Péter Borsányi

A classification method for scaling river biotopes for assessing hydropower regulation impacts

Doctoral thesis
for the degree of doktor ingeniør

Trondheim, February 2006

Norwegian University of
Science and Technology
Faculty of Engineering Science and Technology
Department of Hydraulic and Environmental Engineering

NTNU
Innovation and Creativity

NTNU
Norwegian University of
Science and Technology

Doctoral thesis
for the degree of doktor ingeniør

Faculty of Engineering Science and Technology
Department of Hydraulic and Environmental Engineering

ISBN 82-471-7167-8 (printed ver.)
ISBN 82-471-7165-1 (electronic ver.)
ISSN 1503-8181

Doctoral Theses at NTNU, 2005:140

Printed by Tapir Uttrykk

A classification method for scaling river biotopes for assessing hydropower regulation impacts

By Péter Borsányi

This thesis is submitted to the Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Hydraulic and Environmental Engineering, Trondheim, Norway

ISBN 82-471-7165-1 (electronic)
ISBN 82-471-7167-8 (printed)

Acknowledgement

I would like to express my thanks to all my colleagues, especially to Knut and Ånund for supervising my work.
I am grateful for the support I received from my family and especially from Lucia who tirelessly handled my everyday struggles.
Wolf Marchand, Nils Rüther, Paul Christen Røhr, Bernt Matheussen, Durga Sangroula, Christine Kraxner, Kari Svelle, Ingerid Pegg, Åsta Gurandsrud, Morten Stickler and Håkon Sundt for extraordinary field experience and a lot of practical help,
Nils Reidar Olsen, Hallvard Ødegaard, Ragnhild Sundem and all the other colleagues at IVB and Atle Harby, Jo Halleraker, Hans-Petter Fjeldstad and others at Sintef Energy AS for financial and theoretical support,
István Ijjas and János Józsa, Zoli Molnár, Sanyi Baranya for remote help,
Klaus Jorde, Mike Dunbar, Doug Booker, Piotr Parasiewicz, Moni Rivas, Andi Eisner, Leif Lillehammer, Peter Goethals and other present and former members of COST Action 626 – European Aquatic Modelling Network for all the fascinating discussions and ideas,
Ola Ugedal, Torbjørn Forseth for crash courses on ecology and Tor Håkon Bakken for help with scaling issues,
Peter Goodwin, Tony Minns, Berton Lee Lamb and Annette Semádeni-Davies for help with linguistics and theoretic issues,
Einar Sæterbø and Sverre Husebye and all other colleagues at NVE being supportive and patient with my hectic schedule.
Special thanks to Veronique Vandenberghe for her thoughtful comments and enormous energy when helping with the final corrections and finally to Laci Láng who helped creating a fantastic publication out of this very sad-looking text.

The work has been a part of the Norwegian Research Council EFFEKT programme "Environmental Impacts from Hydropeaking". The Norwegian Research Council, several power companies and the hydropower authorities jointly funded the project. Many thanks for their support.

Summary

This thesis describes the development of a habitat assessment methodology based on theories of hydro-ecology for use in river basin management. The methodology includes a robust habitat classification system and provides tools and methods to utilize this system for upscaling information with small-scale validity to river-scale. The backbone of the system is the method to identify schematics of meso-habitats through hydromorphological units in the water body. The methodology supports environmentally aware river regulation planning and the improvement of degraded river habitats. The application is not limited in terms of geography, however it is mostly tested and developed in Norway. The various phases and aspects of development are presented in detail. Two applications illustrate the use and capability of the methodology. The first presents a scaling study to simulate salmon production of a river, while the second shows a coupled modelling system that links the methodology with models for real time simulation of hydropower production and corresponding river hydraulics. This modelling system can be utilized for decision support in hydropower management. Successes, failures and outlooks are provided with both applications.

Preface and terminology

Coming to Norway for the first time in the spring of 1998 happened by accident. My home university in Budapest, Hungary maintained connections with several universities in Europe and those willing to write their Master's theses abroad were mixed together and sent to the very limited number of places by chance. Five students could come to Trondheim and I was waiting disappointed with rank number six. But one candidate could not make it and I stepped into his place. This is how I arrived for the first time.

Close to finishing the autumn job at Sintef during the same year in November, we were discussing with Atle Harby whether the project I was contributing to could benefit from postgraduate project. It took a year to finish the formalities, but I came out second in the ranking again. The best applicant stepped back though and there were no more obstacles in the way. This is how I arrived for the second time.

After all these years I still look back smiling how unlikely events can happen in real life.

At this early point, I have chosen to list some phrases and expressions. This is to clarify my use of them and to serve as inspiration to the problem motivating the project and its possible solutions.

A definition of the "environment" is given by Pearsall (2001) as follows:

1. The surroundings or conditions in which a person, animal, or plant lives or operates.
2. (The environment) the natural world, especially as affected by human activity.

CIDE (2001) gives a very similar definition:

1. The conditions that you live or work in and the way that they influence how you feel or how effectively you can work.
2. The environment: (the quality of) the air, water and land in or on which people, animals and plants live.

Black (2002) notes that environment is usually divided into natural (such as air, waters, soil, biodiversity, etc) and built parts (such as buildings, roads, dams, power lines, etc.).

Further on the "river environment" can therefore be related to both the natural and altered (human affected) form of rivers.

Pearsall (2001) defines "biotope" as the region of a habitat associated with a particular ecological community, or slightly differently by Microsoft (2004) as a small area with a distinct set of environmental conditions that supports a particular ecological community of plants and animals.

The altered (human affected) rivers are commonly called regulated rivers, regardless of the nature or the purpose of the regulation. These purposes may be reduction of flooding, providing drinking water, ensuring continous water supply for industrial use, irrigation, production of hydropower, etc.

From the various river regulation effects, regulation for hydropower generation dominates in this work. The way hydropower operation affects river biotopes, may be viewed from downstream or upstream of an installation. Helland-Hansen et al. (1995) show several examples of regulation purposes and methods (shortly after finishing the present manuscript in 2005, a new and updated version of Helland-Hansen et al. (1995) was published, so please note that references in this text denote the previous edition). Regulation of rivers in the upstream direction may result in shortening and bypassing of river reaches, changing of soil structure in the channels, reduced or stopped migration of fish, varying water level in reservoirs and higher sedimentation. Downstream reaches sometimes have scouring problems, fish migration barriers, changes in river vegetation, altered flow regime, rapidly fluctuating water levels, changing water quality and sediment composition and perhaps no water at all.

An assessment of such environmental effects may therefore involve a wide set of studies which range from habitat modelling to sediment studies and from eutrophication models of reservoirs through earth slides to flood protection measures.

Piddington (1991) and Helland-Hansen et al. (1995) provide long lists of environmental effects of hydropower constructions. They classify the issues into direct, indirect and external categories. These are then divided into construction and operation related problems. Each problem is linked with possible mitigation measures. Clearly these works were created from the engineering (construction oriented) point of view. They focus mostly on engineering solutions and problems of hydropower developments. Even though they tend to be both general and objective, they fail to cover recent developments of aquatic ecology and more importantly, the change of focus we experience in the society.

Certain issues, like siltation of downstream channels, fish stranding, large-scale ecological issues or tools like habitat modelling are not mentioned and therefore these works can only serve as parts of the background in our analysis. In addition, both works deal mostly with hydropeaking as environment-affecting feature, but dam, reservoir and other "upstream" related issues are not covered. Other works that also focus on hydropower regulation like Steele and Smokorowski (2000) and Morrison (2000) provide a more up-to-date level of impact assessment because of their broader perspectives and foundation that build also on advances in ecological studies.

Lately Dunbar et al. (1998), Leclerc et al. (2003) and Tharme (2003) summarized several works describing various issues and practices of determination of environmental flows. Acreman and Dunbar (2004) and Tharme (2003) present contrasting and partly overlapping classifications of methods for determining environmental flows. Both works provide a summary of the state-of-the art in methods and measures applied for ecosystem development and maintenance where anthropogenic alterations may result in ecosystem degradations. The approaches of the two works somewhat differ from each other in terms of structuring these issues. Tharme (2003) gives a definition for environmental flow assessment (EFA) for a river as follows. "An assessment of how much of the original flow regime of a river should continue to flow in it … to maintain specified valued features of the ecosystem. An EFA produces one or more descriptions of possible modified hydrological regimes for the river, the environmental flow requirements (EFRs), each linked to a predetermined objective in terms of the ecosystem's future condition." The definition leaves some issues open, like how to understand the terms "original flow regime", or "some condition of an ecosystem", however these belong more to the ecological part of the field than to the hydrological. See below for details on ecological approaches to define environmentally friendly flow regimes in Section 1.2.1.

EC (2000) is a recently passed directive (commonly known as the European Water Framework Directive, or WFD) in the European Union. The WFD introduces the concept of surface water status, combining ecological and chemical status. A subsidiary definition is of ecological potential. In the same document, "ecological status" is an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters, classified in accordance with predefined types of components. The components include physical, biological and chemical features.

During preparation of CEN-TC230 (2004), which is a guidance standard for hydrological assessment of hydromorphological features of rivers, the EC (2000) directive was kept in sight, further strengthening and helping the application of the law. Other standards from the same organisation (CEN) are also under preparation with focus on further issues brought up by the WFD. This shows that international law requires fulfilment of "good or adequate" functioning of aquatic ecosystems. Hydromorphology plays an important role in achieving this aim as an important describer of the quality of the water environment.

The WFD roughly specifies the framework of water management, which is built upon catchment management plans. We see though, that both environmental issues and practical water management are addressed on much smaller scales. The difference between those two brings the problem of scaling into sight.

Other works with different backgrounds or purposes may handle the problem of environmental impact assessment in a different fashion and incorporate another range of issues. Here, not all possible aspects are sought to be dealt with, because such analysis is simply far more complex than what one could cover within the limitations of a PhD dissertation, or without deep knowledge of numerous interdisciplinary fields. Therefore, and for practical purposes, a large portion of the environmental components and their effects are neglected.

The presented work belongs to the field of applied hydro-ecology. A compact description of the field is provided by Dunbar and Acreman (2001) as "the linkage of knowledge from hydrological, hydraulic, geomorphological and biological/ ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales". The relation to economy is only briefly touched because of lack of my background in this field. In the future, it would be possible to improve the presented method in order to strengthen relationships with economics.

Table of contents

List of figures

List of tables

List of abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
ANOVA	Analysis of Variance
CASiMiR	Computer Aided Simulation Model for Instream flow Requirements in diverted streams
CEH	Centre for Ecology and Hydrology
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CFD	Computational Fluid Dynamics
COST Action	Intergovernmental framework for European Co-operation in the field of Scientific and Technical Research
DSS (as alone)	Decision Support System
DSS (as in HEC-DSS)	Data Storage System
EA	Environment Agency of UK
EC	European Community
EFA	Environmental Flow Assessment
EFO	Environmental Flow Objective
EFR	Environmental Flow Requirement
EIA	Environmental Impact Assessment
ESRI	Environmental Systems Research Institute Incorporated
EU	European Union
GBA	Geomorphological-Biotope Assessment
GIS	Geographical Information Science or System
HEC	Hydraulic Engineering Center, (within the Institute for Water Resources, U.S. Army Corps of Engineers)
HEC-RAS	HEC-River Analysis System

HMU	Hydromorphological Unit
HSC	Habitat Suitability Curve
HSI	Habitat Suitability Index
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
MAF	Mean Annual Flow
MesoHABSIM	Mesohabitat Simulation Methodology
MPE	Ministry of Petroleum and Energy in Norway
NINA	Norwegian Institute for Nature Research
NIVA	Norwegian Institute of Water Research
NTNU	Norwegian University of Science and Technology
NVE	Norwegian Water Resources and Energy Directorate
PCA	Principal Component Analysis
PHABSIM	Physical Habitat Simulation Methodology
RFO	River Flow Objective
RSS	River System Simulator
RHS	River Habitat Survey
SEFAS	Sintef Energy Research Ltd
STSM	Short Term Scientific Mission, a COST Action mobility program
SSIIM	Simulation In Intakes with Multiblock option
USACE	U.S. Army Corps of Engineers
WFD	European Water Framework Directive
WUA	Weighted Usable Area

1 Introduction

Among the presently available means of power production, hydropower often generates controversial feelings among the public. This is because on one hand there are practically no by-products produced during operation, but on the other hand it is necessary to alter the environment at the location of the installation to some (smaller or larger) extent. The alteration sometimes means construction of reservoirs and dams and always a changed, non-natural character of water regime downstream of the installations. Hydropower production can be categorized according to the effects it introduces to the environment. The term "green hydropower" arose from these considerations and it means that all aspects of the production are certified according to international standards. The certification ensures the environmentally friendly installations and production procedure.

One aspect of these certification procedures sometimes involves evaluation and estimation of direct and indirect impacts of power production on the downstream river environment. The impacts considered may vary depending on the scale and efforts invested in the studies and can range from large-scale environmental impact assessment studies to simple methods focusing only on a few number of environmental variables. The work presented here is to be used for such studies. It introduces a method along with two applications for assessing environmental impacts of river regulation downstream from hydropower installations. The method builds on knowledge of river biotopes and ecological scales and at the same time includes factors that can be quantified and used easily in the contexts of management objectives.

The following sections describe the causes justifying this study, the problems it deals with and a possible proposal for solving them.

1.1 Background

This chapter describes the problem which provided the motivation to write this work and its sub-division into areas with their practical relevance. Global and Norwegian challenges and trends as well as issues of hydropower operation in environmental and economical contexts are discussed.

1.1.1 Challenges and trends in water management

The history of water management shows, that the need for utilizing natural water resources and especially freshwater from rivers is increasing. Water resources management therefore has to face increasing complexity, which results in a growing amount of problems to deal with. Traditional problems described by e.g. Shaw (1994); Yevjevich and Starosolszky (1998); Caissie and El-Jabi (2003) may be related to irrigation, drinking water supply, flood or drought management, power production, landscape or ecosystem protection, or recreation. We experience a growing environmental awareness in water policy as noted by Farhar (1993); Boon (2000); EC (2000); Raven et al. (2002); Rowlands et al. (2002), which requires an increasingly complex analysis of environmental effects related to water management issues. Taking hydropower production as an example, Bratrich et al. (1999) underlines that it seems necessary to shift methods of power production towards “green” methods, or operate according to green standards to minimize loads on the environment. The adoption of the Kyoto protocol (where applicable) should result in reduction of greenhouse gases, to which coal- and traditional gas-based power production contribute largely. This increases the pressure on by-product-free methods such as hydropower, which is possible to produce in both environmentally friendly (green) and less friendly (gray?) ways.

Preparation of “green standards” for power production is under way, because this is the only way consumers of power can distinguish between power products from the environmental point of view. Bratrich et al. (2004) describes one example of such a system, which contrasts fields of environmental science with fields of water management and defines goals or criteria and tools for assessment for each possible interaction in this crossing procedure. From the numerous goals a ranked list is generated to elevate those aspects gaining higher importance among the others for some reason. One important research field noted is the environmental impacts of hydropeaking (see Section 1.1.2.1 as well). This aspect is important in the Green Hydro licensing process, but at the same time little studied and thereby not well understood. The relation to hydromorphology plays an important role in the question, as the study notes referring to others.

1.1.1.1 Norwegian issues

Norway cooperates with the European Union in some fields of legislation, including environmental directives. EC (2000) is a new European act, which is valid also in Norway, enhancing the importance of environmental factors in river regulation and management. The directive, issued to all the involved countries similarly confronts different issues in the various regions of its validity. Recent topical issues in Norway include hydropower management and fishing or production of salmonids.

A typical problem is the conflict between the need for peaking production of hydropower and degraded physical habitat for various fish populations. Harby and Arnekleiv (1994) described a study in Central Norway where environmental studies were conducted before introducing a new flow regime to a small highland river. The studies focused on possibilities to improve physical habitat for brown trout (*Salmo trutta*). Fish densities were compared after test runs of the power station at two sites, one with improved habitat according to habitat modelling based on preferences, the other unaltered. Results prove the success of the project. Later Harby et al. (1999) described the initiation of a project aiming at identifying and analysing a wide range of aspects related to the impacts of hydropeaking on Norwegian riverine ecosystems. The project recognizes hydropeaking as one of the major source of issues among the environmental impacts associated with hydropower production.

