making the turbine prone to more frequent maintenance. Moreover, a requirement to operate under a stipulated flow regime for a given reach may impact on the utilisation of other power plants or reservoirs elswhere in the system.

Alternative operational strategies

Power production models are used to analyse the impact of different operational strategies, and thus to optimise short- and long-term production levels. Information on runoff, reservoir capacity, waterways and energy prices are all included in these models. Plans for future strategies incorporate uncertainties linked to runoff, and market prices which in both the short- and long-term are based on precipitation and temperature prognoses among other information. It is possible using historical data on runoff and power production to compute with relatively high precision the costs linked to various restrictions imposed to meet environmental requirements. Such simulations can be used to identify the most costly measures and also where further environmental assessments should be carried out in order to keep solutions cost-effective. In some cases, environmental restrictions impose major constraints on operational strategies at certain periods, and it is important to evaluate the positive impact of such restrictions against alternative strategies and measures taken during other periods which in total may lead to greater environmental benefits. Many power plants have only limited technical flexibility in terms of their ability to release water or alter discharge patterns in order to meet environmental requirements. For example, a precise minimum discharge will require a bottom gate combined with discharge monitoring, most often with remote measurement and control capability. A further limitation is that in many cases, the reservoir with drawdown capability is located far upstream in relation to the reach where water release will have the most positive benefit. In general, the resulting delay has a negative impact because in practice it is necessary to release more water than is strictly needed in order to safeguard against contravening the restriction.

Effects of regulation

The various power plant installations, reservoirs, intakes, outlets, penstocks and waterways have different environmental effects along different river reaches. In the following we define and categorise the various impacts of regulation at reach level, based on how the flow regime has been modified following regulation.

1. **Residual flow reach:** A reach along which flow is reduced because water has been redirected (to a power plant with an outflow further downstream or transferred another catchment) and where there is no minimum flow. Here, flow varies naturally in response to local runoff from the residual catchment.
2. **Minimum flow reach:** A reach where flow is reduced because water has been redirected (to a power plant with an outflow further downstream or transferred to another catchment), and where there is a minimum flow requirement in place. Depending on the size of the local catchment, different degrees of natural flow variation may be acting in addition to the minimum flow release. Spill flow may arise in the event of reservoir overflow or heavy run-off. In some cases the residual catchment is so small, and the reservoir capacity so large, that flow will almost always correspond to the minimum flow stipulations.
3. **Downstream reach:** Flow at reaches located downstream the power plant outlet depends on the operation of upstream reservoirs and power plants. The flow can be:
    - a approximately natural because storage capacity is small (typical of river power plants),
    - b redistributed seasonally due to the filling and drawdown of reservoirs with storage capacity. Typical redistributions include reduced spring floods and discharges during late spring, and increased discharges in winter. Usually, water temperatureswill also be altered because of upstream storage of water in reservoirs
    - c increased as a result of transfer from neighbouring catchments and redistributed seasonally. Reaches of this type are most often subject to the same type of redistributions, but the differences in flow and frequently also temperature are generally increased.

These general categories are used as the main tools during diagnosis, but must of course be described in more detail in order to include the range of environmental changes (which may vary from large to negligible). In some cases, the power plant can also be used to a greater or lesser extent for hydropeaking, and this may result in rapid changes in flow and water levels downstream.

Other effects of regulation

As well as general changes in flow and water temperature, river regulation may also cause other direct and indirect modifications to environmental conditions relevant to salmon production. In the case of juvenile salmon, ice conditions may represent an important habitat factor subject to change following regulation. During the winter, surface ice may offer protection against predation from birds and mammals, and thus help reduce energy consumption. However, frazil and anchor ice may reduce both access to habitat and winter survival rates. Frazil ice is made up of ice particles formed in open and super-cooled water, typically in rapids, which attach themselves to objects and in some cases form anchor ice. Reduced ice cover is a problem typical of rivers in northern Norway, which under natural conditions are subject to long winters involving prolonged ice cover. In the south, problems may arise due to the increased formation of frazil and anchor ice. In residual and minimum flow reaches, ice occurrence may increase, but for rivers not subject to major ice formation prior to regulation, this will not cause any major problems.

In situations where water is transferred from one catchment to another, or when the flow regime is redistributed differently on a seasonal basis, or when water from a reservoir is released directly to a river reach, chemical conditions in the water may be altered. Changes to nutrient richness (with consequent potential positive and negative impacts on salmon production) and the release of acidified or other forms of polluted water have the potential to influence fish production, and it is thus important to evaluate these issues if inter-basin transfer of water is included. Glacial run-off or other types of turbid water may be released into a river reach which under natural conditions contained only clear water, and subsequently influence productivity. If necessary, turbid water can be redirected directly to lakes or the sea, ensuring clearer water along the reach in question.

In some situations, power plant construction will result in changes in terrain morphology. Such changes may be directly linked to plant operations, such as the canalization of water downstream of the power plant outlet. However, they may also include imorphological changes like the construction of weirs designed to maintain water levels in low flow situations. In some cases, river reaches are extensively reconstructed, and even if this has nothing to do with power production, such morphological alterations may impact on fish production.

Photo: Anders G. Finstad

Opportunities for modification and expansion

It is possible to modify plant operations to comply with new requirements related to changes in run-off, environmental restrictions, or a wish to better adapt operations to market conditions. This may include alterations turbine capacity or changes to daily, seasonal and annual operational strategies.

A hydropower system can be expanded in many ways. The most common of these involve:

A increased output from existing plants (larger plants with more turbines and expanded water ways)

B the transfer of water from neighbouring catchments

C new intake arrangements or modifications to turbine capacity providing greater opportunity to flexible power production, including for example the installation of mini-power plants designed to exploit the head created by releasing environmental flows

In many cases a combination of these measures will be adopted, often involving a need for maintenance, audits and the replacement of existing machinery, equipment and conduits water ways.

Additional regulation may provide greater flexibility, enabling water to be made available for environmental purposes by releasing it during appropriate periods. Water transfer from a neighbouring catchment may provide greater opportunity to make water available for environmental purposes, although there will of course be less water available in the neighbouring catchment. In other contexts, and as an alternative to water transfer, it may be possible to construct a smaller power plant to facilitate the release of water further upstream. This in itself may result in reduced power production, but when compared to alternative solutions may constitute a cost-efficiency measure in relation to salmon welfare. Capacity expansion, or the installation of more turbines and generators, may provide greater flexibility which may have both positive and negative impacts on the salmon population. For example, the installation of turbines that perform well under low flow conditions provides an opportunity to generate more power while also meeting requirements linked to downstream flow during periods of low run-off or low energy prices. If we achieve greater flexibility in power production flows, there will be greater opportunity to avoid rapid changes in flow and water levels downstream of the plant.

Overall description of the power production system and environmental impact

When all data on the power production system has been obtained and organised, a table is constructed at reach level (corresponding to that in **table 17**), including the effects of regulation, flow conditions, water temperature, ice conditions and morphological changes. A brief description of restrictions and expansion opportunities is added. This represents the principal diagnosis in terms of power production and environmental impacts, and an example is presented in **table 18**.

Table 18. Reach level overview showing 1) regulation impact type, 2) power plant installations, 3) environmental changes (flow conditions, temperature, ice conditions and water chemistry), 4) morphological changes along the reach and 5) restrictions and system expansion opportunities. The foregoing text provides an explanation of these factors.

Reach	Length (m)	Regulation impact type	Power plant installations	Changes in flow conditions	Changes in temperature, summer	Changes in temperature, winter	Changes in ice conditions	Morphological changes	Changes in water chemistry	Restrictions	Expansion opportunities
1	4000	Minimum flow	Downstream dam	Major red.	Increase	Red.	Increase in surface ice, red. anchor ice	Weir	None	Minimum flow 2 m^3/s	Mini-power plant
2	3500	Downstream type b	Outflow	Redistributed	Red.	Increase	Removed	None	None	Gradual transitions	Increased turbine capacity New transfer
3	2300	Downstream type b	Dam and intake	Redistributed	Red.	Increase	Red.	Channelling	None	Minimum flow 15 m^3/s	None
etc.											

Diagnosis tools

D1 Mapping of river classes, substrate and shelter

In order to obtain an adequate overview of the river and relevant physical conditions therein, we recommend starting by mapping river classes, and substrate and sheltered habitat distribution. River classes can be categorised either directly or more precisely by using mesohabitat mapping, subsequently pooled into river classes. Mapping starts at the upper limit of an anadromous reach by defining a GPS waypoint prior to progressing downstream. A new waypoint is taken at each each change in substrate class and/or river class (or mesohabitat). Each waypoint is assigned a name to make it clear that it marks a transition from one river or substrate class to another. This process is continued for all changes in habitat characteristics. Access to shelter is mapped along *transects* located at regular intervals (such as 100 m) along the river. At locations where rapid or major changes in substrate are observed, transects must be taken at shorter spacings. Since sheltered habitat is closely linked to substrate composition, the aim here is that records of sheltered habitat should reflect the occurrence of reaches which are uniform in terms of substrate (substrate classes).

This mapping exercise forms the basis for the subdivision of the river into segments according to the criteria illustrated in **figure 5**).

River classes

Subdivision into river classes is based on a classification using so-called mesohabitats. The classification is adapted for use in studies of salmonids and is based on four physical criteria; 1) surface wave height, 2) gradient, 3) water velocity and 4) water depth (**table 19**). The mesohabitat concept is designed to provide a description of the physical conditions that influence the living conditions of fish populations. In the case of salmon we define the following limits; 1) The water surface is defined as "turbulent" if wave heights are greater than 5 cm, or "smooth" if they are less. 2) The gradient is defined as "steep" if it is greater than 4%, and "moderate" if it is less. 3) Water velocities are defined as "fast" if they are greater than 0.5 m/s, and "slow" if they are less. 4) An area is defined as "deep" if the water depth is greater than 70 cm, or "shallow" if depths are less than 70 cm. Mesohabitat lengths may vary. However, in order to avoid too much detail, and maintain a manageable database, they should be as least as long as the width of the river. The composition and extent of mesohabitats will vary according to the flow regime, and in many cases it will be necessary to map them under different flow conditions. Mapping should be carried out by means of field observations made on foot or from a boat, or in some cases by using maps and aerial photographs. The locations of mesohabitats and any other notes (on substrates, sheltered habitat, comments, etc.) are then plotted onto maps, or entered directly into a GPS device. The mesohabitats (A, B1, B2, etc.) are then pooled to determine river classes using Norwegian popular nomenclature (**table 20**), translated into English here and used subsequently throughout this handbook (see also **figure 5**). A simplified, but somewhat coarser, approach is to determine river classes directly.

Photo: Håkon Sundt

Table 19. A classification of mesohabitats based on physical criteria. "Smooth" water surfaces are defined as exhibiting wave heights of 5 cm or less (smooth or small wavelets). "Turbulent" surfaces exhibit wave heights greater than 5 cm (larger wavelets/broken surface). Gradients in excess of 4% are defined as "steep", or "moderate" if the gradient is less than 4%. Water flow in excess of 0.5 m/s is defined as "fast", or "slow" if flow is less than 0.5 m/s. Water depths greater than 70 cm are defined as "deep", or "shallow" if they are less than 70 cm.