The special problem of stranding during peaking flow was investigated by Saltveit et al. (2001). Their study aimed at identifying effects of seasonality and temperature, daytime conditions and origin of fish on stranding and mortality. They found that hatchery fish behaved differently from natural ones, stranding risk is highest during winter and daytime and that stranding may not lead directly to mortality, because some fish could survive in the wet substrate for several hours. This study helped recognizing the key physical factors to be considered for planning environmentally feasible production of peaking power.

1.1.1.2 Present issues

The problems, issues selected above are not new and have already been addressed independently from each other. However, only few approaches addresses the complex problem in a holistic manner, trying to connect the fragmented findings of sub-fields. New possibilities include for example combination of spatial data with high resolution, geomorphology of rivers noted by Habersack (2000). Further on Heggenes et al. (1996), Jorde (1996), Olsen (2002) and Katopodis (2003) describe the use and application of more sophisticated hydraulic models than those usually applied today in water management practice. Killingtveit (1999) shows tools for modelling hydropower production that can be linked to environmental analysis. Parasiewicz (1996) draws attention to the use of advanced surveying and mapping techniques to achieve vital precision. Leonard and Orth (1986), Lobb and Orth (1991), Heggenes (1996), Valentin et al. (1996), Lamouroux et al. (1998) and Scruton et al. (2003) report the deeper understanding of species' behaviour to be used in habitat modelling. Capra et al. (2003) and Alfredsen (1998b) present species-based population models. Alfredsen (1999) shows the theoretical background of a framework for application development and integration in hydroinformatics together with its application for hydrological catchment modelling for flood forecasting. These examples would bring new dimensions and answers to many uncertainties in present practise as well as new problems naturally.

Kemp et al. (2000); Thoms and Sheldon (2002) note that present knowledge of the living river environment is not enough to provide adequate answers to the increasing number of ecological problems in water management. More specifically, in river management we must be able to predict the response of the water environment to certain alteration of hydrological features such as peaking flow regime, changes in sediment load, together with their consequences related to ecology.

Alfredsen (1999) after Abbott (1991) reports on the aspects of computer aided (sometimes disturbed) water management practice. Indeed, the increased use of computers in water management does not only involve short computation time, but unleashes new aspects related to alteration of computational methods, models designed specifically for computer application and finally the self-standing model and database development possibilities with guided or automatic calibration. The issues listed above, with varying degrees of importance, give challenges to modern water management tackling the ecological effects to fulfil anthropogenic needs, while the models and theories listed may be our tools to handle the issues.

1.1.2 Hydropower and environment

Present technology does not allow mass storage of electrical energy in a cheap way. Therefore, power production is adjusted to meet the actual demands of the market. In Norway, electricity is sold on a free (unregulated) market, which determines certain operational methods. Production peaks and drops follow each other in a hectic manner according to actual power price, weather, capacity, social habits and so forth. The works of Karr (1991), EC (2000), Newson et al. (2002) and EAMN (2004) tell that even though production of hydropower is being more and more regulated to comply with the arising environmental concerns, standards and rules do not reflect the state-of-the art neither in technology nor in theory. Norway has a special position in this issue because of the dependence on this particular natural resource. Hydropower contributes some 90-95% to the production of Norwegian electrical energy.

Harby et al. (1999) point out that because of economic considerations and development, the demand for peaking power in hydropower systems is increasing. However the environmental consequences of this may be negative due to, for example, the increased variability in river flow downstream of peaking power plants, as shown in Harby et al. (1999) and Saltveit et al. (1999), or when mismanagement occurs in case of lack of regulations noted by Acreman (2001). Cortes et al. (2002) and Frutiger (2004) report that peaking production of hydropower can reduce habitat availability for species of fish and invertebrates on the affected sections of streams. Helland-Hansen et al. (1995) show, that, in general, peaking may reduce, or at least alter the (quality of the) aquatic environment.

1.1.2.1 Hydropower operation

Forecasting (or practically modelling) of power production and consumption is one of the most complicated tasks on an unregulated energy-market. The high number of participants together with varying capacities of production and the hard-to-predict factors such as weather or operation failure and irregularities of consumption lead to a very complex system. The shrinking flexibility of large power systems and the interest in profit making cause this system to operate somewhat similar as stock markets do.

Models are available to consider the various participants of this market and provide sophisticated means of analysis. Taking hydropower as example, distribution of runoff or precipitation among the catchments in a system, operation schemes of power stations, their production characteristics, release and other operational regulations may be considered. Looking at factors that are more general, the temporal variation of consumption, energy price prediction and others may be considered.

Regarding a hydro-based power production system, a clear trend can be observed towards increased need of peaking operation, because this is the only way to keep up with fluctuations of consumption.

If power is sold in a system that operates within a regular open market, the price can vary substantially seasonally, daily and even hourly. Indeed, the peak-hour price can be several times that of the off-peak price (Figure 1.1).

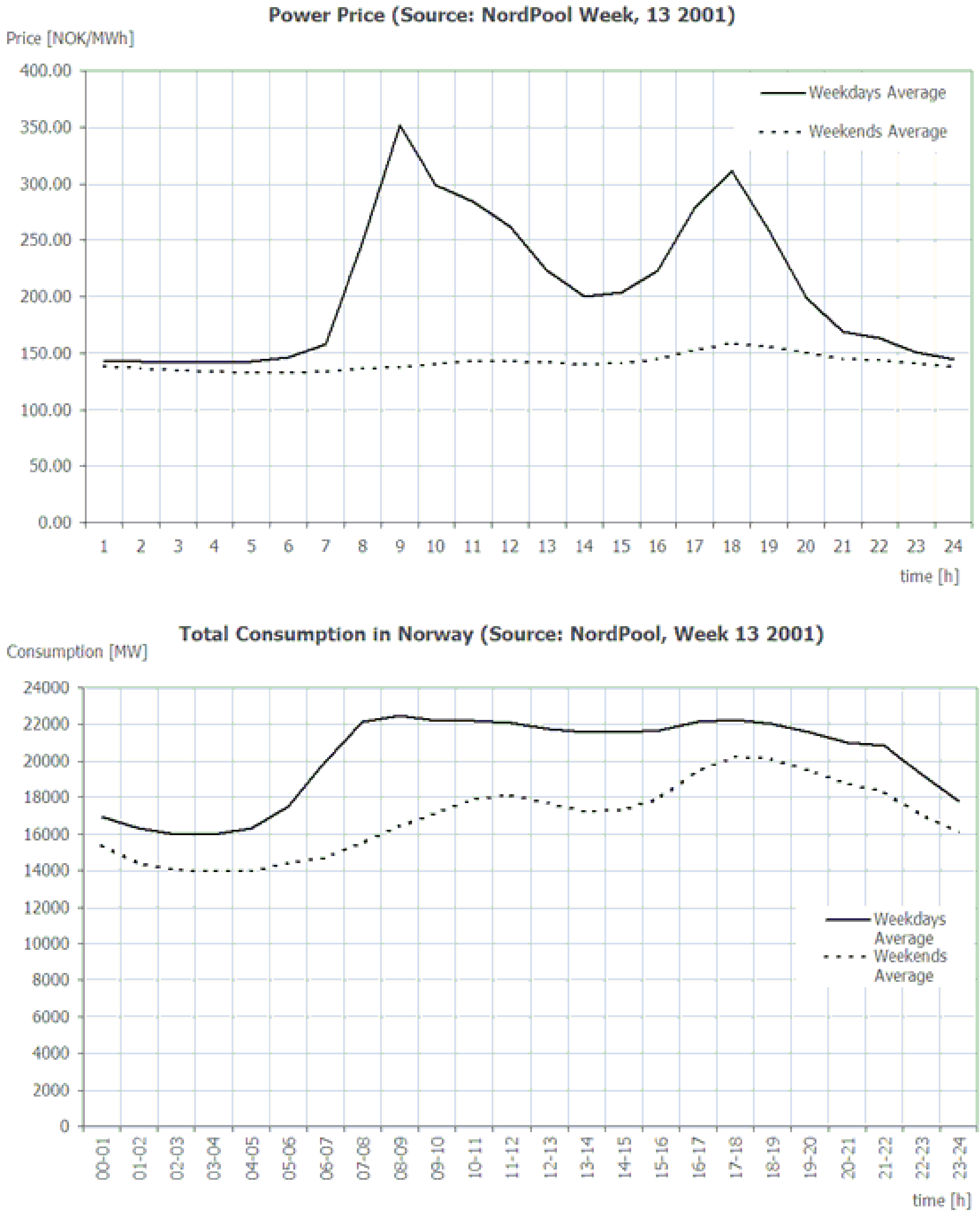


Figure 1.1: Power production and consumption in Norway during week 13 in 2001

Power consumption is high on weekday mornings and early afternoons and is low during night-time or when industries don't operate. Some variations can be seen at the seasonal scale, albeit with a lesser amplitude. More power is used during winter periods than summer (heating, illumination etc.). Since there is no economical way of storing power, production must follow consumption. A suitable hydropower system is capable to follow large variations in consumption by applying peaking operation. So peaking in this context means a frequent variation in production achieved by fluctuating use of stored water.

1.1.2.2 Economical issues

Being a strong economical driving force, hydropower generation can be one of the most important water uses in a regulated river system. Its water use follows market forces, which often oppose those regimes thought to be environmentally friendly. On the other hand, environmental flows cannot be described by market factors (by financial means), unless contrasted with economic losses. This indirect strategy helps finding pricing of environmental constraints and make decisions in issues where economical and environmental factors collide.

Shirakawa and Tamai (2003) developed a subsidy system for setting environmental flow release from hydropower stations. As they report, "Economic measures are useful tools in management because they give strong incentive to conventional water users to change their behaviour." Utilizing this fact, they base their taxing system on a benefit function of environmental flow calculated from flow rate. When applying the method, each hydropower station estimates the amount of subsidy to compensate the power production loss by flow release, and thereby, determines environmental flow.

Tanaka and Lund (2003) estimate and analyse the effects on water management if water was utilized only for the economy in the Sacramento-San Joaquin Delta, SW United States. Even though hydropower is not an issue there, the example clearly illustrates today's typical attempt to resolve multiuse water management issues. They tested effects of increasing use of water export, based on existing regulations. The study shows the capacity of the source to increase exports of water to extra-basin areas, even within significant environmental flow restrictions. However, considering existing regulations, they fail to estimate changes of those and thereby their altered restrictions due to water scarcity among various water users.

King et al. (2003) and Arthington et al. (2003) report on the theory and application of the Downstream Response to Imposed Flow Transformations (DRIFT) methodology, which is a structured mechanism to join information from all disciplines coming into question to produce flow-related scenarios considered in water management. Four modules build up the methodology, the biophysical, the socio-economical, scenario and economic one. They admit that external studies are also necessary in addition to the DRIFT process for (1) the macro-economic assessment of the wider implications of each scenario and (2) organizing public participation process in order to produce acceptable results to the public. Although these studies do not focus on hydropower either, still they provide a description and example of a methodology that involves participation of a very broad range of participants (including hydropower for example) and uses economical means as the ultimate factor supporting decision making in water management. Hydropower however, is not among the typical application fields of DRIFT and therefore application examples cover other typical issues.

1.1.2.3 Environmental impacts of hydropeaking

Valentin et al. (1996) warn that analyses of a peaking environment must differ from those used for less varying flow conditions. They conducted studies of brown trout (*Salmo trutta*) habitat in two rivers in France to quantify its variation over various time spans (from few hours to several months). In addition to commonly accepted factors (such as weighted usable area), that are used for evaluating a steadyly flowing or slowly varying environment, they included flow and habitat chronologies as well as flow (and thereby habitat) duration and frequency in their study. They found that their initiative successfully describes the special features of the peaking environment, however additional biological studies are needed to clarify issues like diurnal behaviour in habitat selection and alteration in search for refuge due to peaking.

Bradford (1997) reported results of experiments with juvenile chinook salmon (*Oncorhyncus tshwytscha*) and coho salmon (*O. kisutch*) in an arificially altered river channel. The experiment aimed at simulating stranding over a gravel bar and pool trapping of these fishes in a rapidly dewatering environment (such as peaking environment). The results show relationship between stranding ratio and species, water temperature, dewatering (or ramping) rate and daytime. The species reacted differently to dewatering rate and some were pool-trapped even at the most gentle decreases of water level. Bradford (1997) suggests that mortality caused by trapping in side channels or potholes can be decreased but may not be eliminated by slower ramping rates.

The Norwegian Research Council and several power producers have initiated a research programme to investigate the impacts on ecosystems of hydro peaking, and to provide tools for analysing the impacts of future hydro-peaking projects. Harby et al. (2001) provide more details on this project, which stated that a decision support tool is needed, that is able to evaluate habitat quality and to calculate power production in different cases of peaking.

In this programme, Saltveit et al. (2001) carried out field experiments with wild and hatchery salmon and trout. They reported that release of peaking water into a natural river may result in adverse effects on the ecosystem. The adverse effects result from the rapid and extensive variations in physical habitat. Both experiments and experience shows that the rapid and large drop of water level causes stranding of fish at particular reaches and increased growth of water vegetation. Stranding is particularly high among young fish on reaches where the substrate is coarse and the riverbed is moderate in slope in the cross-sectional direction. That is, large areas can dry out in a short time and, as a consequence, young fishes are often pool-trapped. They identified dewatering rate, temperature, season and daytime as principal factors influencing mortality.

They suggest that including these in water management, or more precisely following some modified (moderated) peaking patterns would help minimizing stranding.
Under the umbrella of the same project, Flodmark et al. (2002) ran laboratory experiments to study stress level of brown trout caused by peaking in an artificial river. The study showed a rapid normalisation of stress hormone after daily cyclical fluctuations (simulating daily peaking of a river without dewatering of substrate). This suggested that after initial stress, the fish habituated rapidly to the altered environment. Often stress may cause indirect mortality due to shorter life. They also found that blood cortisol is a better indicator of stress than blood glucose.
Still in the same larger project, Halleraker et al. (2003), using the same laboratory experiment facility as Flodmark et al. (2002), performed indoor studies of stranding of fish. With better control over the environmental variables than in the experiment of Saltveit et al. (2001) which was performed in an existing regulated river, they could refine the results of the previous study adding habituation time as an important factor. They experimented with wild brown trout (*Salmo trutta*) in this artificial stream, to provide environmental guidelines for operation of peaking hydropower plants. They varied dewatering speed (water depth reduction over a laterally tilted channel bottom, measured in cm / h) and identified thresholds where the stranding ratio was increased in various water temperatures and light conditions. The temperature and light variations simulated diurnal and seasonal changes. They found that at water temperatures around 7 C^o at night and rapid dewatering resulted in highest stranding rate. They also found, that a second dewatering resulted in significantly less stranding than the first, given all other factors unaltered. They concluded with recommending dewatering in darkness all times and using dewatering rates below 10 cm / h. If dropping discharge following periods with over 30 hours of steady flow increases stranding, as after this period fish habituate the whole channel.
The previous series of experiments show, that the optimum balance between economy driven water management and environmental concerns ought to be decided based on detailed analyses of the physical and biological effects in each peaking river. There are methods of generalizing results from each study. Application however brings up issues of scaling, similarity, transferability, etc, which are neither standardized nor widely accepted among researchers, therefore remaining experimental. Yet, data, tools and methods exist and thereby making better grounded decisions on hydropower operation are available reported by for example Hardy (1998). These allow the improvement of some weak-founded practice or guessing, so their utilisation should not wait any longer.

1.2 Environmental flows

Numerous approaches address the problem of environmentally friendly management of waters and they are collectively termed as “instream flow assessments” (IFAs) in North America or “environmental flow assessments” (EFAs) in South Africa and Australia. Some deal with hydrology or hydraulics not considering ecology directly. These try to maintain certain hydrological (e.g. some percentage of mean annual flow) or hydraulic features (e.g. average wetted perimeter of certain sites) of rivers ensuring subsistence of aquatic habitats in this way. Others deal with micro- (species) scale habitat modelling directly. These address conservation of aquatic ecology by physical description of habitats; therefore, they are considered to be semi-biological. In these cases, certain physical features describe habitats, by means of for example preference curves. According to Reiser et al. (1989), the Instream Flow Incremental Methodology (IFIM), which falls into this category, is the most applied solution to the problem in North America. Stalnaker et al. (1995) provide a historical overview, development summary and not least an explanation of the so called “IFIM philosophy”. Even though IFIM may not be the most advanced IFA from a theoretical point of view, its worldwide success (Dunbar et al. (1998) report that the majority of countries dealing with EFAs developed their own IFIM variants) requires an increased attention compared to others available.

Recently the so-called holistic methods reached application level as well. These may include one or several of the previous attempts as supporting tools at lower levels in the approach. Their operation fashion is highly standardized while dealing with all complexities of each case. Different water users and bodies are represented in a policy making group where details of management (or planning) is worked out.

Reiser et al. (1989), Dunbar (1998) and Tharme (2002) present extensive overviews of methodologies incorporated to legislation worldwide. In addition to the statistics, they classify the methods in a similar way as presented below. Benetti et al. (2004) focus only to the Brazilian legal situation, but their findings are also important showing major differences between developed and developing regions in terms of objectives, methods, practise and implementation.

In the following sections, the ecological foundation of environmental flows is presented first. This is followed by review of some of the works summarizing the theoretical and philosophical differences between present approaches. These should provide background for the understanding of the actual review of methods presented here.

1.2.1 Ecological approaches to establish river flow objectives

Having a practical strategy solving scale problems of water management still does not provide answers to the issue of describing environmentally feasible river flow objectives. Therefore, a short review of literature is presented here showing the development of related theories in ecological science.

Vannote et al. (1980) defines the "River Continuum Concept". This concept builds upon the theory that biotic features follow the continuous variation of physical conditions along a river. Analogous to the energy equilibrium theory in physics, the river ecosystem also tends to find balance in its structural and functional characteristics by conforming itself to the most probable position, the mean state of the physical environmental conditions. This infers that communities situated in different parts of the same river have direct upstream or downstream connections with each other. These connections can be assessed based on physical features of the rivers. Vannote et al. (1980) detail the consequences of this concept. Petts (1990) provides guidelines for application of the concept to developing countries, where objectives of water management fundamentally differ from those experienced in, for example, most European countries. In his article, the focus is on South-America, especially Brazil, where growth of population together with unexploited hydropower capacity results in large number of dam constructions, not experienced elsewhere in the world.

Ward (1989) describes the "four-dimensional nature of lotic ecosystems" ("lotic" from Pearsall (2001) means "inhabiting or situated in rapidly moving fresh water"). In the theory of Ward (1989), the River Continuum Concept mentioned above is extended from the single longitudinal dimension to (1) upstream-downstream, (2) lateral (channel-riparian zone), (3) channel-contiguous groundwater interactions together with (4) time cover the four aspects or dimensions to which lotic ecosystems respond. He argues that a holistic approach utilizing a spatio-temporal framework built upon this theoretical dissection leads to a better understanding of functioning of lotic ecosystems.

Poff et al. (1997) establish the theory of the Natural Flow Regime. The concept stresses the necessity of maintaining the natural dynamic feature of regulated waters in order to be able to provide species appreciated by the society, to sustain ecosystem health and, after all, to sustain native biodiversity and ecosystem integrity. Loosing this dynamic feature consequently results in direct ecological degradation through loss of biological diversity and economical values. The study notes that flow magnitude, frequency, duration, timing and rate of change are the most crucial factors to be maintained to achieve a natural flow regime. This article is also referred to in another context in section 1.2.5.5. Using this theory, Baron et al. (2002) provide a general overview of how the integrity of freshwater ecosystems depends on the mentioned features of river flow. They recommend various ways to maintain, protect and restore these ecosystems.

Lately Benda et al. (2004) derived the Network Dynamics Hypothesis. This is generated from that of Poff et al. (1997) extending its validity to river networks and catchments by including relevant features of the different scales. Features include basin size, shape, drainage density and network geometry. Though not providing easy-to-derive management objectives, this study is still important by supporting the trends of moving towards catchment management and by providing factors and describers to include when catchment regulation is planned.

1.2.2 Classification of methods for environmental flow assessment

A thorough classification and description of methods specifying river flow objectives (RFOs) worldwide to 1998 inclusive is presented by Dunbar et al. (1998). The study is based on the work of Petts (1996) as starting point for the classification, slightly altering that based on extensive review of literature. Although the scope was possible utilization of existing methods in the United Kingdom, the review and especially the systematic analysis of each solution makes this work very valuable. Method classification categories are the "look-up" or "standard setting" techniques, the "discussion based" or "hydrological analysis" techniques and the "biological response modelling" techniques. This classification is updated in Acreman and Dunbar (2004).

The techniques in the three categories differ in background data, preparation needed, operational efforts necessary for their usage, labour required and finally the scale in focus. Looking at these differences in more detail, it also becomes clear that hydrology based or standard setting methods aim to keep their focus on the river environment as a whole, but can loose ecological relevance as they operate on such a higher resolution than which ecological processes take place. On the contrary, biological response modelling techniques shift this focus to individual species or sometimes guilds (selected group of species) and assuming their characteristics valid to the whole community.

Another important note in this work is that RFOs may have disadvantages if they are too simple and thereby damaging to the environment (e.g. a minimum flow setting is too low), or if the mechanisms of the ecosystems are not well understood. In this case, the RFOs may be badly specified. To avoid these shortcomings a set of questions has to be answered in the preparation phase starting with specifying objectives, data needed and available, their collection and methods to be applied, modelling and analysis with feedback to the original setting of objectives, tools for implementation and finally follow-up works such as monitoring, revision techniques, incorporation of successes and failures.

A similar but more abstract attempt for summarizing existing instream flow assessments is shown by Caissie and El-Jabi (2003). They successfully cover the span of methods both from the historical and the methodical point of views, however this study does not dig as deep in the practical issues as Dunbar et al. (1998). The major categories noted are "historical streamflow" methods (compare with “look-up table” methods above), “wetted perimeter” methods (see part of “hydrological analysis” type above) and “habitat preference” methods (see “biological response modelling” above). The article argues the validity of all method groups, underlining the necessity of careful selection for different actual purposes considering their strengths and weaknesses. They draw similar consequences to the previous article when separating methods focusing on ecosystems as a whole or observing few representative species and assuming validity of findings to the communities thereafter. Regarding the development of this scientific field, they conclude that the importance of integration of all types of methods including new issues as well as professional judgement would remain important in the future.

Perhaps the most extensive and probably the most up-to-date overview is published by Tharme (2003). This exhaustive study carefully checks and compares over 200 methods and methodologies for EFA worldwide. Partly similarly to the previous two works, the author identifies four major categories which are the “hydrological”, the “hydraulic rating”, the “habitat simulation” and the “holistic” methodologies. The insignificant amount of methods not fitting in any of the previous four may be classified as either “mixed” or “other” types. Methods in the hydrological class are the most popular worldwide and they rely primarily on data commonly used in hydrology (historical flow records). Hydraulic rating types are less popular because most were replaced by habitat simulation methods in the recent years. They utilize hydraulic variables such as wetted perimeter, maximum depth, etc. at specific (thought-to-be) limiting cross sections or sites. These methods assume the direct connection between river integrity (meaning habitat quality) and the specific hydraulic parameter. Thereby control over the hydraulic parameters result in a control of the quality of habitats or certain biotopes as well. Acreman and Dunbar (2004) indirectly addresses the issue of methods not fitting into larger categories by looking at their complexity from different aspects at the same time and so not classifying methods to one particular group, but rather comparing them in various ways.

Habitat simulation methods are the second most popular among all methods according to this survey and they employ hydraulic habitat modelling relying on numerical hydraulic and ecological information. These methodologies incorporate scientifically defensible ecological-hydraulic connection based on habitat surveys. However, their limitations due to unexplored physical habitat-ecosystem relations as well as data and computer power need prevent them from being the ultimate solution for EFA problems. Actual development trends of these methods point towards incorporation of other hydraulic parameters (e.g. bottom shear stress), selection of species which are more representative and less complicated to observe than individual fish species (e.g. invertebrate communities, or fish guilds) and application of sophisticated hydraulics (e.g. modelling of turbulence and vorticity, 2- and 3-dimensional flow modelling).

The recently appeared holistic methods represent only a slight minority among the other methods. The holistic attribute refers to the large number and broad field of bodies involved in the process. The core of these types of approaches relies on the recognition that structured discussion and multilateral illumination

of viewpoints is more likely to provide success in the process than use of sophisticated models alone, describing for example habitat availability as function of flow scenarios. This may also be due to the data-intensive nature of other approaches, or the large uncertainty inherent in and the interpretation barriers of their results. Therefore, data background, model feasibility play minor roles in holistic methods, while expert knowledge, representation of different (water) user groups and organisation of their communication are more important in the methodology. Holistic methods may be divided into bottom-up, or top-down types depending on the way internal communication and decision mechanisms are organized and this may note the purpose of the EFA as well.
Further methods not being able to fit in either of the above categories may be termed as "combined methodologies". As the name suggests, they incorporate findings, data or methods from some of the four larger groups.
Besides the schemes from the works of Dunbar et al. (1998) and Tharme (2003), in the following, other interesting aspects are considered as well. Within the part dealing with biological response analysis, separate parts focus on issues of preference curves, hydraulic models, physical modelling of habitats and bioenergetics. A limited number of examples are shown only.

1.2.3 Hydrological approaches

Historically, there exists a large number of applications where no modelling was used when preparing regulation or proposing alterations to a flow regime. In these cases, the starting point usually relates the regulated regime to some registered historical features of the flow, which relates to the actual river, the catchment or to the ecoregion. The first classical example is published by Tennant (1976). This method establishes a direct function between mean annual flow (MAF) and river habitat quality in general. The function is based on management experience and other expert knowledge. Though it takes considerable efforts to establish such a system, once it is prepared, its application is straightforward, requiring only few resources and little expertise. It is important to incorporate local geography, climate, species, etc. when localising the method, otherwise its validity may be reduced or completely lost. Variants may be based on other general hydrological features of the watercourse at issue, such as median monthly flow. They may also specify environmental quality in a more detailed way, including seasonality, frequency, duration and other features as well. Caissie and El-Jabi (1995); Dunbar et al. (1998); Caissie and El-Jabi (2003); Tharme (2003) show more examples of development possibilities.
Though among all EFAs this group of methods has been applied for the longest time and is the most used all over the word, some regions still lack even minimal regulations of the field. Scatena (2004) reports a summary of setting instream flow methods in the Caribbean basin, among which hydrological methods dominate, but also admits, that 31% of the countries in his survey (including

70% of all potential continental countries in the area) do not require extraction of surface water permits explicitly, or stating the quantity of water that can be extracted.

1.2.4 Hydraulic approaches

These methods, though not dominant in amount, indicate a fundamental difference compared to hydrological approaches. Instead of incorporating hard-to-verify expert knowledge of various fields and relating that to such an ecologically little relevant feature as e.g. mean annual flow, the method prioritizes one objective measure, the wetted perimeter-flow relationship to describe environmental quality. Naturally, there lies the hidden subjective dilemma of defining the border criteria between acceptable and non-acceptable degradation or losses, but still the philosophical difference is significant. Gippel and Stewardson (1998) point out general problems of this methodology and provide an altered methodology being better founded from mathematical point of view and easier to apply in practice. They identify the mathematical aspect of the problem, which can be formulated by seeking for certain slope or curvature values on the discharge-wetted perimeter function. Thereby the detection of the borderline between acceptable and avoidable flows is done in an objective manner.

While Tharme (2003) understands methods in the present group as intermediate development phases between hydrological and biological response analysis types and explains so the relative few number of actual examples, Caissie and El-Jabi (2003) tell, that river hydraulic methods are widely used though, but little documented. They provide further details and examples regarding this group.

1.2.5 Biological response modelling approaches

Methods in this group share the common idea of extending findings related to only one or a limited number of selected species to the larger environment, naming these selected ones as representatives. The selection criteria may be related to economic relevance, public interest, management objectives or ease of describing behavioural patterns. The selected species or group are observed under varying physical conditions and primarily their position, but in some cases also their behaviour is noted. Provided the actual scientific or financial limitations there may be only existence-absence functions prepared from the collected data, which show the frequency of finding individuals at certain physical conditions and are called habitat use indices (simple individual occurrence frequencies). In this case, (traditionally) the conditions are separated to flow depth, flow velocity, cover type and substrate size. The frequency function may include the actual availability of each physical feature at the observation site as well and then habitat preference curves (availability included) are generated. A hydraulic model is used for generating habitat-flow functions, which sometimes is extended to habitat-time series by utilizing of flow-time series. These models use empirical relationships between a subset of environmental conditions and species' behaviour and therefore are considered semi-biological / semi-physical.

The classical example of this method is the "physical habitat simulation model" (PHABSIM) of the Instream Flow Incremental Methodology (IFIM) documented for example by Bovee (1982) or Stalnaker et al. (1995). Here the preference curves are combined with the hydraulic model output to give one "weighted usable area" (WUA) function, showing the composite evaluation of each physical feature noted at observation along unit river length (measured usually in $m^2/100$ m). The function can then be used to create environmental quality-time series so that critical flow conditions, bottlenecks for the species may be identified. PHABSIM utilizes a 1-D hydraulic model for prediction of the physical features.

Gore et al. (1998) successfully predicted habitat improvement for invertebrates by means of PHABSIM. In this study, the habitat value of placing artificial riffles in a second order stream in an agricultural region of the US (Holly Fork Creek, Henry County, Tennessee) was examined. They compared PHABSIM predicted invertebrate habitat suitability with measurements of invertebrate diversity, assuming higher diversity indicating better habitat. First the riffles were modelled, then physical habitat simulated and finally the riffles built. Measurements were carried out after construction of the modelled riffles. They found significant correlation between predictions and measurements, which proves the success of the model in this case.

Booker and Dunbar (2004) applied PHABSIM to urban rivers in the UK, a little explored field. They used sensitivity analyses to assess uncertainties when applying PHABSIM. They found that habitat suitability indices, calibration of the hydraulic model and time resolution of the hydrograph used to generate habitat-time series are the key factors, having most influence on results of physical habitat simulations. They also found that severely engineered channels have less suitable physical habitat, across the entire flow range when compared to less engineered channels. This is due to the lower morphological diversity in highly engineered channels. The authors underline the necessity of employing carefully collected and prepared data to PHABSIM studies, as variations which may not appear important in the input may result in dramatically different output regarding the named factors.

Conversely, Lamouroux et al. (1998) draw the attention to several potential problems regarding the common practice of coupling hydraulic habitat and biological models for estimating habitat suitability in streams. One of these is that hydraulic models applied for such purpose were derived from hydraulic engineering practice and thereby have limited capability modeling complex flow patterns, in low flow situations in particular. They also are data intensive (precise topographic representation of the channel is needed as input) and describe hydraulics in a scale being different from that of the biological models.

Other problems are that the univariate suitability curves neglect covariance of hydraulic variables and biological interactions, or that the description of local habitat is based on point values, whereas real local habitat is more related to local distribution of those. Finally, they note concerns related to possibility of validating these coupled models, as factors different from those being modelled also influence fish density in stream reaches. Thereby, it is hard to distinguish between modelled and other parameters when selecting criteria for habitat suitability.

Heggenes (1996) summarised criticisms related to traditional methods of biological response modelling, especially PHABSIM as follows. “(1) The relevant hydrophysical variables are not included, (2) the interaction terms are difficult to quantify and not incorporated, (3) the hydraulic models may not operate on a spatial scale that is relevant to fish, (4) the models include spatial but only to a limited extent temporal heterogeneity in habitat conditions and (5) biotic factors are not included”. Morrison (2000) presents a broad but rough review of available techniques used in habitat modelling. The study notes the tendency of incorporating higher order hydraulic models to such studies as well as the immature nature of species-preference models. Leclerc et al. (2003) select the following fields as most important problems of EFA. “Available modelling strategies, the parameterization of habitat preferences of the target species during their life cycles, the behavioural modelling of intra- and interspecific relationships within ecosystems, the selection of proper spatial and temporal scales to represent the habitat, the validation strategies and the choice of minimum levels of river discharge based on modelling results”.

1.2.5.1 Habitat dynamics

Maddock (1999) observes that it is essential that habitat assessment techniques are able to follow flow dynamics. Usually the design structure of the collected methods and techniques in this review allows the repetition of the habitat assessment at different flows, thereby allowing the study of aspects regarding habitat variations linked to flow variation. The flow related habitat distribution can then be estimated by interpolation techniques in the range of mapped flows, or if other knowledge of the river system allows, one may also extrapolate to conditions out of the observed range. Linking observations to historical flow duration curves enable frequency analysis of habitat distribution as reported by Newson et al. (2002). It is obvious, that the actual solution utilized in any method crucially effects its results.