Criteria	Water surface	Gradient	Water velocity	Water depth	Class
Classification	Smooth (small wavelets)	Steep	Fast	Deep	A
				Shallow	
			Slow	Deep	
				Shallow	
		Moderate	Fast	Deep	B1
				Shallow	B2
			Slow	Deep	C
				Shallow	D
	Turbulent (Large wavelets, broken surface, standing waves)	Steep	Fast	Deep	E
				Shallow	F
			Slow	Deep	
				Shallow	
		Moderate	Fast	Deep	G1
				Shallow	G2
			Slow	Deep	
				Shallow	H

*Table 20. Classification of river classes based on physical criteria and obtained by the pooling of mesohabitats (**table 19**).*

River class	Mesohabitat	River surface	Gradient	Water velocity	Water depth
Glide	A+B1+B2	Smooth	Moderate	Fast	Shallow/Deep
Pools	C	Smooth	Moderate	Slow	Deep
Shallows	D	Smooth	Moderate	Slow	Shallow
Whitewater	E+F	Turbulent	Steep	Fast	Deep/Shallow
Rapids	H+G1+G2	Turbulent	Moderate	Fast	Shallow/Deep

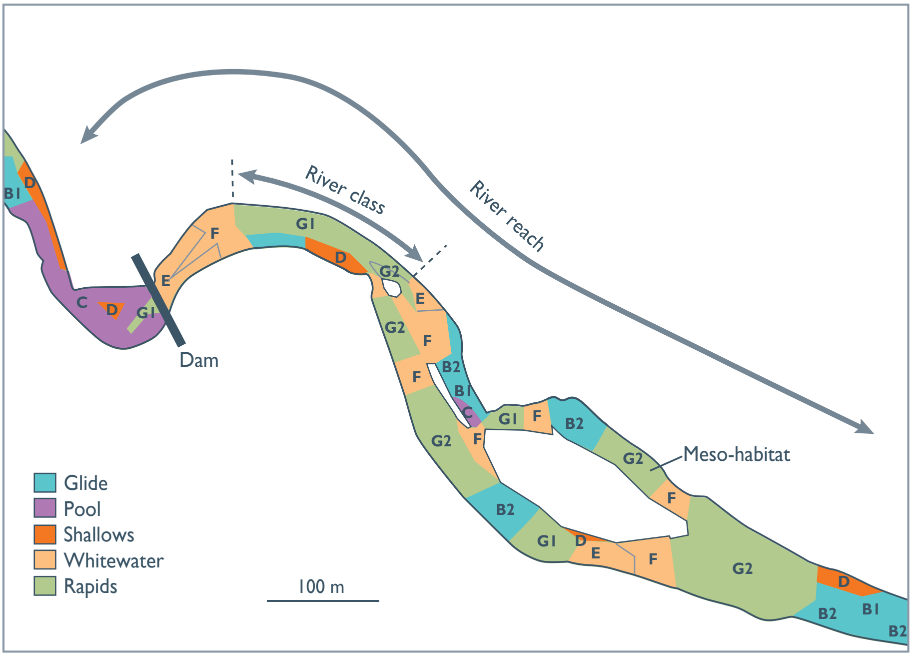


Figure 5. An example of the subdivision of a river reach based on an initial classification of mesohabitats pooled to generate river classes (ref. **tables 19** *and* **20***).*

Substrate

Reaches with relatively uniform habitat are classified according to their dominant and sub-dominant substrate sizes. Substrate is divided into the following categories:

1: Silt, sand and fine gravel (< 2 cm)
2: Gravel and small rocks (2 - 12 cm)
3: Rocks (12 - 29 cm)
4: Large rocks and blocks (≥ 30 cm)
5: Bedrock

These categories are specially adapted to salmon habitat requirements. Categories 1 and 5 are generally unsuitable. Very few juvenile salmon will be found on these substrates. Category 2 represents substrates suitable for spawning, while categories 3 and 4 are ideal for parr of various sizes. Habitat suitability as defined by substrate class is determined by means of direct measurements of sheltered habitat. Substrate mapping is carried out primarily as a guide for where to take shelter measurements.

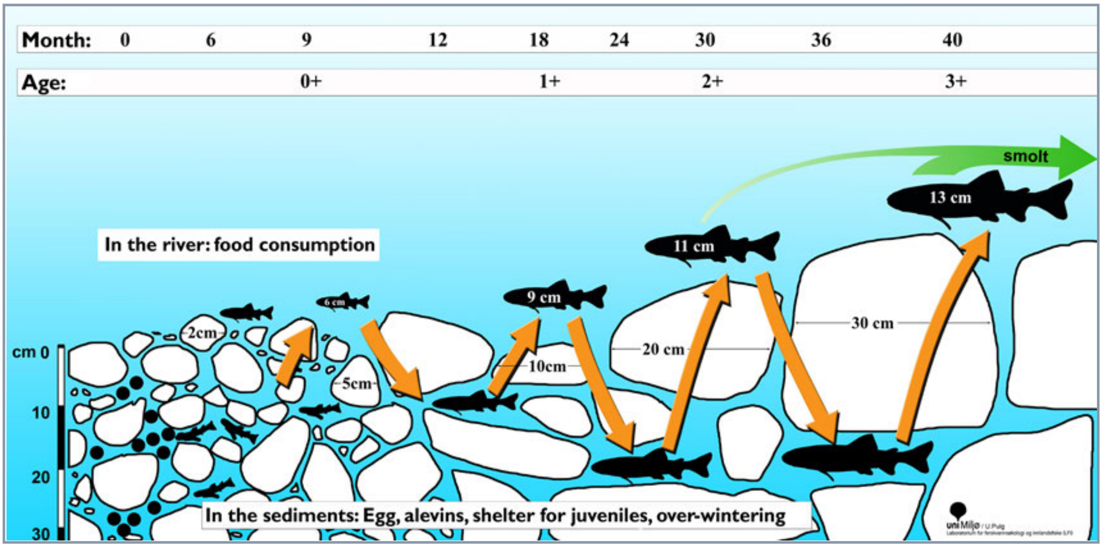
Shelter measurements

Access to shelter in the form of holes and interstitial spaces between rocks is essential to growth and survival, and juvenile salmon spend much of their time hiding between substrate rocks (**figure 6**).

The total number and dimensions of individual interstitial spaces can be quantified by measuring how many times a 13 mm thick plastic hose can be inserted into holes between rocks within the area of a 0.25m^2 steel frame (**figure 7**). The sizes of interstitial spaces are determined based on how far down between the rocks the hose can be inserted. Three shelter categories are recognised; **S1:** 2-5 cm, **S2:** 5-10 cm, and **S3:** >10 cm.

Three measurements (one near the bank, one as close to the middle of the river as is practical, and one in between) constitute a "transect." Within this three-point framework, measurement sites are selected at random by throwing the steel frame into the river. A GPS waypoint is taken to record the location of each transect. The average number of sheltered

Figure 6. *Juvenile salmon exploit the entire upper layer of river bed sediments (approx. 0-30 cm) during their early development. Hiding places (holes and crevices) in the sediments are important in order to avoid predation, for overwintering, for resting, and as refuges during floods.*



habitats for each of the three categories is calculated of each transect. These values are then summed up and weighed to give a value for "weighted shelter" after the following formula;

$S1 + S2 \times 2 + S3 \times 3$

On the basis of the values obtained for weighted shelter, each river segment is assigned a class; "low shelter" (< 5), "moderate shelter" (5-10) or "high shelter" (> 10).

The distance between each transect is selected to obtain the most representative picture of shelter distribution along the river without spending excessive time in the field. Initially, the distance between so-called "fixed transects" will be based on the length of the river. For example, it may be sufficient along short rivers to carry out shelter measurements at 100-metre intervals, while for longer rivers a 500-metre transect interval may be more appropriate. As well as fixed transects, additional measurements should be taken in cases where it is likely that the fixed transect spacing is inadequate to capture the variation in substrate composition (for example in cases where a large area of highly suitable habitat is located between two fixed transects where poorer substrate is recorded).

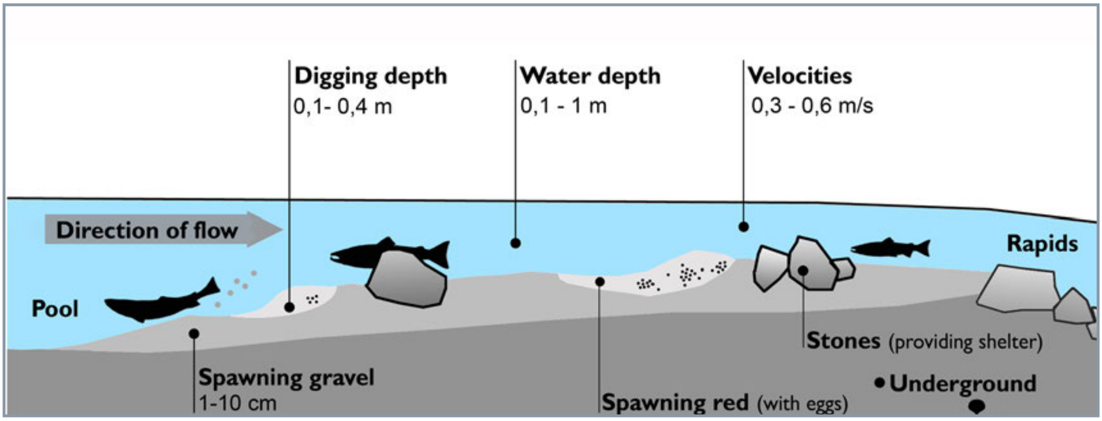
Figure 7. Measurement of sheltered habitat using a 13 mm-thick plastic hose inserted into interstitial spaces between rocks within the area of a 50 x 50 cm steel frame. Photo: Anders G. Finstad

D2 Mapping of spawning habitat

Salmon spawning habitat is defined as an area in which stream bed conditions (substrate composition) and hydraulic factors (in this context water depth and water velocity) combine to provide conditions suitable for spawning (**figure 8**). Substrate is the most robust indicator of suitable spawning habitat because its composition is a result of the hydraulic conditions at the site in question. Water depth and velocity, on the other hand, varies greatly in response to flow conditions. The most suitable spawning substrate consists of a mixture of gravel and rocks with grain sizes normally varying between 1 and 10 cm. Suitable grain size increases with the size of the spawning fish. In general, salmon spawning areas include the categories gravel, small rocks and larger rocks. Suitable water depths and velocities will also vary with body size. Larger salmon prefer to spawn in faster flowing water than smaller fish. In most cases, spawning takes place in water depths varying from salmon body heights (10-30 cm) to ca 1m. In some cases fish will spawn in deeper water. Suitable water velocities for spawning will vary from approx. 0.1 to 1 m/s, the most common range being between 0.3 and 0.6 m/s. In general, classic spawning habitats are found on gravel banks located at the outlets of pools, channels, or lakes where stream bed topography causes currents to accelerate. In general, salmon spawn in coarser substrates and in deeper and more fast flowing water than brown trout. However, there is considerable overlap between the two species, and it is usually impossible in practice to distinguish between salmon and brown trout spawning habitats.