Parasiewicz (2001) combines different types of hydromorphological units (HMUs) and interpolates one so-called flow-habitat curve or habitograph based on the distinct HMU distribution charts (see section 1.2.7.2 for more on HMUs). The method already incorporates biological information to the combined representation of habitat at each flow.

The first step in HMU modelling is to separate HMU types and to prepare flow-"extent of HMU type" curves, which in turn for any flow could provide proportional HMU features, usually areas or volumes. Naturally, the more flows for which HMU maps are available, the more secure the interpolation will be, on the other hand, it is impossible to prepare infinite amount of maps in order to increase total accuracy. We also know that flow dynamics cannot be described by a series of steady situations, because parameters such as "initial" speed, magnitude and direction of flow change all influence the flow status in the consequential moments. See Hamill (2001) or Chow et al. (1988) for parameters describing dynamic flow.

Ecosystem behaviour linked to hydraulic variation, which is also known to be dynamic in terms of habitat use or preference is an additional issue to deal with. See for example Saltveit et al. (1999); Cortes et al. (2002); Halleraker et al. (2003) for studies of habitat dynamics in relation to especially rapid flow variations.

1.2.5.2 Habitat preferences

Leonard and Orth (1986) prepared WUA curves for several fishes, life stages and rivers. Habitat-use guilds were identified by means of cluster analysis of depth, velocity, substrate and cover utilization by the individuals. They recognized four different types of habitat-discharge response curves, which were consistent across streams. They concluded that it is important that target species and life stages in habitat simulation studies are selected from habitat-use guilds to ensure that flow recommendations represent an appropriate compromise between the needs of fast-water and slack-water inhabitants.

Bain et al. (1988) studied effects of different streamflow fluctuations on fish communities by evaluating fish densities between two rivers with natural and regulated flow regimes. They found that highly variable and practically unpredictable flow regimes may cause disturbance that effects fish differently depending on their habitat use and at the same time may reduce community complexity.

Density dependent selection of habitat mentioned in the introduction was confirmed by Bult et al. (1999). They investigated habitat use of Atlantic salmon in riffle, run and pool habitats in enclosures in a natural river in Newfoundland, Canada. The experiment aimed to identify the separate effects of population density, river morphology and water temperature on habitat selection. They concluded that habitat selection might be density dependent and being dependent on other factors than parameters of hydromorphology as well.

Vismara et al. (2001) applied the PHABSIM to a North-Italian stream analysing effects of various choice of Habitat Suitability Curves (HSCs). Results showed significant differences according to the choice of univariate or bivariate selection of the same physical features of habitat preferences. To compare the univariate and bivariate approaches, they calculated the weighted usable area (WUA)-discharge relationships in two different ways. By means of the first aggregation

criterion, all variables receive equal weight, but according to bivariate models, depth is much more important than velocity in defining habitat suitability requirements.
Identification of these problems and those mentioned above have lead to smaller or larger alterations from the original habitat modelling method implemented in the PHABSIM software. For example the uncertainty lying in differences between observed and actual preferences (due to combination of many individual factors) and the non purely physical nature of habitat selection may be reduced by application of fuzzy rules as noted by Jorde (1996). The CASiMiR simulation model shown by Jorde and Schneider (2000) can use both univariate preference curves and multivariate fuzzy rule based approaches. Here, so called "fuzzy sets" have to be defined describing the habitat parameters in linguistic terms such as "low", "medium" or "high". Rules may be for example: if depth is high, flow velocity is high and substrate size is medium, then the habitat suitability is small. Applications of CASiMiR usually utilize a 2-dimensional finite element model for hydraulic modelling, but other models may be used as well. A practical example is outlined in Peter et al. (2004). This way of handling habitat use in assessment studies reduces the uncertainties related to "strict" (meaning explicit functional relation) preference curves as well as allows incorporation of factors with doubtful quality of physical validity. Definition of fuzzy rules relies on expert knowledge, thereby is both the weak and the strong part of these models.

1.2.5.3 Physical models for habitat studies

The uncertainties related to identifying habitat preferences of species together with the large number of uncontrolled factors inherent in natural environment directed some research to laboratory experiments. Sempeski et al. (1998) investigated a habitat selection hypothesis on young grayling. Observations and a 3-dimensional hydraulic simulation showed that the fish selected different types of (hydraulically) dead zones during daytime feeding and night time resting. During feeding, the fish selected deep areas, while at resting areas with a flat bottom and low bottom velocity.
Halleraker et al. (2003) experimented with wild brown trout (*Salmo trutta*) in an artificial stream, to provide environmental guidelines for operation of peaking hydropower plants. This study is described in more detail in Section 1.1.2.3.

1.2.5.4 Direct observation of species

For creating habitat suitability indices, direct observation of the species is necessary in most cases. Locations of individuals are marked, their activity, age, gender, or anything else being the focus of the actual study is noted and physical parameters of the spatial position are measured. Then in most cases, the larger extent of the environment is described by the same variables used in computer models. Linking the studied individuals to physical descriptors of their occurrence allow construction of preference curves of individual physical parameters. If the neighbouring environment is also considered, the relative availability of small ranges of the parameters may be incorporated as well refining the previous results. Gore et al. (1998) for example validated the PHABSIM model suite by direct observation of invertebrates. More details of this work can be found under the introduction to Section 1.2.5.

Gibbins et al. (2002) employed an electivity index (i.e. preference functions calculated including relative availability) of Vanderploeg and Scavia (1979) following the previous studies of Lechovicz (1982) to compare habitat suitability prediction of this method to those calculated by PHABSIM. To calculate electivity and to validate either of the results direct observation of individual fish was necessary. They found that choice of discharge as single but complex preference instead of individual depth, snout velocity, substrate and cover resulted in a more reliable habitat suitability description, especially in discharge ranges not covered during the observations and in complex flow patterns. These studies necessarily involved direct observation of species.

Booker et al. (2004) carried out a complex study to predict net energy intake for drift-feeding salmonids using a three-dimensional hydraulic-bioenergetic model. For testing of the model, individual fish were observed and their position compared to model prediction of net energy intake values calculated from hydraulic and other parameters. They provide evidence that the observed fish locations coincide with those indicated as relatively high net energy intake values by the model. Some further aspects of this study are mentioned in Section 1.2.5.6 as well.

1.2.5.5 Hydraulic models

Application of hydraulic models is essential for several problems in ecohydraulics. This section shows a short summary of computer aided flow-modelling concepts, basic details about CFD. Abbott (1991) in detail, Rüther (2004) in brief or Olsen (1999 and 2002) partly provide overviews of concepts and examples related to CFD modelling. The conceptual CFD model incorporates partial differential equations for conservation of mass, momentum and energy as its core features. The liquid or gas continuum is divided into computational units (commonly referred to as cells) in which these physical parameters are computed. Finite-difference, finite-elements or finite volume discretisation schemes are used and the division method fundamentally influences the approach of the solution. The division method of the continuum also defines the spatial limitation related to the calculation. In certain special cases, one or even two of the spatial dimensions may be neglected, gaining a much more simple design and calculation scheme than that needed for a solution valid in all dimensions. Thereby we distinguish one- (1D), two- (2D) or three-dimensional (3D) models depending on the number of dimensions taken into account. Below examples of studies assuming different degree of such simplifications are reviewed.

One-dimensional hydraulic modelling

One-dimensional (1D) models simulate flow in one direction only, assuming fluid movements in the other directions being negligible. In a practical case, a 1D river model would utilize short reaches between cross sections as computational units and provide one (mean) velocity value pointing perpendicular to the cross sectional plane for each cell. This is a realistic assumption in a straight trapezoid open channel where surface width and flow depth are in the same order of magnitude. Limitations include inability of simulating (and thereby considering in the habitat model) secondary flows, eddies, turbulence and its effects or backwater zones, as well as high sensitivity to flow variations. During calibration (the procedure when simulated model results are verified and adjusted to match measured field data) only few flow situations are considered. Each of those flows requires different calibration parameters and thereby resulting in increasing uncertainty as difference between simulated and calibration flows grows. These parameters are usually represented as friction values, although they incorporate other sorts of energy losses as well, such as eddy-viscosity, turbulence, etc. In practise usually a low, medium and a high flow is considered, covering the whole span of proposed simulation flows.

Habitat modelling within EFAs usually requires a somewhat finer resolution of hydraulic outputs than what is achieved with a 1D model and so hydraulic results are refined. The desired resolution would be close to microhabitat scales of target species, since observations when preparing preference functions consider this scale. Refinement of physical habitat parameters named above, (depth, velocity, substrate and cover) is carried out by assuming unvarying cross-sectional shape and parameters laterally along the hydraulic computation cells. The weakest part of this procedure is the distribution of velocities across the cross sections. This is because the 1D hydraulic simulation neglects physical features from which the procedure of cross-sectional velocity distribution could be performed in a physically correct way. Thereby certain further assumptions, such as the distribution of velocity follows distribution of depth, etc, weaken the validity of the results. The refined cell system is then combined with the prepared preferences providing habitat quality measures and maps.

Two-dimensional hydraulic modelling

If a river is meandering, braided, or scattered by in-water structures, utilization of a higher order hydraulic model usually would give more reasonable model results. 2D models assume 2-dimensional movement of the liquid body and neglecting the 3rd spatial direction. Depending on boundary conditions such as channel geometry or global position, fluids may be discretized along vertical or horizontal axes. In river hydraulics, usually the vertical flow directions are neglected. Addressing the limitations of hydraulic models noted above, Leclerc et al. (1995) show that increasing computational capacity shrink the importance of limitations derived from hydraulic modelling. In general terms we can say that 2D hydraulic models reflect the scale of individual fish habitats and the spatial variability of field data in a better way then traditional 1D models if not else, simply because of the better representation of fluid motions. This obviously doesn't mean that biological models can necessarily make use of the better representation of the fluid. In addition, the flow resistance variables are more realistic in higher order simulations, because they are related to the substrate sizes or lateral shear stresses.

Computational units in a 2D river model are usually defined as a horizontal (quadratic or triangular) grid over the modelled reach, comprising prism-shaped cells with approximately equally sized sides. In the result each node provides one velocity value which is called mean column velocity or depth-averaged velocity. This model is thereby capable of simulating secondary horizontal currents, but not eddies with horizontal axes. The simulation results are evaluated in a similar way as in the 1D case, but additional features may be included as well.

Crowder and Diplas (2000) utilizing 2D hydraulics developed a method providing a measure of certain spatial habitat features. This is done by quantifying local velocity gradients and changes in kinetic energy. This quantification (or metrics), which is derived from results of the hydraulic simulations directly, produce large values for flow patterns exhibiting considerable spatial variation and small values in areas experiencing uniform flow conditions. They expect it to be used in bioenergetics studies for fish (for details about bioenergetics see Section 1.2.5.6). By means of this method Crowder (2002) incorporates mesoscale topography into a 2D hydraulic model and adequately reproduces spatial flows of interest to riverine researchers. He presents the developed version of the first metrics. In the developed version, the first two metrics describe local variations in energy and velocity gradients, while the third metric provides a measure of the flow complexity occurring within an arbitrary area. The method is recommended for channel restoration and evaluation of stream habitat.

Pasternack et al. (2004) report a successful study to improve gravel configuration for habitats. They used a 2D model to evaluate alternative gravel configurations. The scenarios included alternate bars, central braid, a combination of alternate bars and a braid and a flat riffle with uniformly spaced boulders. The scenarios were then compared for their spawning habitat value and for sensitivity to erosion.

Vehanen et al. (2003) followed a similar approach in hydraulics, but instead of using traditional species' preferences, they directly observed the fish equipped by radio transmitters. This way, the use of altered habitat could be directly noted.

Three dimensional hydraulic modelling

Three-dimensional (3D) hydraulic models should best represent real physical conditions in a river. The computational units in these are cells with triangular or quadratic sides dividing the fluid body into arbitrarily small entities. Using 3D hydraulic models, practically almost all physical aspects of microhabitat can be simulated (except small scale heterogenity related to larger substrate and transiant variability related to turbulence) at some costs however. One must find a reasonable compromise between cell size, included and neglected processes and simulation time, as this latter rapidly increases with the overall number of cells considered and parameters included.

Heggenes et al. (1996) suggest the application of higher order hydraulic models to overcome serious limitations inherent in especially 1D models (further details of their findings are shown above). Booker et al. (2001) show a detailed study on shear stress-flow relation in a natural stream. Though the primary focus of this study is to understand features of sediment transport through simulation of shear stress among riffle-pool sequences, still it presents an extensive overview of the capabilities of 3D hydraulic models.

Booker (2003) used a 3D hydraulic model to simulate maximum sustainable swimming speeds (MSSS) of fish, which was hypothesised to be the limiting factor of habitat use in urban streams in high flow events. He successfully applied roughness height values for calibrating the model and thereby enabling simulation of high flows where measurements are impossible to carry out. He concluded by pointing out the necessity of including channel geomorphology in restoration studies, as improvement of water quality alone may not provide sufficient advances in fish habitat availability. This study shows the capability of 3D models to provide us with a large amount of simulated variables of which various sets may be relevant for aquatic habitats. Exploitation of this feature and verification of its use is however not clear yet.

Unsteady simulation

In most cases of habitat simulation, hydraulic models do not incorporate time-dependency and there has only been few attempts to test dynamic hydraulic models for this particular purpose. The problems of flow simulation at wetting drying channels, flashy hydrographs, flood or drought frequencies and magnitudes, etc. may be simulated by means of a hydraulic model with dynamic capabilities.

Poff et al. (1997) note, that the dynamic feature of river ecosystems is important for maintaining their ecological integrity. They report that current water management practices do not identify and respond to this phenomenon. This is because it is limited to protection or conservation of water quality and one aspect of quantity: the minimum flow, thereby neglecting environmental dynamism. They identify

five key factors of water flow being crucial to ecosystems in rivers. These are the magnitude, frequency, duration, timing and rate of change of hydrologic conditions. The hydrologic conditions are governed by flow as the key factor for other related features. Thereby when modelling river ecosystem processes, these five factors (of which four require dynamic hydraulic simulations) are of high importance. Other aspects of this work is reviewed in section 1.2.1
The dynamic capability is not related to the dimensional features (1D, 2D or 3D) of the hydraulic model, in principle all three types of models may be capable of time-dependent simulations. Further information about the theoretical background of hydrodynamics is explored by for example Hamill (2001).

1.2.5.6 Bioenergetics

As doubts related to the application of preference curves along with computational capacity increased, new theories of simulation of habitat use and population development appeared. Traditional habitat models as detailed above are incapable of incorporating large number of species and life stages, features that are crucial for population modelling. The new theories were building on foraging and growth models and utilizing data from 2D or 3D flow field simulations, schematized energy input and loss factors of individuals. These theories build upon the assumption that the animals conduct their foraging manners by optimizing energy losses and energy gains. For example, if a fish is holding position at the bottom of a river, the choice if it catches an approaching prey is determined by fish to prey size ratio, fish energy, flow velocity, flow visibility (usually derived from turbulence), fish to prey distance, etc. – number of features easy to formulate by hydraulics related parameters. Then including this in a general energy budget formula, effective growth is gained over time. In these models, energy is used for growth, reproduction and basal metabolism.
Alfredsen (1998b) reported a test of a bioenergetic model in a natural Norwegian stream for juvenile salmon. Model results were compared to preference based habitat simulations. It was found that the bioenergetic model predicted high relative energy potential at areas where the preference based model indicated good habitat and vice versa. This fact suggested the validity and potential of such models over other historical approaches.
Hayes et al. (2000) outline how models building on bioenergetics or foraging are constructed in general, as well as development of an actual whole-lifetime example for brown trout in New Zealand. The model produced growth curves that can be considered similar to those observed. They successfully identified limiting factors of growth as a combination of temperature regime and foraging costs of energy related to flow speed, invertebrate drift size and visibility. The results can be used in hypothesis generation and as environmental-impact assessment tool.
The spatial metrics developed by Crowder and Diplas (2000) are discussed above. They propose possible utilization of their method for bioenergetics models.

Booker et al. (2004) presented a bioenergetic model built on a 3D hydraulic model of a natural stream in South England. The model was used to evaluate habitats by their relative local energy potential. Model results were verified against direct observations and they support the hypothesis that feeding fish preferentially select areas of high energy gain, but move to areas with lower velocity when resting.

1.2.5.7 Artificial habitats

When calculating habitat preference curves, the animals are observed in their natural environment (their habitat) and their selection of space is identified by its physical means, like for example water depth or snout velocity in most fish observation related cases. In such cases description of habitat is known and in a way assumed "wellness" values are linked to certain physical features of the environment. Thereby on the other hand, in order to improve "bad" habitat, the previously generated preference functions (with different spatial origin) can be utilized by artificial construction or alteration of habitat in order to improve environmental features. This in practice could involve a wide range of improvement measures, for example channel deepening or narrowing, building of meanders, digging pools, enforcing gravel, changing bed material, altering slope, etc.

Harby and Arnekleiv (1994) report on a biotope improvement study in central Norway, where river regulation for utilization of hydropower was combined with artificial inhabitation of Atlantic salmon (*Salmo salar*). The River System Simulator (see section 1.3.1 for details) was used to model and evaluate different habitat improvement schemes. Due to the regulation, low flow periods were planned to appear often during operation. The biotope improvement aimed at establishing habitats for juvenile salmon at low flow situations. The preference curves constructed for velocity and depth habitat showed which intervals and combinations of these were optimal for the specified species and age group. After regulation, population of salmon at the altered site was compared to population at an intact reference site. Early observations partly prove success of the method.

Vehanen et al. (2003) report on a similar approach, but with better instrumentation, modelling and follow-up work. Habitat for adult European grayling (Thymallus thymallus L.) was created in a channelised river reach at a reservoir. After the improvement works, some individuals were tagged with radio transmitters and their movements were followed. The observed fish largely stayed in the restored area and tended to avoid the unchanged channel of the river, which demonstrates the success of the method.

Gore et al. (1998) observed invertebrate communities, in order to verify predictions of habitat quality by PHABSIM. Artificial riffles were built as improvement measures. Results show a significantly high correlation between observations and predictions. Scruton et al. (2003) tagged individuals of salmon and trout with radio transmitters in order to follow their movements during peaking flow habitat. This type of flow variation (see details in section 1.1.2.1) is expected to appear more often in areas with deregulated energy markets than today, but its effects on particularly fish is little explored. Results show the different reaction to certain phases of peaking as well as the difference between the reactions of the species.

1.2.6 Holistic methodologies

The name of this group shows that this type of environmental flow assessment aims to cover the widest possible analysis of impacts of flow alteration. This is achieved through identification of a set of different flow scenarios and their complex analysis for evaluating their capability of maintaining entire river ecosystems.

King and Louw (1998) report on the application of the Building Block methodology in South-Africa. The primary application field of the methodology is where biological data and understanding of the functioning of the river are limited, however it works well in data-rich situations also. It utilizes existing data and expert knowledge through structured organized discussion (expert user workshop), where each participating scientist is provided with existing data in a form that is easy-to-understand but also contains all available and relevant information. The experts take different roles representing the various users (or uses) of the water. The workshop output, agreed by all participants, is a quantitative description in space and time of a flow regime that should ensure the maintenance of the river ecosystem in some design state proposed for the future. Such way, the achieved result is much easier to communicate to the public and thereby probable success is ensured.

Maddock et al. (2001) describe compensation flows to minimize the ecological impacts of regulation in number of rivers whilst protecting the yield of a critical public water supply. PHABSIM was used to evaluate separate reaches for variations in habitat quality, but unlike earlier studies, here a range of species (Brown trout, Grayling and four invertebrate families) were included in the analyses and thereby ensuring its holistic feature. The authors note the necessity of further conversation between the users (here the Environment Agency, the water company and other local interests).

McCartney and Ackerman (2001) report on managed flow releases from dams. The concept shows the necessity of periodic releases of large volumes of water (artificial floods). These may be damaging, but in some instances can sustain a range of natural resources that are beneficial to downstream populations or activities. Finally, the benefits would be more significant than the damages and managed floods could therefore be a useful improvement tool at dams.

1.2.7 Scales in habitat modelling

In environmental flow assessment, the problem of scaling becomes increasingly important. An example is that there are important difference between scale where observation of individuals takes place and scale of ecosystems for which the assessment is prepared. Another problem is operation related in water management, as it extends its boundaries to larger scales than what is usual historically. Kalma and Sivapalan (1995) thoroughly examined scaling related issues in hydrology in general. Later Blöschl (1999) reported findings on scale theory and used snow distribution modelling as an example. Though modelling snow processes have little relation to hydro-ecology in general, still similar conclusions apply and similar methods are applicable to chemical and biological processes in both cases.

The differences inherent when stepping from one scale to another (from historical to present practice) cause problems in data management and particularly in interpreting research results in an easy way to compare from the different sources. This has to be overcome by utilizing intermediate systems for scaling data and results to equivalent levels of validity. Frissell et al. (1986), Kemp et al. (2000), Parasiewicz (2001) and Pollard (2002) report that the utilization of meso-sized units seems useful for such purposes, because they lie in between those micro and macro scales in size, are both feasible for river management and are representative for habitats. Meso-scale is also capable of extending existing micro-scale information (which is typical for species' studies) to be utilized at macro-scale (which is required by actual water management) according to Davies et al. (2000), Tickner et al. (2000) and Dovciak and Perry (2002). Luz and Loucks (2003) provide an actual example of the problem. They used the Northern Pike (*Esox lucius*) as indicator species in a large-scale habitat quality assessment at a coastal wetland of Lake Ontario in the United States. Using water level and temperature time series together with classical preference indices (see section 1.2.5.2 for details), time series of habitat suitability were created. These were used to test alternative land-use effects on overall habitat quality by means of various reliability, resilience and vulnerability performance indices.

1.2.7.1 Methods focusing on microscale habitats

The classical assessment of habitat quality involves observation and data collection of the micro-scale of species. The classical overall method of IFIM is described by Bovee (1982). Later Bovee (1996) described the development of habitat suitability criteria. Capra et al. (1995) used an improved version of the method, which provides not only a static relationship between an index of potential habitat (like WUA) and flow, but including three additional factors, the habitat-time series, the habitat duration curves and the continuously under threshold duration curves as well. Their major finding is the illustration of the improved method with an example application assessing spawning areas of 0+ brown trout.

Vismara et al. (2001) reports a comparison study between using univariate and multivariate habitat suitability curves for adult and juvenile brown trout in Northern Italy prepared for a PHABSIM simulation in the area. They found significant difference between the results from the two methods. This indicates the sensitivity that selection of preference curves put on habitat quality analysis. Similar findings are reported by Booker and Dunbar (2004), who carried out sensitivity analyses of various factors having on PHABSIM results. More details of this work are shown under the introduction part of Section 1.2.5.

Gibbins et al. (2002) compared the “electivity index”, which is based on direct observation of fish to PHABSIM results. They found that the two models provided similar results at low flows, while there appeared a significant difference at higher flows. They suggest the use of electivity indices in cases where PHABSIM is likely to fail, such as predictions of habitat quality out of observation ranges, complex flow patterns, or other cases where 1D simulation of hydraulics is inappropriate. However, longer time is necessary to prepare the indices than what is used for traditional preferences. Also, transferability from one river to another is not discussed.

Crowder and Diplas (2000) developed formulae of spatial metrics assessing micro-scale habitat. By means of a 2D hydraulic model, additional variables to classical ones (like mean velocity and flow depth) can be incorporated to surrogate habitat studies. The new variables include local velocity gradients and variations of kinetic energy. Comparing their results with data from other studies (see their references) suggests that the metrics produced in the modelled flows are consistent with values found near fish resting and feeding locations and, thereby, provide specific micro-habitat information. In addition, the habitat metrics may be used in bioenergetic models for calculating energy expenditure rates of fish.

1.2.7.2 Methods focusing on mesoscale habitats

The issues mentioned above in this section introduction (1.2.7) have directed some research towards alternative assessment methods of physical habitats. In fluvial hydromorphology, gravel-bed rivers are often characterised by their pool-run-riffle sequences. In freshwater ecology, these forms are then identified as primary meso-scale habitat entities, which are playing important roles in relation to individual behaviour and population development. It is important to note the difference between hydromorphological units (HMUs) and the ecological term of mesohabitats, even though these often are referred to as similar features. In practice they are assumed to represent the same entity of the water body, however it is only the HMUs that are possible to investigate by means of direct physical measurements. Therefore, mesohabitats are linked to HMUs and often modelled utilizing physical features of those.

Newson and Newson (2000) report that there is a major difference between methods depending on whether they describe functional or physical habitats, which implies that the method philosophy is more on the ecology or hydromorphology side. This is reflected in the describing factors and the structure of the systems. Kemp et al. (2000) and Newson and Newson (2000) showed that there are direct connections between entities of these two fundamentally different system types, and therefore, the two different phylosophical approaches describe the same features in different ways. The physical descriptors of classes may be flow velocity, substrate composition, surface flow type, etc., while existence of overhanging vegetation, emerging plants, floating leaves, etc. reach on the side of functional habitats. Keeping in mind that these describe practically the same units within rivers, their general description should incorporate a combination of these.

Structures of mesohabitats

The historical literature classifies stream segments into riffle-run-pool structures. These follow each other in varying order and are understood that each segment spans across the whole width of the river. Thereby this type of system provides classes large in extent and few in number compared to classes of other systems. The work of Jowett (1993) is an example using this method.

Another example of the most common approaches is the registration of class area proportions in regular distances, but without their actual physical locality. Such a method is used by Armitage and Cannan (2000). This solution is often utilized when the extent of the study site does not exceed short sections and only some sites are studied or when no physical measurements are planned, therefore registering their actual locations are not needed.

Raven et al. (1998) presents a standardized system developed in the UK to assess river quality, which features both hydromorphological and biochemical factors. Even though it also employs the simple riffle-run-pool structure, the standardized methodology and the possibility to link these features to each other on a representative site-basis, makes it more advanced than the previous examples. This method is a national standard in the UK. Similar national solutions are developed in Germany reported by Schneiders et al. (1993) and in other countries as well.

Probably the most time consuming method is when mapping of classes aims to follow layout of actual biotopes, so their extents are exactly defined, therefore the result is more fragmented than inthe case of riffle-run-pool methods. The fragmentation can still follow some structure, or can be amorphous as reported by Parasiewicz (2001). These techniques provide a higher sophistication in further analysis, not only because of the additional amount of data collected, but also they provide real habitat scale information with direct spatial linking.

Detailed hydro-morphology-based works like that of Rosgen (1996) apply several scales for river classification. The methods mentioned above only apply to those of the meso-scale extent, when classes have similar sizes to functional habitats.

Mesohabitats in the literature

As mesohabitats gained focus in research, it quickly turned out that their identification is far from being uniform or standardized. Therefore Jowett (1993) conducted a study to derive an objective method for distinguishing pool, run and riffle habitats. Slope, water depth, velocity and substrate data were collected in a river and were used to calculate average substrate size, relative roughness, velocity/depth ratio and Froude number. The results show, that the velocity/depth ratio, Froude number and slope were the best determinants of habitat type. For definition of Froude number see Hamill (2001). A somewhat similar study was carried out by Kemp et al. (2000). But unlike Jowett (1993), they stepped forward from pool-run-riffle sequences to general mesohabitats and finding physical describers of functional habitats. In their understanding, functional habitats are ecologically meaningful meso-scale habitat units, while flow biotopes are hydromorphological features. Froude number was the best physical describer of functional habitats through their link with flow biotopes.

Driven by the uncertainties related to subjectivity when identifying physical biotopes (and their related functional habitats), Padmore (1998) carried out investigations where flow types were tested statistically by discriminant analysis. The habitat units were identified by dominant flow type as a particular combination of substrate and hydraulic parameters. The physical biotopes were shown to be hydraulically discrete in terms of Froude number and other combined hydraulic indices. Biotope mapping at different flows was used to find out how the biotope sequences vary when altering discharge. Threshold discharges, where biotopes change show relation to biotope "patchiness" and "diversity". By means of biotope mapping, based on physical features, the flow regime may be designed to maintain "natural" or "desirable" biotopes to fulfil management objectives.

Cohen et al. (1998) used mesohabitats to describe four ecoregions in the Loire basin, France. The study tested various hypotheses regarding mesohabitat distribution and structure between the regions as well as large-scale factors describing mesohabitats. This case represents a border between meso-scale and macro-scale focused approaches, as catchment features were also looked at (however neglected later).

Maddock and Bird (1996) and Maddock (1999) present an overview of the available rapid habitat assessment methods as possible improvements or replacements of PHABSIM. They note that the major issue is firstly the definition of the levels of detail that are appropriate for worthwhile yet cost-effective habitat assessment and secondly, the determination of the features that are biologically important and hence can be considered habitat features rather than simple geomorphic features. The idea is that some uncertainty, as well as data and labour requirements in PHABSIM may be overcome by mapping mesohabitats and measuring limited amount of data in them. They present a method built upon the findings in their study.

Inoue and Nakano (1999) analysed mesohabitat use for juvenile salmon. The study reach was divided into equal-sized units in a structured manner. These were grouped then into mesohabitat units according to combinations of three physical features, depth, mean velocity and substratum conditions. Cluster analysis was applied to decide on class criteria for grouping and as a result, eight separate class types were used (for example deep-moderate subunit). Results prove the use and advantages of mesohabitat mapping. In addition, the results suggest that habitat quality is determined by both the characteristics of the habitat itself and by adjacent habitats (class combinations).

Brunke et al. (2001) applied a mesohabitat-based method to assess alterations in habitat of benthic invertebrates. Eight mesohabitat classes were used distinguished by their hydromorphological features. They found, that the use of mesohabitat-specific relationships between flow velocity and discharge seemed the most appropriate approach to assess the impact of flow variation in this case. They conclude that this approach can be used to develop a minimum flow level that mitigates the effects of flow reduction.

Pollard (2002) focusing similar problems presented the Geomorphological-Biotope Assessment (GBA) method in a South-African case study. Here GBA results and effectiveness is compared to the traditional IFIM approach. She suggested that the GBA method offers a more robust and ecologically-appropriate approach to understanding habitat for biota than IFIM, because it preserves spatial reference and habitat heterogeneity.

The study presented by Emery et al. (2003) addressed a need for a quantitative means of classifying flow behaviour that can be applied in functional eco-hydraulic river rehabilitation designs. They found that overlaying hydraulic patch class boundaries on channel reach topography provides a simple but innovative method of exploring and defining the spatial hydraulic habitat implications of riffle-pools of different topographic forms.

Pasternack et al. (2004) applied knowledge of mesohabitat use by spawning Chinook salmon (*Oncorhynchus tschawytscha*) in order to improve habitats. A 2D hydraulic model was used to test different theoretical substrate scenarios, where boulders and gravel were manipulated. They tested four cases referred to as "alternate bars", "central braid", "combination of alternate bars and a braid" and "flat riffle with uniformly spaced boulders". The test considered two different purposes, first to have high spawning habitat value and second to have stability against erosion. Results show, that the "flat the riffle" test provided the best habitat quality, but on the other hand it was much less stable than the "bar and braid" test and therefore should not be taken as best solution. Combined analysis of both features provides more realistic results than habitat quality alone.

However the methodology of Rosgen (1996) does not fit exactly to the present category; it is mentioned here because of the core features of this extensive study and guiding work. The broader scope of the study, which builds on the theory of the hierarchical river inventory, is to:

- address stream system inventories at appropriate levels,
- provide an organisation for integrating and analyzing information at various levels,
- help the assessment of cumulative catchment processes and
- provide method for predictions of erosion, sedimentation and stability issues.

The theory defines four levels (I-IV) of stream characterization. “Level I” covers geomorphic characterization (stream types “A” through “G”) based on macroscale features, which are detailed below in section 1.2.7.3. “Level II” includes morphological description or delineation criteria of the stream types identified on the previous level, six sub-types of each stream type (“A1” to “A6” through “G1” to “G6”) based on mesoscale features, such as cross section, longitudinal profile and plan-form features. All these describers are based on measured field data. “Level III” gives stream condition in form of analysis of functional habitat and morphological features in relation to their theoretical feasible values. Finally, “Level IV”, the validation level identifies stream types according to calculated values from the previous level. The work is profusely illustrated with schematic figures and real life pictures of the various types of stream types on all levels from all over the US.