Spawning habitat is mapped by means of observation from the bank, combined with wading or snorkelling. Snorkelling will be necessary in most large rivers, where it is not possible to wade across the river. Spawning habitat is identified on the basis of the criteria listed above, and logged using a GPS device or recorded manually and plotted on maps or orthophotos. The result is a map displaying the extent and distribution of available spawning habitat in the river system. In order to reduce the chance of habitat identification errors, mapping must be

Figure 8. Longitudinal river profile illustrating salmon and brown trout spawning habitat.



carried out by trained and experienced personnel. We recommend that logging is collated with records of the actual occurrence of redds (spawning depressions) and/or observations of spawning fish. In many cases redds appear as paler areas characterised by disturbed substrate, remaining on the stream bed for periods of several weeks or months after spawning. However, it is not always possible visually to identify redds following spawning. In such cases it may be possible to identify them in winter by carefully searching the substrate for eggs using a spade designed for the purpose. The identification of redds and/or eggs provides important supplementary information which can be used to confirm that spawning habitat has indeed been identified. The level of certainty of spawning habitat identification will increase with increased knowledge of the characteristics of active spawning habitats.

Experience indicates that spawning habitats are found in the majority of river classes. The most typical locations are outlets at the margins of pools containing suitable spawning substrate. However, it is also common to find fish spawning in pools, channels and rapids if substrate and hydraulic conditions are suitable. As a result, spawning area extent may display considerable variation. In gravel-rich rivers, although large parts of a reach may apparently be available for spawning, it is common to find that spawning activity will be concentrated at shallower pool margins or other areas where hydraulic conditions are particularly favourable. However, in other types of rivers, larger spawning areas may be few or non-existent. Examples include areas where the substrate consists of large rocks or blocks, sand, exposed bedrock or vegetation, and/or where current velocities are too high or too low to be favourable for spawning. In such rivers or river stretches it is not uncommon for salmon to spawn in favourable substrate dispersed in the form of small pockets (1-10 m^2). Even if such gravel pockets are limited in extent, they may make up a large proportion of spawning habitats in many rivers, especially in those with steep stream bed gradients. If such pockets are absent, it is possible that large areas of a river may lack spawning habitat totally.

It is common that river regulation will have a direct impact on the occurrence of spawning habitats. Dams may obstruct sediment transport and starve downstream reaches of gravels. Man-made structures built along the banks will reduce gravel supply resulting from lateral erosion, and changes in flow conditions may have an impact on the erosion and deposition of gravel. These phenomena are described in more detail in the chapter addressing the use of various measures to deal with the different types of impact.

When mapping is completed, the presence of spawning habitat is calculated for each river segment as a percentage of total stream bed area. Total stream bed area is calculated based on "normal flow" conditions, which in most cases is equivalent to median flow. If spawning habitat constitutes 1% or less of a given segment, it is defined as "low". Values between 1 and 10%, and greater than 10%, are defined as "moderate" and "high", respectively. The results are then summed up for the entire salmon-bearing reach in order to provide a measure of the presence of spawning habitat for the total stream bed area. The threshold values for "low", "moderate" and "high" must be regarded as provisional, and may be adjusted if and when more empirical data are obtained from Norwegian river systems.

The distribution of spawning habitat has a major impact on fish production because fry are restricted in their ability to disperse. Fry density will thus decline rapidly with distance from the spawning area. Due to the high levels of competition among fry, density-dependent mortality will mean that the presence of several dispersed spawning areas will lead to higher levels of recruitment to the population than fewer, larger, and more consentrated areas. River segments offering little or no opportunity for spawning may thus exhibit only limited recruitment. Our assumption is that, in general, fry will establish themselves no further than 200 metres from spawning areas. If the distance between spawning areas is greater than 200 metres, it is likely that the fry will not disperse sufficiently to exploit the local carrying capacity.

D3 Water-covered area under different flow conditions

There is a direct relationship between water flow and water-covered area in a river system that depends on topography, and which may thus vary significantly from reach to reach. This relationship can be determined by means of mapping the water line along river banks under different flow conditions, or by calibrating a hydraulic model of the reach in question. The approach selected will depend mainly on a river-specific assessment of the method which is most cost-effective and technically feasible. Surveying of the stream bed topography can be carried out in different ways. The use of differential GPS enables the use of hand-held technology for measurement of terrain locations both within and outside the river margin. The analysis of orthophotos makes it possible to obtain a rough topographic impression of an area, depending on image resolution quality and the analytical tools available for image processing. Weather conditions will influence image quality. Another approach is to use drones (remotely-controlled micro-aircraft and helicopters). These either employ laser mapping techniques or take high-resolution photographs. Modern drones are small and can be manoeuvred into suitable sites above the river. Laser techniques can be used to obtain high-resolution topographic data of the stream bed, but cannot be applied to areas under water. **Tabell 21** provides a summary and assessment of the various methods. When the relationship between flow and water-covered area has been established, it can be integrated with run-off series and temporal analyses of water cover variation. An overall assessment of such factors along individual segments will indicate which reaches are especially vulnerable to periods of low-water.

Table 21. Selected methods for stream bed surveying, with their benefits and shortcomings.

Stream bed surveying method	Benefits	Shortcomings
Levelling (trigonometry and distance measurement)	Little preparatory work, highly detailed data	Requires unobstructed sight lines from base station
Differential GPS	Little preparatory work, highly detailed data	Requires satellite availability, no access to deep areas of the river without boat/kayak
Orthophotos	Little preparatory work, use with correction service from national mapping authority requires no base station	Lower levels of resolution
Drone mapping	Reliable, enables easy access	Requires considerable preparatory work, lower level of detail
Laser scanner	High resolution data above water	Considerable post-acquisition data processing. Requires unobstructed sight lines from base

D4 Analysis of hydrologic alteration

Flow analyses are based on historical measurements or flow and run-off modelling. Where no measurements are available for a given locality, it is possible to establish computed run-off series based on other data. Measurement series can be extrapolated from neighbouring catchments or by using hydrologic modelling, for which precipitation and air temperature are important input parameters.

Systematic analyses of flow provide statistical parameters such as minimum, maximum, average and median values for a variety of variables such as instantaneous flow, flow per hour/day/several days/month/year, and calculations for pre-defined time intervals (annual, seasonal, monthly, etc.).

A flow duration curve can be constructed by ranking flow data in descending order. Such curves show the length of time for which flow has exceeded, or been less than, a given value (**figur 13**). Curves can be constructed for selected periods such as seasons, a single year, or for all the years for which data are available.

Statistical parameters and flow duration curves provide an indication of the scale and duration of different flow conditions, and provide data used as a basis for comparisons between different river systems. A number of parameters or hydrologic indices can be computed which provide additional information on ecologically relevant flow parameters. We recommend that such analyses be carried out in catchments with at least ten years of historical or calculated data.

The most widely recognised methods for computing hydrologic indices are divided into five categories;

1. Magnitude of average flow (often monthly)
2. Magnitude and duration of extreme flow conditions
3. Timing of annual extreme flow conditions
4. Frequency and duration of high and low flow conditions
5. Rate of change and frequency of fluctuating flow conditions (how fast and how often flow changes from increases to decreases)

In a Norwegian, salmon-related, context, one of the most relevant indices is the seven day low flow index (the lowest average flow measured over seven successive days). The handbook refers to this as "lowest weekly average", as well as simple indices for magnitude, duration and the timing of extreme flow conditions, and indices for fluctuating flow which also take hydropeaking into account.

It is also useful to display the general hydrological alterations taking place within the power production system and affected rivers. This can be done using colour coded maps (**figure 9**). Such maps make the subdivision of a river into reaches easier to envisage, and also provide an immediate overview of alterations to the flow regime. However, it is important to remember that overviews of average alterations do not provide the complete picture because salmon will at all times adapt to actual flow conditions, and not to average values. In most natural and regulated river systems, prevailing flow conditions tend to be somewhat lower than average for long periods, and much higher than average only for short periods (floods).

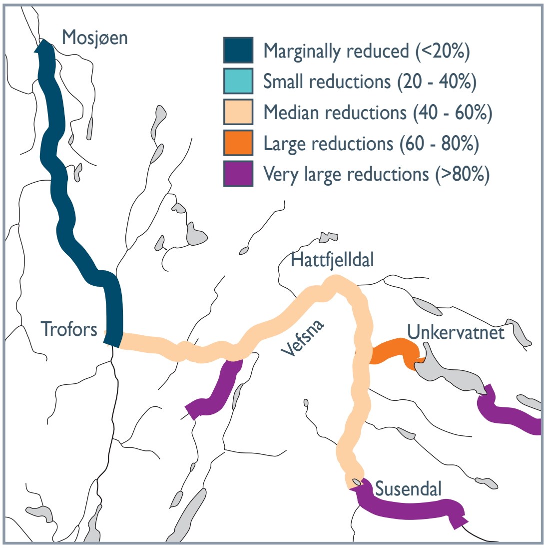


Figure 9. An example of an illustration of hydrologic alterations along different river reaches in complex river systems (from a study carried out in Vefsna, a river system in Nordland county, Norway). The various reaches within the river system are colour coded.

D5 Temperature modelling

Water temperatures in rivers and lakes depend on a variety of physical factors such as;

- Climatic conditions (primarily air temperature and solar radiation) which control the influx of energy to the water surface.
- Flow conditions – transport in rivers and the supply and release of water to and from lakes and reservoirs.
- Magnitude and residence time in lakes and reservoirs, and the location of outflows
- Groundwater

River regulation may lead to changes in temperature and ice conditions as a result of reservoir operations. These changes will in turn impact on the ecosystem. Water release from reservoirs may result in changes in water temperature variation patterns during the year, leading to higher water temperatures in winter and lower values in summer. Changes may have the opposite effect along reaches with severely reduced flow, with warmer water in summer and colder during the winter. Groundwater and local runoff may have an increasing influence on water temperature in some river systems.

The impact of river regulation on water temperature can be measured and computed. Computational models may be based on simple mixture calculations or more sophisticated approaches incorporating energy balance equations in which radiation and air temperature constitute important input parameters. In connection with environmentally-designed hydropower operations, it will be possible to make relatively precise temperature estimates for a variety of water release scenarios. Historical data from the reservoir and the downstream river reaches must then be available. Potential modelling tools fall into one of the following categories;

- Hydraulic water temperature models; These models simulate water temperature along the reach in question as a function of 1) the energy balance along the reach, 2) flow conditions along the reach, and 3) the water temperature within the reach. HEC-RAS, MIKE11, RICE and SNTEMP are examples of models which can carry out such simulations. Such models provide detailed temperature simulations (**figure 10**), but they are relatively complex to set up because they require input in the form of cross-sectional profiles and high quality climatic data in order to achieve a satisfactory result.

- In the case of lakes and reservoirs, a correspondingly large selection of models are available, all based on a physical system description. As with the models used for rivers, these also require climatic data and detailed input on the lake or reservoir in question in order to produce a satisfactory result. The challenges linked to their use are approximately identical, even though lakes commonly exhibit less complex hydraulic characteristics. Examples of such models include GEMSS, QUAL-2W and MyLake.
- Simplified temperature models; There are several simplified models available for estimating water temperature as a function of various climatic and physical variables. These usually link simplified energy supply approaches to the surface area of the river or lake in question. They require less input data than the more complex models, but on the other hand are more sensitive to variations in system variables.
- Regression models for rivers: In situations where observational data of water temperature are available over a given period, statistical models can be adapted and used to simulate water temperature.
- In order to obtain detailed temperature estimates, especially in situations where an estimate is required as a function of altered flow conditions following regulation, detailed temperature models will provide the best results. It has also been demonstrated that in situations where high quality data is available from the start, regression models may also deliver adequate results, provided that the models' limitations are not exceeded.

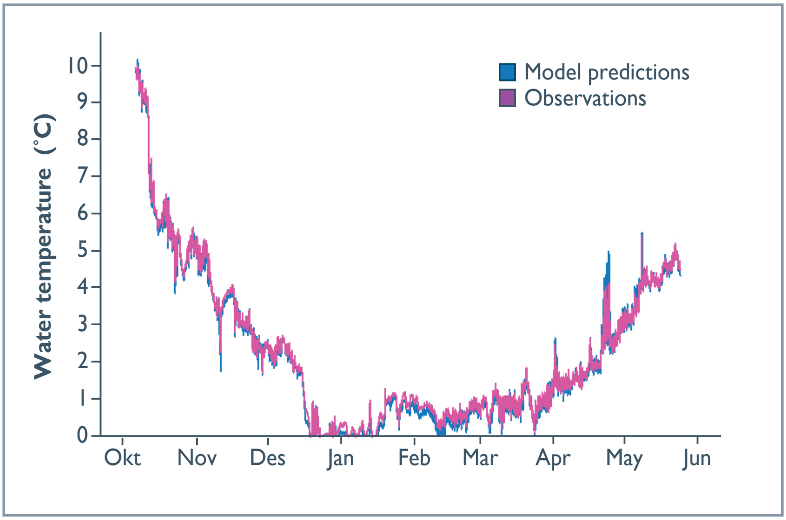


Figure 10. An example of simulated (blue) and observed (red) water temperatures at Marienborg on the Nidelva river in Trondheim in Norway. The simulation has been carried out using the HEC-RAS program.

D6 Temperature response

Egg development models

The impact of altered temperature regimes on egg development and the timing of initial feeding ("swim-up") can be estimated using the Crisp model for egg and alevin development rates. This is carried out by starting with the following model which defines the time interval between fertilisation and hatching;

$$\log D = b \log (T - \alpha) + \log a$$

where D is the number of days from spawning until 50% of the eggs have hatched, T is the temperature, and b, a *and* α are constants. The following constants are used in the case of salmon; $b = -2.6562$, $a = 5.1908$, $\alpha = -11.0$. By using a daily average temperature, daily egg development can be estimated as a percentage (100/D). In order to estimate the timing of "swim-up", the daily sums are themselves summed for development (100/D) from spawning and beyond into the development stage. An estimated hatching time is found when the sum for development reaches 100%, and the estimated time of "swim-up" when development reaches 170%. An example of the model set-up for estimation of development is shown in **table 22**.

If the spawning period is known, hatching and "swim-up" times can be estimated for eggs fertilised at the start of spawning, during peak spawning, and at the end of the spawning period. If the spawning period is not known, development is calculated from the assumed spawning peak.

Table 22. Example of calculation of the estimation of time of "swim-up" using the Crisp model and based on daily average temperature (T) at a given spawning time (1 November). The median egg hatching time is obtained when the sum of 100/D reaches 00%, while the estimated median "swim-up" time is when the sum reaches 170%.

Date	T	D	100/D	Sum (100/D)	
1Nov.	4.3	110.7	0.9	0.9	← spawning
2 Nov.	4.3	110.7	0.9	1.8	
3 Nov.	4.2	112.6	0.9	2.7	
.	.	.	.	.	
.	.	.	.	.	
.	.	.	.	100	← hatching
.	.	.	.	.	
.	.	.	.	.	
.	.	.	.	170	← swim-up

Growth modelling

The impact of altered temperature regimes on the growth of juvenile fish can be estimated using laboratory-based growth models which are able to predict growth based on water temperature data. This can be carried out by starting with the following model which defines weight increase among juvenile fish as a function of water temperature;

$$\begin{cases} M_t = M_{t-1} & T < \mathrm{T_L} \text{ or } \mathrm{T} > \mathrm{T_U} \\ M_t = \left(M_{t-1}^b + \mathrm{b}\left(\frac{(\mathrm{t\,x\,d})(T - \mathrm{T_L})\left(1 - e^{\mathrm{g}(T - \mathrm{T_U})}\right)}{100} \right) \right)^{(1/\mathrm{b})} & T \geq \mathrm{T_U} \;\&\; T \leq \mathrm{T_U} \end{cases}$$

where M_t and M_{t-1} are the fish's weight at two successive points in time (t and t-1), t is the interval in days between these two points, T is the average water temperature (daily average) for the period in question, T_L and T_U are the lower and upper growth threshold temperatures, respectively, b is the growth of a fish weighing 1 g at optimal temperature, while d and g are two parameters which in themselves have no biological significance. Calculations of the fish's increase in weight are normally made on a daily basis, i.e. $t = 1$. However, experience shows that calculations carried out on a weekly basis ($t = 7$) produce approximately the same result.

Laboratory-based growth models of this type have been developed for several Norwegian salmon and brown trout populations. Experience indicates that a growth model applied to juvenile fish growing at moderate rates from *Stryneelva* (a river in Sogn og Fjordane county, Norway) provides an adequate basis for modelling the average growth rates of juvenile salmon in other Norwegian rivers. The model has the following parameters; $d = 0.374$, $g = 0.201$, $T_L = 6.9$ and $T_U = 24.3$. Experiments have demonstrated that for salmon the scaling factor $b = 0.31$. In practical situations, the growth model should be calibrated using growth-related data taken from the locality under investigation. This is most easily achieved by varying the "d" parameter so that the predicted growth progression corresponds as closely as possible to the growth pattern observed.

There is a need for knowledge about how growth patterns altered by regulation have impacted smolt migration age, and thus also on smolt production, as well as the impact of measures designed to change water temperatures (ref. Design Solutions). This can be done by coupling the growth model to an individual population model (using 1000 fish, for example) which, as well as providing an estimate of annual survival, incorporates criteria for establishing relationships between the size of juvenile fish and smolt migration probability. In order to obtain a realistic assessment of potential impacts on population, we must take growth variation among individuals into account, and so introduce a realistic variation in size with age. This variation can be modelled by allowing the growth parameter *d* to vary among individuals during their lifetimes. Every fish included in the model is thus assigned its own growth parameter (*d*) drawn from a distribution (such as a normal distribution with a given standard deviation). An alternative approach is to introduce variation in fish size for each year's cohort (following a completed growth season), and use this to predict the proportion of the cohort that will have grown sufficiently to migrate as smolt in spring at different ages. Variation in size with age should be calibrated with data taken from the local population being modelled (e.g. a standard deviation in size for each age group). The criteria for a relationship between size and probability of smolt migration will probably vary between populations. An individual assessment must thus be carried out in situations where there is a need to make a model-based assessment of how changes in growth conditions impact on smolt age and smolt production. For example, the probability of smolt migration can be expressed using a logistic regression model based on data from the population under study or transferred from similar populations.

A simple population model of this type (run as a spreadsheet or programmed) will be able to provide a growth progression for sets of temperature conditions (either for before and after regulation or for temperature scenarios resulting from different design solution measures; **figure 11**), smolt age distribution, and estimates of changes in smolt production.

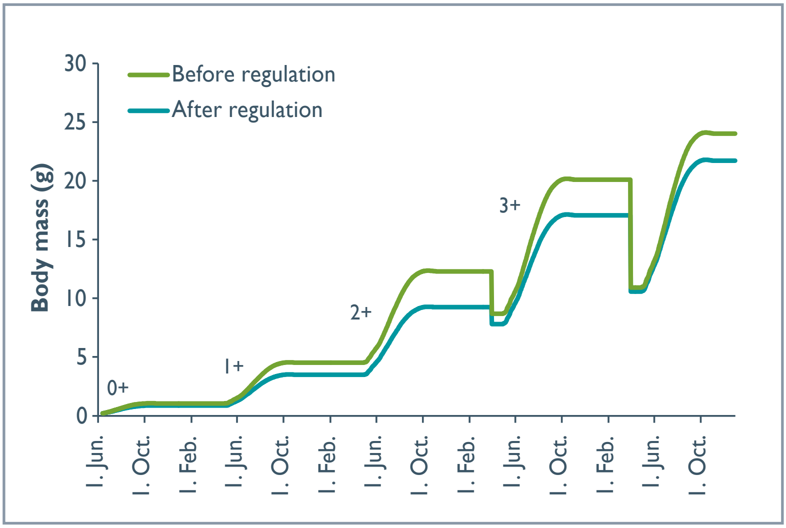


Figure 11. Example of body mass development before and after regulation based on growth and population modelling. In this example, summer water temperatures were reduced because of regulation. The figure shows the median mass (in grammes) and reduction in median mass after ages 2+ and 3+ are a result of the fact that the largest fish (in the model) have migrated as smolt.

D7 Sampling of population data

In order to determine the population regulation stage and identify population bottlenecks, it is essential to obtain population data with adequate spatial distribution. Such data should be acquired at several stations distributed systematically (stratified sampling) along river reaches using electrofishing techniques. Stations are chosen on the basis of shelter mapping (ref. **D2**), i.e., along segments exhibiting a selection of good, moderate and poor shelter values. Each segment (ref. **table 17**) must be represented by at least one station, and there should in principle be three stations per reach kilometre. The shelter categories should be represented in proportion to their total occurrence along the reach in question. It is thus important also to collect fish at stations where shelter is traditionally regarded as "poor". In most rivers fish can be collected using electrofishing equipment mounted on a backpack. The size of the stations can vary from a minimum of 60 m^2 to up to 200 m^2. Stations must be larger for low-density than for high-density populations. Stations should not be located at sites where shelter close to the riverbank deviates from the overall shelter classification. It is not necessary to employ multiple pass fishing in order to obtain a picture of the spatial variations in fish density and the relative strength of age cohorts. If the intention is to extrapolate the results to population sizes, empirical data for catch efficiency (0.4 for first-year fry and 0.6 for 1+ and older) can be used, combined if necessary with estimates from selected stations. Fishing should be carried out in autumn before the temperature falls below 5 degrees. Small landing nets can be used along slow-flowing segments, but larger landing nets or seines will be necessary in faster-flowing areas.