1.2.7.3 Methods focusing on macroscale habitats – population modelling

Hydro-ecological science recognizes physical factors influencing habitats at larger spatial scales than discussed above. Features of catchment characteristics, such as size, shape, climate, geography, stream order and length, geology, etc. are function as foundation for local habitat quality, besides human activities. Benda et al. (2004) describe the Network Dynamics Hypothesis. The study takes into account fires, storms and floods in general and sediment fluxes, basin size, basin shape, drainage density and network geometry in detail as regulators of spatial distribution of physical diversity in the catchment. The overall concept attempts to provide a general ecologically based view, how channel networks structure riverine habitats in a natural catchment.

Davies et al. (2000) performed a test to identify local habitat-catchment characteristics relationships so that local features could be predicted from larger-scale features in south-eastern Australia. A model was created to predict quality levels locally and these predictions were compared to observations at over 50 sites in one catchment. The observed-to-expected ratio, which is calculated for each site shows information about the degree of (human or natural) impact. The sites are impacted, where this ratio departs from one. In these cases habitat assessment from the habitat predictive model was compared with biological assessment from the Australian River Assessment System (AUSRIVAS) predictive model. It was possible to identify whether habitat degradation or water quality degradation was the cause of biological impairment, thus forming a catchment-based habitat quality assessment tool.

Sauvage et al. (2003) developed a complex model covering the catchment of the Garonne River, France. The purpose is general impact assessment, especially the effects of pollution. For this, a dynamic 1D hydraulic model was coupled with dilution-diffusion and biological modules to predict propagation of particles or chemicals in the catchment with the flow, as well as their degradation through biological processes. Such a model may be the pioneer version of real life application of the Network Dynamics Hypothesis in real catchment management.

Hardy and Addley (2001) employed advanced instrumentation such as multi-spectral digital video imagery in order to create a GIS database for habitat assessment in a whole catchment. They combined aerial photography and multidimensional hydraulic modelling with a real-time GPS hydro-acoustic mapping technique to refine channel topography and to gain a 2D velocity field. All layers of information were combined in the GIS for validating modelling results. They propose the technique to improve habitat modelling by relating species behaviour to real spatial data instead of usual oversimplified systems.

Models estimating population dynamics mostly operate on macro-scale level. Such models estimate growth rate, fertility and survival in different age classes of one or several species, based on general hydraulics and other macro-scale parameters such as temperature, flow and timing of these. Van Winkle et al. (1998) developed a model for brown trout and rainbow trout. The study uses PHABSIM, which provides the hydraulic parameters, such as depth and velocity distribution as well as the availability of spawning habitat, cover and feeding stations. This was linked with an individual-based model, which simulated reproduction, growth and mortality of individual trout as a function of flow and temperature. Comparison of a prediction test of the model calibrated for the North Fork Middle Fork Tule River, California, United States showed good agreement regarding lengths of individuals with observations for nine test years. On the other hand, prediction of abundance was less successful. This indicates uncertainties incorporated to the model by inaccurate field data and uncertainties in the model structure and parameter values. The authors conclude that population modelling with such tools remain a challenge. This indicates the large number of uncertainties developers of population models have to face.

Gouraud et al. (2001) developed a dynamic population model to study the impact of changes of biotic and abiotic environmental factors on trout populations. The model was tested in two fundamentally different (in ecohydrological terms) rivers in France. The model assumed that habitat availability calculated from WUA curves directly leads to increased mortality and fish displacement. The test revealed two different types of stabilizing mechanisms in the population. One is the capacity for population restoration that affects young fish. This was well represented by the model through the phenomenon of density-dependent mortality in the first months of life. The other was related to the adult population, by its adjustment to the carrying capacity of the environment. The authors conclude that the model is capable of identifying key periods during which carrying capacity (related to the hydrology) becomes a limiting factor for fish and, therefore, the model is a useful tool to be used in river regulation and management planning.

Regarding the factors influencing population development, Lonzarich et al. (2000) found that distance between habitats may be a crucial factor. They studied fish movements in two types of habitats, one where pool habitats were separated by short (<10 m) riffle habitats and another, where similar pool habitats were situated farther from each other, separated by longer (>50 m) riffles. They found significant differences between emigration and frequencies of movement in upstream-downstream directions between the two groups. They underline the importance of relating spatial variability in habitats to studies of distribution and dynamics of fish populations and assemblages. They recommend the use of such relations to predictions of habitat alteration.

Kocik and Ferreri (1998) present a method to delineate functional habitat units (FHUs, understood as separate habitat entities in a stream in their study) using habitat maps, fish ecology and spatial habitat characteristics. They utilize the concepts of interspersion (degree of intermixing of discrete habitat types) and juxtaposition (relative location of discrete habitat types). They employ a simulation model to illustrate how modelling FHU structure of various habitats in a stream can improve understanding of juvenile Atlantic salmon production dynamics. They found that, using their method, it is possible to identify a geographic area of greatest production significance, and thereby, focus restoration/improvement efforts to these. Moreover, they suggest that changes in overall smolt production are caused besides changes in FHU complexity also by changes in spawner distribution patterns between the FHUs. They conclude that Atlantic salmon populations likely function following the hypothesis that the spatial arrangements of habitat components can ignite variation in population dynamics at various spatial scales. They also highlight the need to integrate physical habitat data with traditional population dynamics (mortality, fecundity, immigration and emigration).

1.3 Approaches of catchment management

This section describes two examples of existing (more-or-less) integrated approaches designed for environmentally friendly river management. The approaches fundamentally differ from each other, as one, the River System Simulator, was meant to be an everyday tool for operational and design purposes in Norway. The system was composed in a way that allows simulation and study of a wide variety of river management issues. The other, MesoHABSIM, originates from a modern habitat-modelling method, which later incorporated

several additional management aspects and thereby became a general hydro-ecological tool for river management. The majority of its applications are restoration projects, but the system allows other fields as well.
Both can be called hybrid-type approaches, because they incorporate knowledge from several of the previously listed "archetypes" of methods.

1.3.1 The River System Simulator

The River System Simulator (RSS) was designed to be a user-oriented, multi-objective decision support system in river regulation, for both long term planning and short-term operation. The major objectives are environmental impact assessment regarding physical habitat for fish, diluted/suspended pollutants, sport fishing and abnormal ice production due to hydropower operation. Each of those are linked with models specialized for the separate tasks. In addition to the modelling framework, RSS provides a common database, ensuring internal flow of data and optional combination of them. Models computing runoff, hydropower generation, simulating steady and dynamic flow in open channels, water quality in lakes and rivers, ice and temperature conditions, effects of groundwater and impacts on the ecosystem were included. Expert panels as working groups stood behind each objective during design phase. The design groups were hydraulic modelling, temperature modelling, water quality modelling, regulation modelling, fresh water biology modelling, data processing and user aspects.
The project started in 1991 as collaboration between Norwegian research organisations and the so-called "River Regulators" which were mostly the power producers of Norway. Wathne (1992) summarized the initiation works and Killingtveit and Sælthun (1995), Killingtveit and Harby (1994) provided reviews of the first years of testing.
A pilot project for testing capabilities of the system was conducted at Meråker site in Central Norway. The site was planned to be subjected to heavy flow alteration, the RSS was used to find such artificially generated flow regimes, which could improve fish habitat. Harby and Arnekleiv (1994) report how the RSS was used for this purpose. Expert knowledge and fish preference indices from other rivers in Norway were used to simulate fish habitat. The sites provided only little amount of usable habitat in their pre-regulation conditions for juvenile fish. After the simulated improvements, a significant increase of usable habitat was expected to appear. The enhancement was expected to produce approximately 30000 juvenile salmon. A biological program was established to examine the effects of the improvements on salmon life, including habitat use (both in reference sites and experimental sites), growth and mortality. Results showed a significant higher density of salmon at the experimental sites than the reference sites.

1.3.1.1 Hydraulic module

This module has a crucial role in RSS as providing input to many other modules. It has to model flow velocity, depth, wetted area, turbulence, shear stress, substrate, backwater effects in both steady and unsteady situations. Flood propagation modelling is particularly important for hydropower operation. The hydraulic module requires channel geometry, reach connectivity, initial and upstream/downstream boundary conditions and calibration data as starting point. Simulation time resolution is one hour, occasionally finer. The results have to provide further GIS connectivity. Historically, two separate models covered all these fields, HEC-2 described in Bonner (1992), which was replaced later with HEC-RAS, see HEC-USACE (1998 and 2002), and DAMBRK, explained in BOSS-International (2001). If RSS was updated, HEC-RAS alone would be sufficient, but by the time of development, DAMBRK was the only well-tested, widely available dynamic hydraulic model available. Appendix A.3 provides technical information about this software.

1.3.1.2 Temperature module

The module can be used to predict ice production in lakes and rivers. The uses are prediction of consequences in operation changes, or short/medium term forecasting. Input data are wind, humidity, precipitation, cloud cover, heat exchange with ground, lateral inflow. The river model is RIVICE, see Morse and Hicks (2005) and the lake model is FINNECO, described in Tjomsland and Faafeng (1987).

1.3.1.3 Water quality module

The module has lake and river modelling tasks. Different models are capable of doing this, for lakes FINNECO and QUAL2E for rivers. See Brown and Barnwell Jr. (1987) and Shanahan et al. (1998) for details on QUAL2E. It is assumed, that 1D hydraulics is sufficient for most cases. The main task to cover is phosphorous-algae interaction in most cases. FINNECO in addition is capable of modelling ice production.

1.3.1.4 Regulation module

This module has also high importance providing input data for many of the other modules. It enables representation of a schematic network of regulations in a river system, including river network, reservoirs, power plants, inter-basin transfers and all regulation rules. For hydropower, the general driving mechanism behind regulation decisions is calculating trade-off between marginal

value of energy stored in reservoirs and the actual energy price on the market. Besides the pure economy, restrictions apply to certain parts of the system, such as assuring release of environmental flows, reservoir operation levels, power plant operation schedule, stop and start-up periods, etc. Restrictions may be either general or special (with local validity). A special driving mechanism is flood control. In this case power production economy is of no interest, but decisions must be made manually. This is because methods of controlling floods are unique to each system and therefore their generalization is of little use.
The module uses runoff, the regulated river network with all regulating entities (reservoirs, power plants, bypass channels etc), the regulation rules and simplified production-flow functions as input. Of these daily (or hourly) flow values are produced at each regulating entity together with the assumed production value and costs over the different periods. First version of the model is called ENMAG, and an extended version, called nMag is available today. Killingtveit (1999) provides a detailed manual and description of an example application of this particular unit. Appendix A.3 provides technical information about this software.

1.3.1.5 Fresh water ecology module

This module incorporates two different processes. Regarding lakes and reservoirs, the issues cover certain aspects of fish population modelling, such as zooplankton and benthos production, description of physical conditions for spawning, hatching and growth of juveniles. From the ecological point of view, Norwegian lakes are easy to categorize as brown trout dominated, trout-char-whitefish dominated and trout-perch-minnow dominated types. In case of rivers, the focus is kept on fish and invertebrates are not (yet) accounted for. This river sub-module operates on two scales, the reach/site (macro-) scale and the species (micro) scale. Once the river system is divided into macroscale units, the microhabitat distribution can be evaluated by means of a classical preference-based habitat model.
It uses flow release values at certain parts of the river network together with related channel geometry, substrate etc. and temperature as input and produces quantitative fish production values (not fully implemented) and evaluates alterations in fish habitat quality in the overall system. Alfredsen and Killingtveit (1996) report on the first stage of this unit. Appendix A.3 provides technical information about this software.

1.3.1.6 Data processing modules

The unique and most powerful part of RSS is the common database that stands behind the modelling modules. In order to fulfil this task, portability has to be assured, which practically means the requirement of standardized input to and output from each modelling unit. The database communicates with the modelling modules as it is required by each of them. This is because each modelling unit was developed externally to the RSS project, therefore the inputs have to be accepted as they are.

The operation module is another part providing the common interface and design possibilities for combining the modules. The individual modelling modules are called in a serial fashion, which implements a limitation to the regulation module. This is because feedback from the individual modules are not accounted for during regulation modelling since they are run only once at each time-step.

The presentation module (not fully implemented) presents individual results in tables, multidimensional graphic form, in combination with maps, graphs etc. Data interchange with a GIS is possible.

1.3.1.7 User group

The proposed user group of this DSS is made of experts involved in daily river regulation problems in Norway such as planning departments of power producers, consultancies cooperating with these, or R&D organisations. In addition, authorities or officers engaged with law preparation or long term planning in water management with sufficient background of understanding the mechanisms of the separate modules. Additionally to the primary users, scientists and research groups are of significant (but secondary) importance, using the RSS for assessment studies or perhaps testing complex and presently unrealistic operation scenarios. This second group could also implement its own modules or replace / improve the standard ones if capable of this task.

1.3.1.8 Results

Despite of the best efforts of its designers, the RSS could not gain the expected importance among all user groups. The reasons for this are not analysed in publications.

On the other hand, a large amount of the specialized models included in the system are controlled and developed by external institutions, which consequently results in smaller or larger alterations and incompatibilities with the original modules. This fact requires constant maintenance and follow-up work, practically a continuously working development team, the financial background of which was underestimated or not ensured in a feasible manner. In practise, the form of the framework providing the database is crucial when establishing links to cooperation partners. Incompatibility with external systems and keeping downward compatibility brings up a serious problem, which may not have been treated seriously enough.

1.3.2 MesoHABSIM

The method described by Parasiewicz (2001, 2003) exists owing to the criticism the PHABSIM method gained through the years. PHABSIM is described by Bovee (1986, 1996). The primary focus in MesoHABSIM is on the scale of applicability, in which PHABSIM is weak, because of its high spatial detail and data needs. Instead of analyzing a limited number of representative sites in detail, MesoHABSIM maps a whole river (section) with constant but without high detail all the way. It also uses the information for scaling separate types of data from the mapped entities representing features of smaller scales. The application purpose is river restoration projects, where establishment of environmental flows and/or channel modification design are considered. Parasiewicz (2003) reports that three types of scaling are necessary to improve traditional IFIM type approaches to be valid on catchment scale. These are the spatial, biological and temporal upscaling of local information with short time extent to scales of time and space feasible for river management.

1.3.2.1 Issues of scaling

Spatial upscaling is necessary to overcome the validity problems inherent in microscale habitat analysis. The tasks are the selection of appropriate scale for fish habitat data, the development of a hierarchical framework linking this with management scale as well as the procedures connecting broader ecosystem analysis to small-scale habitat studies from the spatial point of view. The biological part of this last problem involves biological upscaling, (fish-) community composition, selection of a subset of species for modelling, definition of species-independent habitat response functions and procedures for analyzing habitat use by fish communities. Temporal upscaling include analysis of habitat dynamics, which are habitat prediction outside of observed ranges of data, description of habitat space dependency on time and definition of habitat variability ranges.

1.3.2.2 Functional habitats

By the initial mapping of hydro-morphological units (HMU-s) at different flows and collecting additional layers of information describing the functional habitat features (such as existence or lack of overhanging vegetation, riprap on the shores and so forth) of each HMU occurrence, MesoHABSIM provides series of very detailed physio-biological maps of the studied river sections. The information from these is used to delineate the river according to morphological features. In practise, the shapes of HMU-s follow the natural functional habitat shapes, but forming distinct entities with clear and unique composition of physical variables. Ten HMU composition types are used, these are altered versions of those from Bisson and Montgomery (1996).

The method takes channel gradient together with general notion of depth and velocity as key factors with eight additional factors in order to describe habitat features. Describers of one mesohabitat class are the name of the basic HMU type together with the additional features of habitat descriptors. These might be substrate, flow type and vegetation related for example. The HMU composition is described by identification of HMU-habitat feature relations using means of multivariate statistics. The presence (somewhat preference) of each species observed may be related to a combination of functional habitat features registered during the mapping process and such way, the most important habitat features are identified. The management objectives (based on for example historical catch records) determine a certain composition of species and thereby a proposed "ideal" distribution of habitats as well.

1.3.2.3 Flow-habitat relation

In a river network, the flows vary between branches, however observed species are found close to both the upstream and downstream parts. Relating species abundance or avoidance to flow may thereby be confusing. The solution MesoHABSIM provides to the problem is the utilization of standardized flow or flow yield (l/km^2) instead of discharge (m^3/s). Utilization of fish sampling methods described by Lobb and Orth (1991) and Bain et al. (2000) address the concept of biological integrity. These provide tangible ecosystem quality criteria in management language.

Altogether, the model provides a robust, multiuse large-scale habitat modelling system that can be utilized for a large variety of applications, that successfully overcomes the problems identified in the widely spread PHABSIM model. Numerous successful applications strengthen its validity.