In large rivers containing deeper, slow-flowing reaches, it may be necessary to use electrofishing boats. Such boats make it possible to fish across relatively long transects, and the number of catches per specified time unit can be used as a relative measure of fish density.

The most important parameter in the diagnosis system is the relationship between the density of first-year fry and one year-old fish. Under normal circumstances, first-year fry can be identified using length distributions. Some overlap will be expected between one year-old and two year-old fish, and it may be necessary to analyse scale samples in order to determine a size limit which distinguishes one year-old from older juvenile fish. All collected fish (with the exception of definitive first-year fry in cases of sample sizes greater than 20 at a single station) should be measured for length. We recommend total length. Scale samples must be taken from a selection of fish which probably fall in the transition size range between one year-old and older. The extraction of scales from stunned fish should present no problems. All fish can thus be returned to the river. It may also be possible to compare the relative strengths among other age cohorts, but this requires age determination of the majority of sampled fish. In order to study the relationship between first-year fry and one year-old fish along the different river reaches, fish must be collected over two successive years in order to follow the age cohorts in question.

If collection is carried out in autumn, the size of first-year fry can be used in combination with growth modelling (**D6**) to assess whether lower water temperatures resulting from regulation (which inhibits growth) represent a population bottleneck.

Photo: Ulrich Pulg

Part 2 – Design solutions

Based on diagnoses of the fish population, hydrology and the power production system, design solutions can be developed aimed at optimising the relationship between salmon and power production. Depending on the circumstances, optimisation may involve both so-called "win-win" and "maximum win-minimum loss" solutions. A maximum win-minimum loss solution involves seeking the maximum environmental benefit (increased salmon production) weighed against the least possible loss in power production. Experience indicates that win-win solutions are the most probable outcomes in situations where opportunities exist to expand the power production system. The data obtained during the diagnosis can be applied in the search for new solutions. We are not able in this handbook to describe all the different solutions because these will vary from system to system. However, we can describe both the way in which we analyse situations as a basis for arriving at solutions using a variety of tools, and how many of the measures can be implemented in practice.

Solutions are sorted into two categories which we refer to as "*water use*" (addressing hydrologic bottlenecks), and "*habitat measures*" (addressing habitat bottlenecks). The term water use encompasses factors such as flow and its distribution throughout the year, water temperature, reservoir and power plant operation and water ways (heating and cooling processes).

In some cases water use will be the key focus, while in others, habitat measures will be more important. It is not uncommon that a combination of approaches will be both the most beneficial and necessary. In some cases where water use initiatives are too expensive to implement, less expensive habitat measures may replace losses caused by hydrologic bottlenecks. In the following we will review the tools we use to develop proposals for habitat measures and modifications to water use. In terms of approach, the analyses are based on individual reviews of identified bottlenecks and/or population-reducing factors, and the use of a variety of different tools to identify and prioritise measures, and estimate their impact.

Photo: Håkon Sundt

Water use

Water temperature

In cases where water temperature is identified as a bottleneck for 0+ survival and growth, or where increased smolt age is the cause of reduced production, we must look into potential measures which will modify water temperature. There are many ways of influencing water temperature in a regulated river system.

- Water can be obtained either from reservoirs with different temperature regimes or from different depths within a given reservoir by applying flexible water release strategies or methods for mixing water from different layers.
- Discharge from reservoirs during key periods may influence water temperature by means of a variety of heating or cooling effects.
- The selective use of different water conduits (long or short) may also provide heating and cooling effects. Water released via natural water ways can result in increased temperatures in summer and cooling in winter.

In cases where it is possible to modify the power production system to implement one of the above measures (either by utilising the current system or by building new installations), it may be possible to use measurements and temperature modelling (**D5**), followed by temperature response modelling (**D6**), to compare the current with potential new situations. The first method, involving switching between reservoirs or the use of flexible release strategies, has the greatest potential to produce an impact. The two other methods will commonly involve larger interventions in current operation regimes in order to have an effect. Since much of the growth among first-year fry and parr takes place during a period of four to six weeks following "swim-up" (when the fry emerge from the gravel) or when temperatures increase in spring (for parr), considerable benefit can often be obtained by raising water temperatures during this relatively short period.

Discharges and the water pool

In bypass reaches where water is withdrawn from the river for power production, minimum flow releases are often applied. These releases are often unfavorable both for power generation and effective salmon production. Reaches downstream of a power plant, from which water has not been re-directed, may be subject to downstream flow requirements which make it necessary to produce and discharge water during periods which are unfavourable for power production. In other cases, requirements may exist for short-term discharges such as artificial migration freshets and flushing flows on stipulated dates, which do not always coincide with natural flow variation. In situations where hydrologic population bottlenecks have been identified, the key issue in environmental design is to determine how the total water volume covered by plant operation regulations can be utilised to produce optimal impact. The question then remains as to whether it is possible that water from other parts of the system can be used to reduce the impact of the bottlenecks (see also Expansions and Water negotiations), and whether any additional water is required to achieve a specified positive impact on the salmon population. A further objective is to prepare proposals for other types of situation-dependent water releases which ensures effective smolt migration or habitat maintenance. In order to systematise this work, we recommend use of the so-called "building block method", which is useful both for highlighting challenges and developing design solutions.

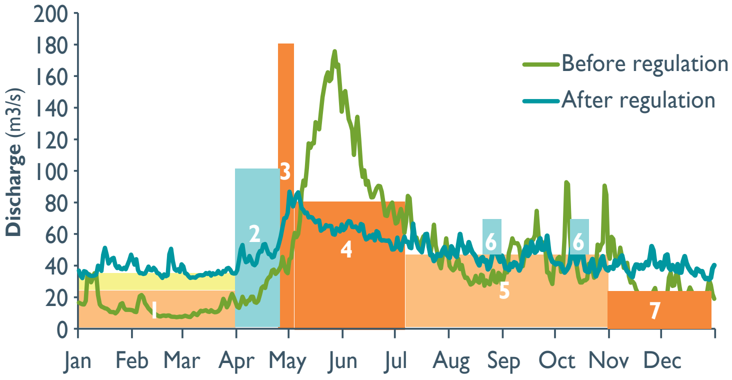
The building block method involves subdividing the river's annual water cycle into stages (building blocks) reflecting the major challenges faced by juvenile, smolt and adult salmon. The building blocks should also act as illustrations of hydrologic bottlenecks and production-reducing factors. In situations where habitat deterioration resulting from a reduction in flooding events is identified as a problem, flushing flows (represented by narrow blocks) can be inserted when regulated flow is high (but not during the period when fry are emerging from the gravel). Daily or weekly average flow values before and after regulation are annotated below the boxes so that it is possible to read off the natural and regulated flow regimes within the river system, as illustrated in **figure 12.** If the river system includes reaches of

Photo: Tor Haakon Bakken

varying hydrologic and regulation-related character, a figure of this type must be constructed for each reach. Data obtained locally from the river in question are used to determine block width (duration of the various periods) and height (flow). Events such as the smolt out-migration period, the time at which fry emerge from the gravel, and spawning time are plotted based on data obtained during the diagnosis. In this handbook, winter is defined as the period from when average temperatures drop below six degrees in autumn to when they pass above six degrees the following spring. The most important part of the growth season starts at the end of winter (as defined above), and ends six weeks after the fry have emerged from the gravel. In some cases, the growth season and smolt out-migration period will overlap.

Block height is a measure of average or total water discharge during the period in question, and applying the sum of the area of the blocks (water volume or so-called "water pool") enables us to prepare a variety of proposals for design solutions based on the same water pool. Use of the summary diagnosis (**table 17**) makes it possible to rank the significance of the different blocks using a shaded colour code (pale to strong), as illustrated in **figure 12**. The dates marking transitions between the blocks can be annotated on the figure together with actual minimum flow requirements.

Figure 12. An example of the building block method showing average flow curves before and after regulation, and the key flow blocks. Duration (x-axis, width) multiplied by flow (y-axis, height) provides a measure of the volume of water in question (area of the blocks) and these can be summed to give the reach's "water pool". 1=egg survival and winter habitat, 2=smolt out-migration, 3=flushing flows, 4=juvenile fish growth, 5=juvenile fish habitat, 6=artificial freshets to facilitate angling interests and promote spawning migration, 7=spawning. The colours indicate prioritisation – from orange (high) to blue (low), based on the severity of identified hydrologic bottlenecks.



The next step is to determine the water volumes available to facilitate environmentally designed discharges. Flow downstream of the power plant in reaches where water has not been re-directed is in the first instance determined by a combination of run-off and release from the reservoirs (where present). In such situations, there is no stable, delimited water volume available for environmental design (as is the case in the example in **figure 12**). In such situations assessments must be based on water volumes during dry, normal and wet years. Along relevant minimum flow reaches, a total discharge volume is calculated, which under current conditions can be implemented to meet the minimum flow requirements. This volume (in m^3) is defined as the reach in question's water pool. In some cases, this water pool can be increased by means of expansion measures or by moving water from other parts of the system according to so-called "water negotiations" (ref. the section Expansions and Water negotiations).

Minimum flow reaches commonly include residual catchments which make contributions over and above minimum flow discharges. Flow duration curves based on historical average weekly flow data are useful tools for assessing how much water is needed to increase flow during specified periods (ref. the example in **figure 13**). Such curves enable us to read off for how many weeks flow must be increased in order to achieve higher minimum flow values. Flow duration curves are constructed for each of the hydrologic bottlenecks for relevant periods of the annual cycle as described in the building block figure. In many cases it will be necessary to discharge small volumes of water during short periods in order to achieve a significant impact on fish production. In other cases larger volumes will be necessary.

As a final option, it is possible to construct a table which illustrates the relationship between the significance/severity of the bottlenecks and the discharge from the water pool required to reduce the impact of a given bottleneck **(table 23**). Combinations on the lower left (coded

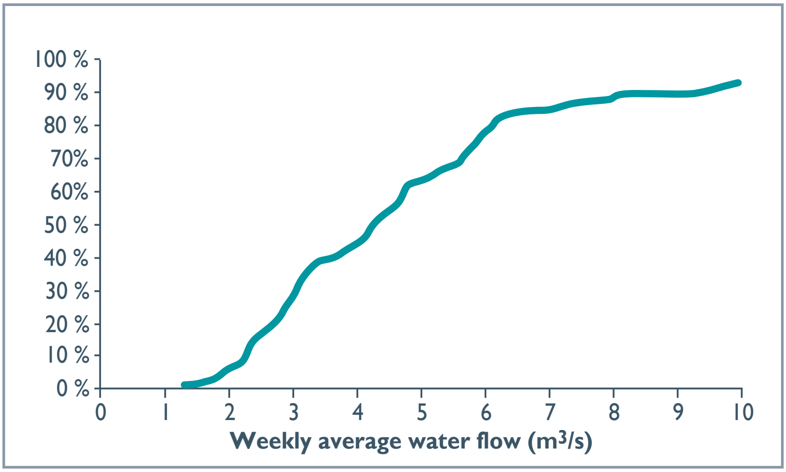


Figure 13. Example of a flow duration curve for weekly average flow in winter (October to March). The curve shows that for "Y"" per cent of the time (y-axis) during the period in question (October to March), flow is less than "X" (.x-axis). The curve displays flow values less than 10 m^3/s.

green) represent the most easily accessible options, and are thus assigned highest priority in relation to water use. Those on the lower right (blue) involve severe bottlenecks and require large volumes of water. They are thus assigned secondary priority. Factors on the upper left (red) also require large volumes of water, but the bottlenecks here are weak to moderate. In these cases, an assessment of the use of habitat measures as alternative options must be made. The last combination (yellow) must be assessed if no other (green) bottlenecks are assigned higher priority. In the following we present some potential design solutions and, where possible, describe the magnitude of the impact the various flow measures may have.

Table 23. Prioritisation of water use from the water pool based on a classification of the discharge volumes (low to high) required to address population bottlenecks (sorted according to severity). Green coded combinations are assigned highest priority, followed successively by red and yellow. Conceptual measures have been inserted for the purposes of illustration.

Bottleneck severity		**Discharge volume**		
		Low	**Moderate**	**High**
	Weak	Flushing flow	Artificial smolt migration freshet	Minimum flow, summer
	Moderate		Minimum flow, winter	
	Severe	Spawning water level ratio		

When we have described flow requirements in the form of building blocks for a normal year, we can also adapt it to illustrate the case of especially dry or wet years. In such cases it may be relevant to include variations in flow requirements onto particular blocks in the figure (such as absolute minimum, absolute maximum and a desired average value). We can do the same with block widths (time intervals).

Minimum flow in summer and winter

A key question is by how much minimum flow has to be increased to achieve a good impact on salmon production along reaches in which winter or summer flows constitute important bottlenecks. There is no definitive answer to this question. For example, how do we define a "good impact" in this context? We employ the following rules of thumb to estimate the impact of the various flow increases.

1. We assume that an increase in lowest weekly average summer flow will result in an impact on the population which is directly proportional to the increase in water-covered area. In other words, if water-covered area increases by, for example 20%, fish production will also increase by 20%. This simple rule of thumb can be modified if is considered probable that newly accessible habitat (new water-covered area) is of better or poorer

quality than that available under prevailing flow conditions, or if increased flow results in lower water temperatures which may reduce the potential benefits of new water coverage.

2. The impact of increasing minimum weekly average winter flow will depend on the magnitude of flow reduction following regulation;
   a. If minimum weekly average winter flow is less than halved, the impact on the population is estimated to be of the order of 0.4 to 0.6 times the increase in winter flow. In other words, if minimum winter flow is increased by, for example 30% (x 0.3), fish production will increase from 0.3 x 0.4 = 0.12 to 0.3 x 0.6 = 0.18, i.e. by between 12 and 18 per cent.
   b. If minimum weekly average winter flow is less than halved, the impact on the population is estimated to be of the order of 0.1 to 0.2 times the increase in winter flow. In other words, if minimum winter flow is increased by, for example 150% (x 1.5), fish production will increase from 1.5 x 0.1 = 0.15 to 1.5 x 0.2 = 0.3, i.e. by between 15 and 30 per cent.

This rule of thumb is used to provide quantitative impact estimates. Follow-up assessments of introduced measures are important to provide support for or revise the rule. Due to a lack of knowledge of the underlying mechanisms, the levels of uncertainty for impact estimates following increases in winter flow are high.

Spawning water level ratio

In situations in which spawning water level is identified as a bottleneck, an imbalance exists between flow during spawning and flow during the subsequent winter. There are two ways of resolving this bottleneck;

1 If possible, flow during the spawning period should be reduced to levels which still permit the fish to spawn in areas which remain water-covered throughout the winter. This approach assumes that key spawning areas can be utilised even though flow is reduced. In other words, that such areas do not become dewatered, water depths do not become too shallow, and water velocities do not become too low (see **T2** for limiting values). This approach will be of particular interest if winter flow does not constitute a severe bottleneck and/or water consumption for increasing winter flow is high (cf. **table 23**).

2 Increase winter flow. This approach must be considered in the context of an increase in winter flow designed to boost winter survival among fry and parr (see above). It will be of particular interest if winter flow constitutes a severe bottleneck and/or water consumption is low or moderate (cf. **table 23**).

In both cases (1) and (2) the bottleneck can be reduced considerably if water levels reductions can be restricted to 30 cm or less (see **table 8**).

Situation-dependent discharges

There are two types of water releases which do not necessary need to be carried out on an annual basis, or according to stipulated dates. These are termed "situation-dependent". Such water releases are designed to ensure that smolt migrate when flow is high, and so-called "artificial freshets" are implemented to help maintain habitat quality along the reach in question. If flow during smolt out-migration is considered to represent a major bottleneck, it may be possible to discharge water during the migration period in order to provide increases in flow which stimulate migration. However, such discharges will only be necessary in years when natural flow and reservoir release is low and stable. They will not be required if flow is already high and variable. For example, the situation can be examined halfway through the smolt out-migration period. The following is an example of a set of criteria used to justify water discharges of this type (cf. **table 10**).

1 Flow has been high (on average in excess of 80% of that prior to regulation) with a coefficient of variation (CV) greater than 50% – no water release necessary.

2 Flow has been moderately high (50-80% of that prior to regulation) with a moderate CV of 25-40%) – a single water release should be implemented.

3 Flow has been low (less than 50% of that prior to regulation) with a CV of less than 20% – two separate water release events should be implemented with one week's interval.

This is a conceptual example and such criteria must always be adapted to local conditions and the extent of regulation. Discharges must as far as possible be adapted to weather conditions (implemented preferably during periods of overcast and/or rainy weather), and variations in natural flow (it is always best to reinforce natural flow increases). Flow increases, including the natural increase in flow must be greater than 30% of initial flow values.

If it is likely that reduced flood frequency magnitude are contributing towards habitat deterioration due to silting and the blocking of interstitial spaces, it may be advisable to implement flushing flows, either on an annual basis or at longer intervals. Water release of this type should be carried out so that they reinforce natural flood peaks (often in spring or autumn). For example, it may be possible to stipulate that one release should be implemented every three years, and carried out only when flow conditions are already favourable. Discharges must be carried out in such a way that the overall flow regime generates a flood sufficient to disturb and mobilize the stream bed substrate. In many cases this will be equivalent to an average flood (largest annual flow average prior to regulation), which statistically will occur at intervals of between 1.5 and 2 years. If such floods occur naturally during the period in question, it will not be necessary to implement flow releases of this type. As in the case of artificial smolt migration freshets, the criteria applied must be adapted to local conditions. Discharges must not be carried out during, or for an interval of three weeks after, the period during which the fry are emerging from the gravel (ref. **D6** on how to determine the correct time). Since deposition processes and the growth of vegetation have a self-reinforcing effect, the magnitude of a necessary flushing flow will depend on the frequency of such discharges and natural floods. Long intervals between flushing flows will increase the need for larger discharges. The volume of sediment supplied to the river system from unregulated tributaries and other sources, such as agricultural run-off, will also influence the need for flushing flows. In some river systems, ice jams and scouring will help towards mobilising stream bed sediment, and there may be no need for a flushing flow. This must be evaluated for each river system on a case-by-case basis.

Situation-dependent flow releases may also be carried out to improve angling conditions, but these are not discussed in this handbook.

Expansions

The term "expansions" in this handbook is understood to mean expansions of both the power production system and of areas dedicated to salmon production. Such expansions have the potential to lay a new foundation for the development of measures which, taken together, will have a positive impact on both power production and salmon production.

Norway has a long tradition for increasing the salmon-carrying reaches for angling purposes, especially in unregulated river systems. Currently, the environmental authorities are in general more restrictive in relation to such expansions than in the past. However, this does not mean that salmon-carrying reaches cannot be expanded, and measures applied to regulated rivers remain fully feasible. Such expansions may include tributaries or reaches of the main river system located upstream of barriers to fish migration in locations where measures to promote up- and downstream migration may be implemented to compensate for the impacts of regulation, and/or combined with measures aimed at boosting production. In order to be able to utilise such areas, a licence application must be submitted to the environmental authorities. Normally, the following issues will come under consideration;

1. The possible impacts of the introduction of salmon (and thus also of brown trout) on other fish populations (ecology) and angling (socio-economic) interests to the reach in question.
2. The potential impact on biodiversity, i.e., the effects of the introduction of salmon on the remainder of the ecosystem.

3 Possible issues linked to fish diseases.

4 The impact of modified management regimes (from inland fish to salmon).

In addition to making use of new areas, it will in some cases be possible to increase the area available for production by re-opening old river courses (ref. **T1**).

It is not within the scope of this handbook to present a full list of potential power plant expansion options. Our point of departure is that both the energy and environmental authorities have pointed out in general terms the possibilities linked to the expansion of existing plants, in particular in connection re-licensing processes. The expansion of existing plants can commonly be implemented with little or no additional impact on already affected river systems. When we us the term "expansions" it refers to the measures that also can be used to improve conditions for salmon populations. This can be achieved in the following ways;

- the provision of greater flexibility in flow and a larger water pool which can be used to facilitate environmentally-designed water discharges,
- the provision of better water distribution throughout the year, or
- of water releases that can be carried out without major reductions in power production.

Expansions of particular relevance include:

- the transfer of water from neighboring catchments to the actual catchment, and allocation of parts of this additional water to the river system's water pool for environmental purposes.
- the installation of small power plants which exploit existing, and increases in, water releases to provide minimum flow conditions for the benefit of salmon.
- the installation of small power plants which exploit new environmentally-designed water releases in other parts of the river system, such as residual flow reaches.
- increased and more flexible capacity within the main power plant designed to exploit high flows and flood events, which may increase as a result of climate change or greater opportunities for power production under low flow conditions. This may compensate for losses incurred when minimum flow discharges are increased.

Depending on local conditions, expansions of this type can result in "win-win" (more salmon - more power), "win-no loss", and "maximum win-minimum loss" scenarios. Naturally, some of the expansions will have other environmental and socio-economic impacts which will have to be evaluated in the usual way by means of impact assessments.

Water negotiations

The term "water negotiations" refers the process by which a critical review is made of plant operation regulations and resulting flow conditions in order to see if other approaches to water allocation or use may be of greater benefit to fish production, and in some cases also for power production.

Based on the analyses of fish population production conditions and bottlenecks (summarised in **table 17**), the description of the power production system, including identified restrictions and expansion opportunities (**table 18**), and the various solutions drawn up using the building block method (**figure 12**), it may be possible to carry out the following:

- identify water releases or other provisions which are neither favourable for power production nor important to salmon populations, to see if it is possible to move water between periods,
- assess whether increased power production in parts of the system, or during certain periods of the year, can be traded against increased water releases or downstream discharges in particularly important parts of the river system or periods of the year,
- identify whether by employing physical measures in some parts of the river system it might be possible to achieve the same effect as a flow release, in order if possible to move the release to other parts of the river system or to other periods of the year, and
- investigate whether there are restrictions linked to reservoir filling which result in operational practices with unfavourable impacts on salmon-carrying reaches, and whether it is possible to modify these in the context of an overall assessment of impacts on the reservoir and river system.