1.4 River basin management in Norway

This section describes some of the topics related to the energy sector and water management in Norway. The national objectives and techniques such as hydropower-related issues, provide a unique background for water management. Some extracts of the regulation project of the River Orkla are shown as examples for complex regulation strategies.

1.4.1 Organisational background

This text is based on information extracted from MPE (2004). The Parliament ("Storting") provides the political framework for the energy sector and water management. The responsibility is exercised by the Ministry of Petroleum and Energy (MPE). One of MPE's four major departments is Energy and Water Resources. It ensures the economically and environmentally sound water management of water and other energy resources. The department is the government owner of Statnett and Enova companies. Statnett is responsible for operation, development and maintenance of the national grid, while Enova is an agency formulating governmental efforts for restructuring energy production and use.

The Norwegian Water Resources and Energy Directorate (NVE) is a subordinate agency of the Energy and Water Resources Department. NVE's responsibilities are widely spread from ensuring coherent and environmentally sound management of watercourses, through promotion of efficient energy trading and cost-effective energy systems and energy use, to emergency response to flooding, dam failure and finally the operation and maintenance of the national hydrological measurement network. NVE in its mission statement sees itself as the national hydrological institution of Norway.

1.4.2 Legal background

The first legal measure dealing with watercourses was created in the 12th century. Restrictions on watercourse changes and particularly the protection of fisheries were introduced by this act. In 1687, King Christian V retained most of these rules when adopting the so-called Norwegian Law. Later on from the 19th century a new problem arose, the utilization of watercourses for hydropower production. An urgent reaction was needed to avoid loosing the control over the steep rivers, since foreign businesses were trying to grab the possibility and take their ownership. Therefore, the government decided to control waters, so foreign ownership was prevented and hydropower remained in Norwegian

hands by laying the Watercourses Act in 1887. A revised version of this act came into effect in 1940. Private property was kept in focus, stating that the person who is the owner of land is the owner of water too. The act allowed only limited water disposition for serving public interest. In 1990, a commission started preparing the proposal of a new act on the field. The resulting Act Relating to River Systems and Ground Water (commonly referred to as the Water Resources Act) is operative since 1 January 2001.
NVE prepared guidelines and directives that serve as key documents for water management procedures to give practical suggestions to application of the law. These guidelines outline application requirements and procedures for fields such as aquaculture facilities, small hydropower stations, constructions in or across watercourses, gravel extraction, etc.
Norway signed a special cooperation agreement with the EU, which includes the adaptation of national legislation to EC (2000), also known as the European Water Framework Directive. Numerous institutions and legal bodies jointly work on this task since 2002.

1.4.3 Norway specific objectives, techniques

NVE maintains the evaluation and issue of hydropower licenses. Licensing is required, but may be simplified depending on the design capacity and direct impacts on the environment. If concession is required, then the case specific operational regulations are summarized in the concession document. The regulations normally require environmental flow assessment studies to be carried out, the parameters of which are discussed with the public through representatives of local interest groups and the expert board of NVE. The legal background provides a flexible environment for licensing and the measures are not limited to “minimum flow”-type measures only. The discussion related to specifying environmental flow is routinely practised, even though habitat modelling is not carried out in every case. The implementation and operation is monitored primarily through gauging at different parts of the regulated river system and the data is collected in the central gauging database of NVE. In case the water user or operator fails to fulfil the requirements specified in the concession, the licence may be withdrawn.
The NORWIS geographical information system has been developed by NVE to enable reaching a high level and good quality of management of water resources and the environment. The mostly geographically linked data can be presented on maps as well as charts, lists, catalogues or publications. The components of the system are catchments, topography maps, lakes, rivers, glaciers, land use, hydropower related constructions and installations (reservoirs, transmission lines, hydropower stations, water intakes and transfer pipes etc), precipitation and runoff maps, protected areas and so forth in addition to usual commercial

map data. Besides combining a wide range of spatially related data, the system is utilized for simple field calculations used in daily decision-making, for example flood risk, hydropower licensing or sport fishing projects.

1.5 Objectives of the thesis

This chapter has provided background supporting the actual work to be detailed in the next chapters. Explanation of the most important terms, a detailed description of the problem, historical approaches as previous partial solutions and their related fields and a brief review of associated practice and actual legislation in Norway were summarized and presented. We may summarize chapter 1 as follows:

1. Review of existing water body characterisation methods for environmentally aware river management;
2. Identifying requirements of development in a Norwegian environment beyond the generalities studied above;

Utilizing 1. and 2. we are able to start the design of a biotope-based classification method for scaling purposes that utilizes meso-scale hydromorphological units and is primarily applied in the hydropower affected environment of Norway. The tasks may be broken down into the following chapters:

1. Theoretical design of a biotope-based river characterization system with applicability for basin-scale habitat assessment in Norway and with link to economically relevant factors;
2. Application of the theoretical solution in practice and by evaluating the development steps, providing feedback to refine the original methodology;
3. Application of the enhanced methodology as an element of a scaling system. This is shown by means of two projects. The first one aims at assessing and supporting the improvement of salmon production potential and the second one shows the development of a decision support system to be used in hydropower planning considering environmental impacts.

The method of development (Section 2.1) and the resulting method "The Norwegian Mesohabitat Classification Method (NMCM)" (Section 2.3) are presented first. Example applications illustrate the use of the method afterwards (Chapter 3).

2 Development of a scaling and classification system

Meso-scale classification of rivers has been used for decades in hydrology and ecology. Recent research has demonstrated a large potential for using this in eco-hydraulics. Habitat modellers have to look at complex systems (e.g. catchments), where problems in applying models developed for small scales for larger scales need to be overcome. The use of meso-scale classes extends information and helps to overcome the problems arising from scale alteration. The procedure is called upscaling and is done by means of a system based on meso-scale sized classes.
The method detailed below deals primarily with the links between meso-habitat classes, food consumption, growth and production of juvenile Atlantic salmon. It has been tested in Norway and in Great Britain on rivers of various size and has a flexible structure, so it can be adapted to different situations. Rapid applicability was among the key issues during development, in order to be able to create a cost-efficient, effective, robust but still flexible system. This way it can be used for example to identify the critical habitat combinations, which may be a bottleneck for the development of a population of salmon under different flow conditions.
Below an overview of the development history is given. This took place at several locations in Norway and in the UK, therefore a short description of these locations is provided in appendix A.1. Certain components of the actual work formed parts of larger projects with different purposes. These naturally determined some aspects of the development process and therefore short descriptions of the projects are provided in appendix A.2.

2.1 Method development

This method was primarily developed to serve as a classification tool in the EFFEKT project (see A.2.1) and later in the Mesohabitat project (see A.2.2). It presents the physical habitat modelling part of the larger impact assessment-type models aimed in these umbrella projects. In order to achieve the proposed goals of the projects, existing microhabitat data had to be used. By means of this method, which operates on the meso-habitat scale, micro-scale information can be extended for use on catchment or at least longer river reach scales. The method employs hydro-morphological units (HMUs) of rivers and is based on compilation of works of Bisson et al. (1981), Hawkins et al. (1993), Takahashi (1994), Hardy (1995) and Rosgen (1996).

2.1.1 Method elements

This chapter describes the cornerstones of the proposed methodology, hereafter referred to as Norwegian Mesohabitat Classification Method (NMCM). Each of the reference works listed above is described with special focus on what parts and methods are used in our work.

2.1.1.1 Hydromorphological classification

Bisson et al. (1981) provided a system of sorting and naming “habitat types” (HMUs) in small streams, with examples of habitat utilization by salmonids during low streamflow. This research illuminates the fact that the amount of terms used for river habitat description is confusing. The authors note that ordinary terms as riffle, pool or glide are hard to define by physical means and emphasize the common problem of overlapping and mixing between their meanings. The authors propose a standardized system for classifying mesohabitat types with illustrations. This system uses three types of riffles, six types of pools and one type of glide. The definition includes approximate physical description of the HMUs, by means of flow velocity, depth, surface flow type, gradient, bank or channel condition and predominant substrate (either physical or biological). The describers vary with HMU type, as different parameters are used for classifying riffle and pool types. In practice the HMUs are drawn on a map and their describing features being measured. These measurements allowed analysis of HMU length (in flow direction), surface area and volume. The authors present averages of these from all measurements and use them as describers of habitat distribution. By linking different HMUs to fish observations, a habitat mapping and analysis tool is gained, where each HMU represents a certain habitat value for the observed species. Cover was analysed separately, meaning that cover features were not associated with defined HMUs in this method.

In order to avoid confusion between the elements of our developing classification system, it was decided not to use classical terms, but note HMUs that describe mesohabitats by letters of the alphabet (Figure 2.1). We examined the HMUs used by Bisson et al. (1981) and decided to use eight (A – H) HMUs for our purposes for a first trial. In our method, HMUs are defined by flow velocity, depth, surface flow type and longitudinal channel gradient, based on physical parameters by definition, however assuming representation of functional habitats. This is an opposite attempt to that of Bisson et al. (1981), because they identify the functional habitat first and then classify it according to their HMU classification system. It was also decided to note substrate size independently from the HMU classification and exclude cover information, as it contained little regularity in physical terms and seemed to be hard to describe in such a regulated way. Also, cover was expected to vary significantly between different rivers. Therefore it was included separately and it was adjusted to the actual application needs in each case, under the guidance of fishery biologists.

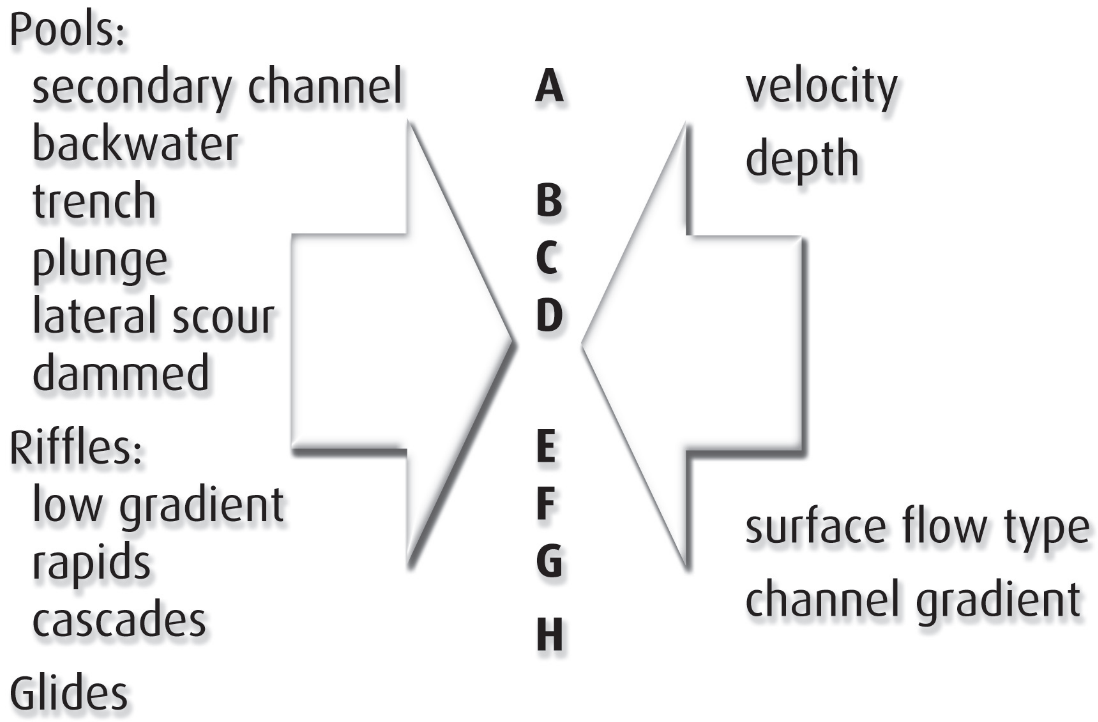


Figure 2.1: Proposed notation and core features of the NMCM. Common describers of functional habitats on the left and of HMUs on the right

Hawkins et al. (1993) provided a hierarchical approach to classify stream habitat features. Their work is based on that of Bisson et al. (1981), with refinements. In this work HMU types are divided in a hierarchical manner: "Level I" uses flow velocity to classify HMUs into categories of fast (run) and slow (pool) types. "Level II" uses turbulence (in its common, non-engineering meaning) for further division of fast HMU types and rough channel form for further disctinction within slow HMU types. Finally, "Level III" combines several parameters for each type, such as gradient, surface flow type, bed roughness, mean velocity and capability of energy dissipation in case of "fast types", while channel shape in lateral and cross sectional directions, substrate character including various substrate features and the reason for the slow flow velocity type in case of "slow types". The authors note that aquatic organisms distinguish among HMU types according to one or more of the different factors used in their classification scheme (e.g. speed, turbulence, channel form). Such way, eighteen HMUs are defined, some of which are easy, but others presumably hard to distinguish from close lying types in the system. No field protocol is presented in this case. The authors confirm the existence of confusing terminology and, partly for this reason, they exclude the category "glide" from the system. They also consider glides as intermediate types in between those two larger groups they already classify. An important character of the system reported by Hawkins et al. (1993) is that, in case of numerous features, they grade the feature instead of measuring it. For example, surface flow type is graded from 1 to 6 according to "how supercritical" the flow is, meaning in this case simply the amount of broken surface found in HMUs. The same manner of classification is followed for all "fast types".

It is clear that the hierarchical classification procedure is important both from the habitat point of view and, for practical problems, expected at the field protocol (Figure 2.2). Certain HMU types can be easily grouped according to their various common or differing features, while on the other hand identifying only one feature at the time could make the procedure more fluent and easier to carry out. The validity of an alphabetical HMU naming method is confirmed, because many HMU terms used in this study were found hard to distinguish by simple linguistics. It was also found that the eighteen HMUs were far too detailed for survey purposes. So it was decided to use the grading manner of classification in a simplified way, distinguishing between low and high values of the chosen parameters. Thereby HMUs were classified according to fast flow or slow flow, but continued to other parameters as well: to high or low gradient, shallow or deep flow depth and little/no or very broken surface.

Step 1: Surface flow type
Broken <--> Smooth

Step 2: Channel gradient
Steep <--> Moderate

Step 3: Velocity
Fast <--> Slow

Step 4: Depth
Deep <--> Shallow

Figure 2.2: Proposed classification decision tree and classes of the NMCM

Both the work of Bisson et al. (1981) and Hawkins et al. (1993) is further refined and placed in a broader classification system in the work of Bisson and Montgomery (1996). Here the whole catchment area is classified, first into hill-slopes and valleys, then into “valley segments” such as colluvial, alluvial and bedrock segments. Alluvial types are divided further into “channel reaches”, which are braided, regime, pool/riffle, plain-bed, step-pool and cascade segments. A nearly allied HMU-based classification as those of Bisson et al. (1981) and Hawkins et al. (1993) is used finally to break each channel reach into “channel geomorphic units”. This final dissection of the segments builds also on 18 HMU types. This work also describes a field protocol to carry out the whole classification process.

The methods applied in this study are developed to classify higher levels of river morphology and extend classification to macro-scales of rivers. It was shown that classifying rivers into HMU classes alone could not provide a complete description of macro-characteristics of a catchment. In order to achieve such a goal, describers of sediment processes need to be added as well. Therefore three sediment classes were added to the HMU class scheme, fine, medium and large sediment sizes as an additional layer of information to be registered during classification besides HMU types.

Frissell et al. (1986) divide catchments into five levels of scales. These are stream, segment (approximately macro-scale), reach, pool/riffle (approximately meso-scale) and microhabitat (micro-scale) systems. They provide descriptors of boundaries and extent between the levels and a list of variables to be used for classification for each level in this hierarchy. For the meso-scale level, which is the level of our interest in this context, bed topography, water surface slope, morphogenetic structure or process, substrate-embedding grade and substrate structure/slope, bank configuration and side slopes, channel pattern and riparian vegetation are the “variables” used.

This gives an important list of “variables” (or rather features) that have to be used as describer in any HMU based classification system. If we describe these by real physical variables, we find that water surface gradient, water surface pattern, depth-velocity combinations, substrate composition and embeddedness mainly cover most of them. This proves the validity and adequacy of the variables that were chosen before for this purpose. On the other hand, the focus on substrate composition and embeddedness draws the attention to the importance of detailed substrate information. Either only dominant or both dominant and subdominant substrate sizes were expected to provide sufficient information on substrate. These attributes are easy to estimate as long as visibility allows. It is known that sedimentation is usually very low in Norwegian streams compared to other European rivers, therefore visibility is not expected to be a limiting factor for substrate observation.