Habitat measures

Habitat measures can be implemented as extensions of or alternatives to increased water use. They are of special relevance in situations where large volumes of water are required to reduce flow-related bottlenecks (ref. **table 23**). However, it is important to be aware that habitat measures will not necessarily exert a full impact as long as severe flow-related bottlenecks remain in the system. In such situations it is often necessary to employ both types of measures.

The purpose of habitat measures is to reduce the impact of habitat bottlenecks using the overall diagnosis presented in **table 17** as a starting point. Measures may range in scale from minor to moderately large, such as the restoration of spawning or sheltered habitat (**T1-T3**), to more comprehensive projects such as the removal of weirs or the development of "river in the river" initiatives (**T4-T5**). The planning principles behind the least extensive measures are straightforward;

- In river reaches where productivity is low due to lack of spawning habitat, existing spawning areas can be restored (**T1**) or new gravel beds artificially installed for spawning (**T2**). This is particularly relevant where spawning habitat is identified as a major habitat bottleneck along successive downstream segments of the reach in question (ref. **table 17**).
- In river reaches where productivity is low due to a lack of shelter for parr, silted habitats can be restored (**T1**) or new sheltered habitat can be created artificially by placing rocks in the river bed (**T3**). This is particularly relevant where shelter is recognised as a major bottleneck along successive segments of the reach in question. However, since parr can move over longer distances, the threshold for carrying out such shelter-improvement measures must be somewhat higher than for spawning habitat initiatives.

The impact of such measures can be roughly assessed by assuming that they improve productivity along the segments/reach from, for example, category 1 to 2 or 3. If there exists population data (such as parr or pre-smolt densities) linked to a productivity classification, it will also be possible to estimate the benefit of the measures in terms of smolt units. In the absence of local population data, a coarser estimate can be derived from empirical, habitat quality-related, smolt production data taken from other river systems, as follows;

- Low productivity reaches (category 1): 2-4 smolt/100 m^2
- Moderately productive reaches (category 2): 5-9 smolt/100 m^2
- High productivity reaches (category 3): 7-13 smolt/100 m^2

In some situations, changes to habitat following regulation will be so extensive that larger-scale measures will be necessary. This applies in particular where weirs or other barriers have been constructed to maintain water-covered area, or where residual flow is distributed across a wide stream bed. These situations commonly result in slow-flowing shallow water reaches, generally unfavourable to salmon. In locations where weirs have been constructed along minimum flow reaches, recent experience indicates that effective results can be achieved by their removal (**T4**). In some cases, deeper water, weir-enclosed reservoirs will constitute important refuges for spawning fish prior to spawning. If the removal of all weirs will result in only a few, and only small, deeper pools, we should consider preserving some of them. In cases where slow-flowing, shallow-water reaches still remain after weir removal, or where, along bypass reaches, only minor volumes of water are flowing in a wide stream bed, it may be possible to build a "river in the river", by confining the water course and constructing pools, riffles and meanders within the stream bed (**T5**).

Since fine-grained sediment tends to accumulate in weir basins and slow-flowing, shallow-water reaches, it may also be necessary to support such large-scale initiatives by additional measures aimed at creating spawning areas and shelter (**T1-T3**). As above, a coarse impact assessment can be made based on estimates of improved productivity. In both cases, the possibility that benefits may be reduced if flow-related bottlenecks are not addressed, must be taken into account.

*Photo:
Ulrich Pulg*

Overall action plan

The approaches described in this handbook are based on the identification of bottlenecks, and the development of measures designed to reduce or remove them. There will always be constraints on both salmon production and power production, and it is thus essential to adopt a holistic perspective. Mitigation measures should not simply result in shifts from one bottleneck to another.

In order to arrive at the best overall action plan, which often involve a combination of habitat and water use initiatives, we must evaluate sets of mitigation measures ("scenarios") as part of a process of iteration. In other words, we develop a selection of prepared scenarios to compare estimates of their cumulative impact on salmon production. As far as possible, estimates of smolt production should be quantitative (expressed numerically or as percentage of change). This can be achieved by using the rules of thumb and approaches described in the previous chapters. In the case of water use, we recommend that a variety of levels (for environmental flows or other environmentally-related discharges) be applied in the various scenarios. Some of the habitat measures will require both investment and maintenance costs. Changes in water use will impact on power production and the utility company's profitability, and major modifications of the power production system will naturally require investment and will impact on power production. In some cases investment and operations costs will be so high that some initiatives will be regarded as impractical, and it will be necessary iteratively to search for alternative scenarios.

When comparing different scenarios, it will often be necessary to obtain data on the impacts they will have on power production and profitability. Estimates can be derived using power production simulation models. Such analyses may be performed by the personnel carrying out the study if they have adequate expertise in the energy market and use of modelling tools. However, in many cases it will be the power production planners employed by the utility company who will carry out the simulations and present the results.

As well as the factors described in this handbook, additional assessments must be made. Consideration must be given to assessing the impact of, and if necessary applying limits to, rapid changes in water levels and hydropeaking. Assessments of the potential impact on the upstream migration of spawning fish and the downstream migrations of overwintering kelts and smolt must also be carried out.

When all factors have been weighed against each other, and a single or combination of scenarios has been chosen, an overall action plan must be prepared which identifies where and how the measures shall be implemented. An overview can be prepared using the diagnosis table (**table 17**). The details of the plan will depend on how far the development of a new environmental design has progressed. In the case of habitat measures in particular, it will often be necessary to carry out supplementary studies, calculations or modelling, in order to ensure precise placement and design of the measures in question.

Photo: Atle Harby

Description of methods

T1 Flushing of silted gravel banks and juvenile salmon habitat

If gravel or boulders on a given stream bed with substrate sizes suitable as spawning habitat (ref. **T2**) or parr development, are found to be subject to silting (presence of an armoured layer), or vegetated, the bed can be flushed as an effective mitigation measure to restore spawning and sheltered habitats (see **figure 14**). In practice, such measures are carried out by harrowing the sediment using an excavator. In cases where silting or vegetation growth are at a relatively early stage, it may be worth considering harrowing or loosening the gravel using high-pressure hoses or rakes. Harrowing imitates the effects of natural floods, causing fine-grained sediment to be flushed away, leaving only clean and unconsolidated gravels. This method will require follow-up maintenance unless the sources of silting and vegetation growth are removed. Intervals between maintenance can be increased using measures such as the construction of current deflectors (see below) which promote more favourable hydraulic conditions in spawning and juvenile salmon habitats, or by reducing the supply of fine-grained sediment or other forms of water pollution. This reduces silting and vegetation growth, and thus the need for maintenance.

T2 Installation of gravel habitat

If there is a general lack of suitable spawning substrate, and it is impractical to carry out large-scale river restoration, new spawning areas can be created by installing suitable substrate artificially. If carried out correctly, experience shows that such measures can be relatively robust and cost-effective. One advantage of a well-planned initiative is the opportunity it provides to control the location of the gravel introduced, thus increasing the extent of spawning habitat and its distribution within the river. It also makes it possible to "encourage" the fish to spawn in areas safe from dewatering in the event of low flow conditions, or flushing during floods.

The major problem with this measure is that if the gravel is introduced to unsuitable areas, it will be subject to either silting or flushing. Experience shows that flushed-out gravels commonly become spread out over areas which are too large to permit the establishment of new spawning areas. In some situations, flushed-out spawning substrates become stranded in areas prone to dewatering. Salmon may thus be attracted to spawn in areas where the eggs are at risk of becoming dried out under low flow conditions in winter. If flushing occurs during the period when eggs and alevin are present in the gravel, there is a risk of significant egg loss, in which case the measure will have resulted in the opposite of its desired effect. Good planning will help to avoid such outcomes. On the other hand there must also be sufficient current to ensure adequate oxygen supply to the eggs, and to prevent silting and vegetation growth. It is thus essential during the planning and design of these measures to

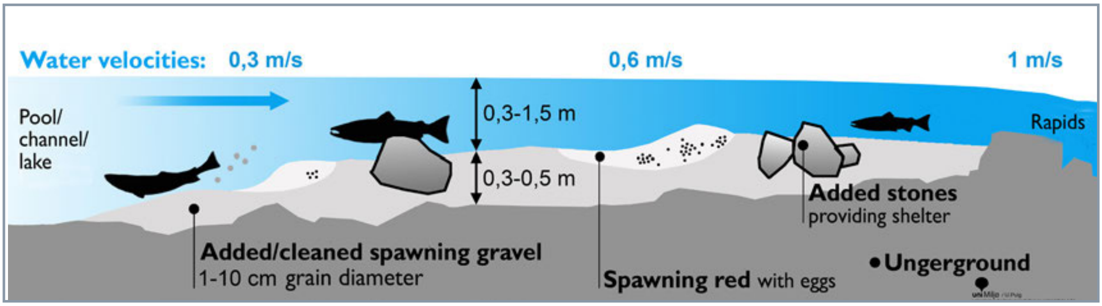
Figure 14. *An example of the flushing of gravel banks (from the Aurlandselva river in Sogn og Fjordane county, Norway). The original situation involved an armoured and vegetated stream bed offering very little shelter (top left). Sediment harrowing using an excavator (top right) resulted in a substrate with a high density of holes and crevices and sporadic patches of gravel for spawning. Photos: Ulrich Pulg*

take both hydrologic conditions and suitability in terms of the salmons' spawning requirements into account (ref. **figure 15**). In particular, the following factors must be taken into consideration:

- The spawning area must remain sufficiently robust to withstand flushing under normal flood conditions. A ten-year flood should be the minimum requirement. It is vital that flushing does not occur during the incubation period (October to July).
- Spawning areas must be exposed to currents strong enough to facilitate adequate flux and oxygen supply to the eggs, and minimise the accumulation of fine-grained sediment and the growth of vegetation.
- Spawning areas must not become dewatered at low flow periods during incubation (October to July).
- Water depths and current velocities must meet the salmons' requirements in terms of spawning habitat. Typical values are within the limits 30-150 cm water depth and 30-60 cm/s water velocity. Good spawning areas are commonly located in the shallow outlets at the margins of deeper pools and channels, where currents tend to accelerate.
- The composition of the spawning gravel must have the correct grain size distribution, as follows; 20% 8-16 mm, 60% 16-32 mm and 20% 32-64 mm (see the details regarding spawning gravel below).

The correct grain size distribution is vital to achieving success using this measure. Rounded-clast gravels from moraine or alluvial sources are preferred. Gravels must be sieved of obtain the correct grain size distribution, and gravel composition will depend on the size of the

Figure 15*. A profile sketch showing the typical features of restored salmon spawning habitat. Gravel is laid at the shallow outlet to a deeper pool, channel or lake at the transition to a faster-flowing reach downstream. Such conditions provide an ideal hydrologic setting for spawning.*



fish and hydraulic conditions. They must not consist of a single single size fraction, but of a mixture of different grain sizes. In the case of salmon, gravels should be mixed from the following fractions; 8-16 mm, 16-32 mm and 32-64 mm, using a size distribution as set out in the bullet point above. However, this distribution can be weighted towards the coarsest fraction if the spawning fish are large or if there is a high risk of erosion. This will depend on the stream bed gradient and flow dynamics. The fine-grained fraction (<1 mm) must be as small as possible. If the gravel appears to be "dirty", or contains a significant amount of fine-grained sediment, it must be flushed or washed prior to its introduction to the river.

Gravel must be installed during a low flow period when access to the river is easiest and when it is possible to ensure that it is not introduced to areas prone to dewatering. Ideally, it must be installed in good time prior to the spawning season (preferably in winter) in order to allow for a sufficiently prolonged period with several flow peaks, and to ensure that gravel which remains in particularly exposed locations is flushed before the fish spawn in it.

The volume and location of gravel installation must be adapted to local conditions. In the case of creation of a new spawning area covering about 100 m^2, a typical volume requirement will be about 3-5 lorryloads each containing 10 m^3 of gravel. This must be transported as close as possible to the location where the gravel will be laid. The gravel is installed by means of a "shaking" process using an excavator. If it is not possible to gain direct access to the river, the gravel must be transported in boats or by helicopter in large sacks, each

Figure 16. Installing spawning gravel using an excavator (from the Aurlandselva river in Norway). Trained personnel in snorkelling gear guide the operator as to volume and location, and then spread the gravel using scrapers and rakes. Photo: Bjørn Barlaup

containing approx. 600-800 kg. Regardless of the method used, qualified personnel must be present in diving suits and snorkelling gear to ensure that the gravel is laid in the correct locations (**figure 16**). Snorkelling gear is necessary in order to obtain an overview of stream bed conditions and to locate exactly where the gravel should be laid. This approach will ensure an effective distribution of the gravel, taking full advantage of local current and stream bed conditions. The installation of too much gravel, or too large banks, should be avoided. Layers about 30-50 cm thick will be adequate in most localities. Gravel should be laid in channels and shallows at the outlets of deeper pools, and must be tailored to the topography of the stream bed so that it imitates natural spawning areas as closely as possible. Existing substrate distributions at the locality in question can be used as guidance for prevailing hydraulic and hydrologic conditions. Good results are achieved if it is possible to lay the gravel in areas where gravel and boulders of similar substrate size distribution are already present.

Once the gravel has been laid, it must be spread out using a scraper or rake. It is an advantage if both spawning fish, and subsequently fry, can find shelter close to the spawning area. This condition can be met by laying gravel in small patches, measuring between 5 and 10 m^2, inbetween larger rocks. If no such rocks are available, making the newly created spawning area appear as an open and uniform surface, counter measures should be taken by installing boulders and/or blocks after the gravel has been laid. This will ensure that the fish are provided with shelter and that the spawning area represents a sufficiently diversified habitat.

Normally, the laying of gravel alone will not remove the cause of spawning habitat loss, and some form of habitat maintenance will be required. To counteract the flushing-out of gravel over time, newly created spawning areas must either be supplemented, or the installation repeated. Areas subject to silting may have to be flushed clean of fine-grained sediments and vegetation. Functional duration will depend on local conditions and may vary from a few years to decades. If spawning takes place on newly created gravel areas on an annual basis, the spawning fish will commonly carry out maintenance themselves, and keep the gravels free of fines and vegetation.

T3 Establishment of shelter

An absence of shelter in the substrate is due either to the presence of too much fine-grained sediment on the stream bed, or to fines (especially sand) blocking the interstitial spaces between larger rocks. Both phenomena are typical of reaches exhibiting low water velocities. Although much empirical data are available from a number of shelter creation approaches involving salmon, our knowledge base is limited when compared to that for the establishment of spawning areas. However, our main assumption is that if it is not possible to restore existing habitat (ref. **T1**), the artificial provision of rocks will enable the holes and crevices between them to provide refuges where fish can obtain shelter (**figure 17**). We have very little knowledge about the types of measures which produce most shelter per cubic metre of rock, but the following strategies provide useful starting points;

1 The construction of current deflectors (rock ridges) extending from the bank and out into the river. Such deflectors are commonly built to mitigate erosion. However, use of the correct sizes of rocks may also contribute towards creating good habitats for juvenile fish. Shelter is provided by the rocks themselves, while the deflectors generate currents which break up the water surface. The lateral slopes of the deflectors should not be too steep (recommended gradients; 1:1.5 - 1:2). Longitudinal gradients should be less steep (1:15 - 1:200), depending on local conditions. As far as possible, deflectors should be submerged under normal flow conditions – constructed and fixed to support the forces from a 50-year flood. Rocks of predominantly 0.4-0.7 metres in diameter should be used to construct a covering layer. The size of the rocks used must be adapted to the forces at the locality in question. Existing stream bed material may be used to construct the deflector cores, provided that they are suitable to handle the stress and forces generated by local water and ice conditions. For optimal erosion protection purposes, deflectors should be shorter than three times the water depth during floods, or one quarter of the surface width of the river. However, they may be extended for the purposes of creating juvenile fish habitats. The distance between deflectors will depend on terrain conditions at the locality in question, but will typically be between 3 and 10 times the deflector length. The higher the upstream angle of the deflectors, the more they will be able to influence, and generate attractive variation current regime. Increased current velocities across the deflectors will inhibit the accumulation of fine-grained sediments, and such measures will be highly suitable along reaches exhibiting moderate to high water velocities.

2 The construction of rock clusters each consisting of up to three large rocks (0.7-1.5 m in diameter) and surrounded by smaller rocks (0.3-0.5 m). This measure may be useful in slow-flowing, relatively deep water reaches.

3 The construction of longitudinal rock ridges. These consist of arrays of stones (0.4-0.6 m in diameter) anchored on the stream bed parallel to the current direction, and which remain submerged at all times. Such structures can be relatively long. A ridge's typical cross-sectional profile is approximately horizontal (rounded) at the centre (50 cm wide), with a slope down to the stream bed of approximately 45°. This design will prevent fine-grained sediment from accumulating and blocking cavities between the rocks. This approach is ideal along reaches exhibiting moderate water velocities.

4 The construction of cell weirs consisting of rocks 0.4-0.6 metres in diameter (together with some larger rocks to provide anchorage). These are laid in such a way as to create cells similar to those seen in beehives, but in less regular patterns (**figure 18**). Parts of

the cells may be emergent under normal water levels. By adjusting the precise location and height of the cells, currents can be controlled in such a way as to prevent sediment accumulation and promote the upstream migration of spawning fish. This approach is highly suitable along reaches exhibiting moderate to high water velocities.

5 In most cases, the optimal solution for any given reach will involve a combination of approaches 1 through 4. This will create river bed variation imitating the characteristics of suitable, natural juvenile fish habitats, and will also be more aesthetically acceptable. The planting of vegetation on river banks, in locations where it has previously been removed, combined with the placement of dead trees, branches and roots, may also have a positive impact, especially in small river systems and along tributaries (**figure 19**).

Figure 17. An example of gravel laying designed to create shelter and a more varied hydraulic environment along a uniform and channelled reach. From Frafjordelva river in Rogaland county, Norway. Photo: Ulrich Pulg

Figure 18. An example of a reach along which cell weirs have created a dynamic hydraulic environment with abundant shelter. From the Sima river in Hordaland county, Norway. Photo: Ulrich Pulg

Figure 19. An example of using a combination of branches and dead trees to create sheltered habitat – here for juvenile trout.. Photo: Ulrich Pulg

T4 Restoration of natural gravel transport dynamics and the removal of weirs

If physical interventions have been the cause of poor spawning and juvenile growth conditions, opportunities to remove the cause of this should be assigned high priority. In many cases, the most effective approach will be to restore the original river course, remove unnecessary erosion protection structures, and facilitate more natural sediment dynamics. For example, weir construction has resulted in the destruction of spawning areas by altering water depths and velocities to the extent that these no longer meet spawning habitat requirements. Weirs have also resulted in reduced access to shelter because the backwater upstream pool created by the weir acts as a sediment trap. In many cases weirs were designed to provide large, aesthetically pleasing, water-covered areas, with little or no attention to biological considerations. Several studies have shown that the removal or lowering of weirs may be useful in helping to re-create or improve spawning and juvenile salmon habitats (**figure 20**). The resulting increases in water velocity may in themselves be sufficient to encourage salmon to return to such reaches to spawn. Removal may also improve spawning conditions downstream of weirs, provided that natural gravel transport processes are restored. It is common for such processes to cease because large weirs act as sediment traps. Similar approaches to the restoration of original river courses and their natural dynamics may involve channelling, the introduction of rocks, or other physical interventions. It is important during the planning of such measures to take hydraulic conditions into account. This will make it possible to ensure that the desired biological outcome is obtained by optimising habitat quality and the extent of water-covered area. We recommend the use of hydraulic modelling based on terrain and flow data as a planning tool. Small weirs and constructions

Figure 20. *An example of the re-creation of a reach suitable for salmon following the removal of a weir. It is taken from a bypassed reach of the Nidelva river near Arendal, Norway, from which a concrete weir was removed.*
Photo: Svein Haugland

can be modified on site in order to obtain desired outcomes. If suitable spawning substrate is not present at the locality in question, modifications to weirs and other structures can be combined with the installation of gravel.

T5 Re-designing the river course – "a river in the river"

In bypassed reaches subject to minimum flow releases and considerably reduced flow, the river's natural course will no longer be adapted to prevailing flow conditions. The physical setting is altered dramatically, and we typically observe low water velocities, shallow stream depths and the accumulation of fine-grained sediments. This is a natural development which can be mitigated by implementing design measures which, involve confining the stream course and introducing alternate reaches of riffles and pools. Such measures are named "a river in the river". Current deflectors, rocks and other structures are used to narrow river width permitting current velocities to increase and the river to meander more. If necessary and feasible, deep pools can be excavated and small weirs constructed to produce alternate slow- and faster flowing reaches, respectively. The use of cell weirs will create other possibilities. The approaches described in sections **T1**through **T4** are all valid tools for use in combination with river narrowing. Such initiatives will significantly reduce water-covered area, and are thus only practical along reaches where flow is considerably reduced. They also require maintenance, especially if the reach in question is subject to natural floods and bank overflow. **Figure 21** shows an an example of a reach where the "river in the river" concept has been put into practice.

Figure 21. An example of the "river in the river" design concept in a reach with a broad stream bed where flow has been severely reduced. From the Dalåa river in the Stjørdal system, Nord-Trøndelag county, Norway. The restored reach meanders within the former river course with areas alternating between pools and riffles.
Photo: Knut Alfredsen

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This "Handbook for environmental design in regulated salmon rivers" describes how to evaluate, develop and implement measures to improve living conditions for salmon in regulated river systems, while taking hydropower generation into account."

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Cooperation and expertise for a sustainable future