Rosgen (1985, 1996) describes a relatively similar method for classifying streams based on river morphology. This method was developed independently from the works of Bisson et al. (1981), Hawkins et al. (1993) or Frissell et al. (1986). The first attempt focuses more on macro- to mesoscale characteristics of rivers, while the second, more developed version extends from catchment scale through meso- to microscales of rivers. The objective when developing this method was to provide a detailed, reproducible and quantitative method to be applied in "wild-land hydrology". The author refers to the method as a hierarchical stream inventory. It features stratification capabilities of stream systems appropriate at their levels, an organizer suite for integration and analysis of these levels, an assessment aid to follow up cumulative catchment impacts. Further, this inventory analyses erosion/deposition capacity and follows an alphabetical system for naming HMU types. A more detailed review of this work is presented in section 1.2.7.2. This methodology aims at a much broader set of applications than NMCM. However, the structure of delineation and some of the variables help in developing our own method. Rosgen (1996) groups the variables describing "Level II" features in his method into cross sectional, longitudinal and plan form sets (they actually correspond to meso-scale HMUs, see section 1.2.7.2). This work shows that HMUs may be divided both longitudinally and in cross-sectional directions. Therefore, the HMU based dissection of river bodies shall not be limited to units extending to the whole section, but may cover only parts of it. It is shown that infinite fragmentation of such kind is not useful above all limits and therefore the longitudinal division of a section was artificially limited to at most three units across the stream. The higher importance of longitudinal divisions compared to cross sectional divisions was also shown and therefore it was defined an order between the directions: first limiting cross sections are identified, then longitudinal slices within these.

2.1.1.2 Habitat mapping by means of hydromorphology

Takahashi (1994) describes a method for classifying river reaches based on their riffle-pool sequences. In this method four HMU types are used: pool, flat riffle, vigorous riffle and heavy riffle. The author mapped a river reach by means of his method, analysed its characteristics by comparing lengths and aggregated single bed slope values of each entity to each other and to absolute values derived for the whole reach.
Takahashi (1994) shows the use and importance of longitudinal accumulation or aggregation of HMUs, because these show a different feature of a river reach than the single value of average bed slope. Such an aggregation can form the basis of upscaling meso-scale features to river reach, segment and catchment levels and therefore is incorporated into NMCM. For this purpose it was decided to group basic HMU types, starting from either upstream or downstream, summing their areas and noting their absolute distances from the starting point along the river (Figure 2.3).

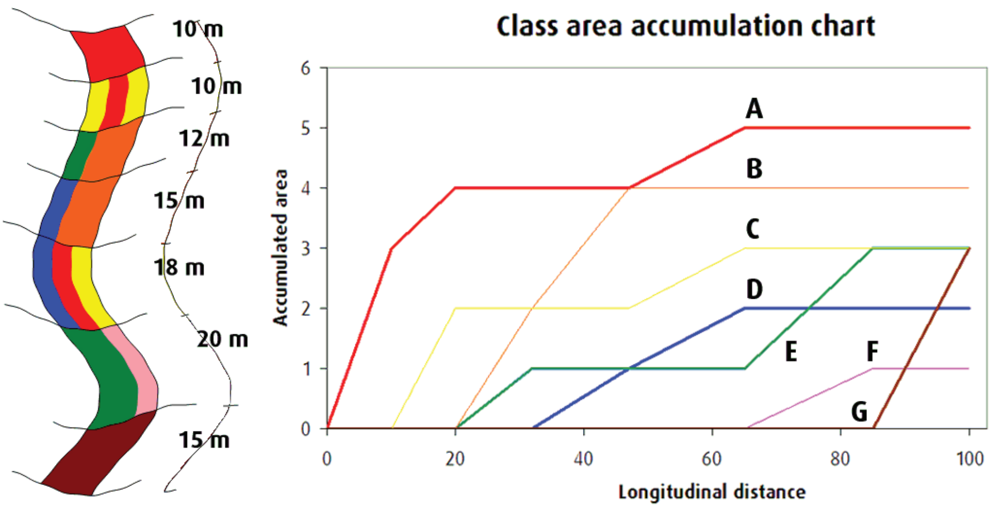


Figure 2.3: Schematic HMU class accumulation chart in the proposed NMCM

Hardy (1995) distinguishes between three different habitat mapping approaches. These are "representative reach mapping", "habitat mapping", "mesohabitat mapping" and "cell-by-cell mapping", listed in an increasing level of detail. The last level requires such a detailed analysis, that it practically cannot cover long (see Frissell et al. (1986), >1000 m) continuous reaches, only selected parts of those. Mesohabitat mapping operates on the highest level of detail, that is still acceptable for classification of longer river reaches. Following this analysis, river segments (>10 km) require the rougher habitat mapping option and finally catchments need to be classified by representative reaches.

It is shown that the different options have different application fields and different practical needs as well. This study showed that, if HMUs are mapped along long continuous reaches, an intermediate level of habitat description is assessed between micro and macro scales, which can be used for both scales of analysis later by aggregating or dissecting its features. This HMU mapping can be performed objectively by means of unambiguous parameter. Kershner and Snider (1992) follow a somewhat similar train of thought to what is presented above in this chapter. In their study, they identify mesohabitats using 18 types of HMUs in a river and reaches based on the statistical analysis of HMUs. Later, they aggregate HMU types into five combined types based on local fish population data. The mesohabitats are separately analysed by traditional microhabitat means, namely the PHABSIM method (Figure 2.4).

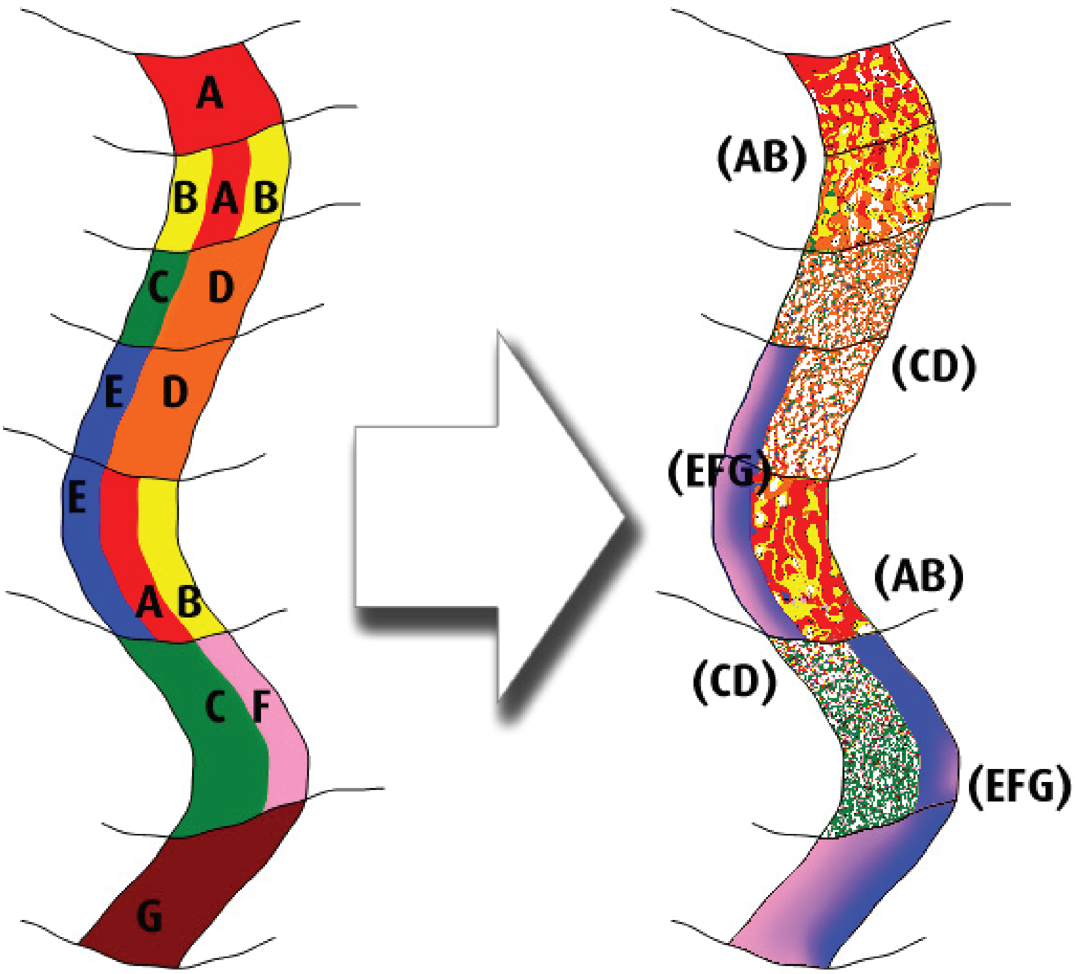


Figure 2.4: Schematic HMU aggregation. The original 7 HMU types (A-G, left) are reduced to 3 types (AB, CD, EFG, right)

During HMU mapping in the NMCM, it was decided to use a standard template for all cases to identify HMUs representing different types of mesohabitats. HMUs would have unequal lengths, structured form and their describing physical features would be defined in advance. In order to provide basis for aggregation of HMUs there is also a need to gain description of proximity or neighbouring. The basic set of HMU types used in the survey would be interpreted by meso- or microhabitat means to provide a link between hydro-ecology and hydro-morphology.

2.1.1.3 Temporal habitat predictions

Habitat predictive capacity in time of a mesohabitat/HMU based methodology relies heavily on the solution the method uses to handle different flows. Flow variation may be predicted for whole rivers ahead in time, but temporal habitat variation is a more complex process and not easily modelled. HMU surveys are carried out preferably for only a few flow situations, which do not allow providing predictions in the same time resolution as flow forecasts. The more flows HMU surveys cover, the more accurate interpretation of the between-survey-flow situations are possible. Since each river and river reach has its unique set of hydromorphological features, it is not possible to predict actual variation of HMUs or habitat entities one-by-one, because variation trends change depending on the location. A feasible solution is the survey of the study reach at several flows which are determined by the purpose of the actual study and interpolate HMU distributions for non-surveyed flows from these. Then the actual locality of certain HMUs will be missing, but an overall distribution of HMU types is gained.

A unique flow-HMU map for several flows is prepared in the NMCM. So, for each HMU, it is desired to be able to calculate separate surface area values to use for statistical analyses. This way mesohabitat mapping, which in practise is HMU surveying, can be used easily as basis for scaling. A limited number of HMU maps for different flows form the basis of habitat analysis on the temporal scale.

2.1.1.4 Summary of the pilot version

The reaches of small rivers are mapped at several discharges and the mapping is carried out in a structured, objective manner. The entities building up the river map imitate functional habitats by means of hydromorphological units (HMUs). The surveying is carried out in a technically easy-to-analyse way that is, all mapped HMU-s are deformed quadratic shapes. First, a series of cross-sections is produced and the resulting segments may be further divided into two or three HMUs. This structure is useful for hydraulic modelling, HMU aggregation or other practical river management issues (Figure 2.5).

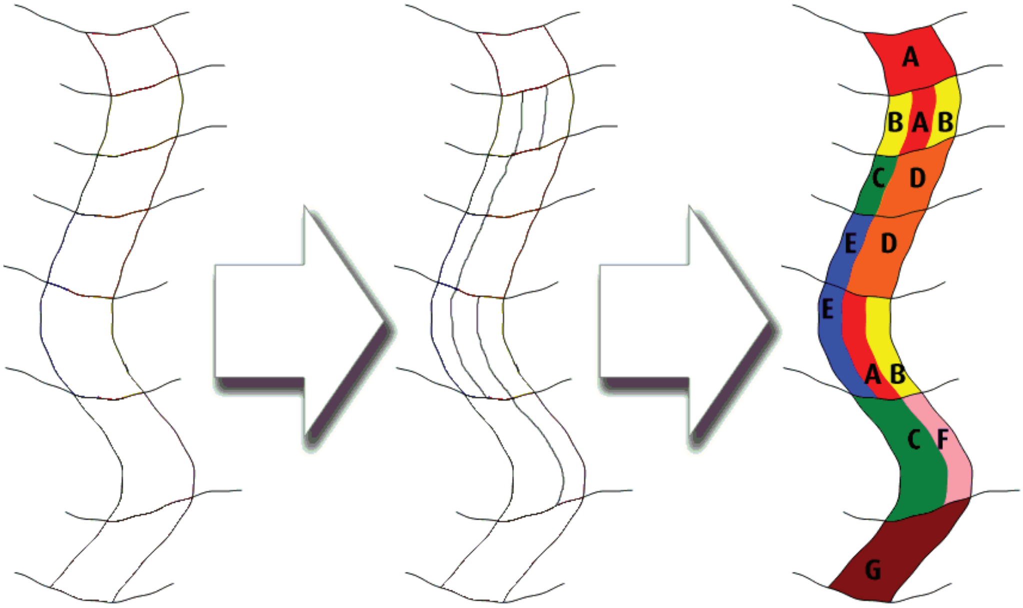


Figure 2.5: HMU survey procedure in the NMCM

HMU types are described by four major factors: surface velocity, depth, surface gradient and surface flow type. Two choices of each factor (for example fast or slow surface velocity) give sixteen possible HMU types, but in case practically impossible combinations are excluded, it results in eight types (Table 2.1). In addition to HMU types, substrate information is also recorded, which includes dominant sediment sizes grouped in three classes. Dominance in this case means one of the classes: fine, medium, large that provides the largest estimated fraction in the bed material. The criteria for classifying HMUs into either of the two classes regarding each feature is based partly on compilation of similar criteria from the literature listed above and partly on personal experience. Related literature provides some guidelines as detailed below.

Hawkins et al. (1993) present the idea of classifying HMUs by grading their features. Grades run from 1 to 7, 1 noting the highest magnitude of the features. However the authors do not detail the division method between grades. Bisson et al. (1981) do not provide an objective method for HMU classification, however refers to shallow water as being less than 20 cm deep or later as less than 10-30 cm deep. They refer to low gradient HMUs to be less than 4% steep and to swiftly flowing water in case the flow is faster than 50 cm/s. Bisson and Montgomery (1996) present a more structured description of classes. Even though these are not similar to those HMUs referred to above, it still can be noted that the range of gradients vary between 0.1% and 30%, being 4% approximately a mean value. Hardy (1995) gives the following details of division criteria. He classifies HMUs as low gradient types below 0.003 (0.3%), as shallow types below 45 cm depth, as deep types above 0.5 m-1 m (– 2 m) depth. Finally Kershner and Snider (1992) give guidelines for classification according to the gradient criteria. They utilize three classes of gradients with borders of 1-1.5% and 4% after Rosgen (1985). However in this original reference, the majority of stream types are classified as either steeper or less steep than 4%.

Table 2.1: First version of HMU classification decision tree in the NMCM

surface pattern	surface gradient	surface velocity	water depth	Code	NMCM name
smooth or rippled	steep	fast	deep	A	Run
			shallow		Non existing combinations
		slow	deep		
			shallow		
	mild	fast	deep	B	Glide
			shallow		Non existing combination
		slow	deep	C	Pool
			shallow	D	Walk
broken or standing waves	steep	fast	deep	E	Rapid
			shallow	F	Cascade
		slow	deep		Non existing combinations
			shallow		
	mild	fast	deep		
			shallow	G	Splash
		slow	deep		Non existing combination
			shallow	H	Rill

Table 2.2: Proposed classification criteria for HMU features in the NMCM

surface pattern	smooth / rippled	wave height <0.05 m
	broken / unbroken standing waves	wave height >0.05 m
surface gradient	steep	>4%
	moderate	<4%
surface velocity	fast	>0.5 m/s
	slow	<0.5 m/s
water depth	deep	>0.7 m
	shallow	<0.7 m

Regarding the feature of gradient, 4% seems to be a generally accepted border point among most authors. Flow velocity is mentioned only by one author and is therefore taken from there (0.5 m/s). Flow depth groups are generally divided in the lower range between 0.5 and 1 m, arbitrarily set to 0.7 m. No classification information regarding surface flow type is found, therefore the criterion is set to 5 cm wave height (estimated from own experience). Table 2.2 summarizes the conclusions.

It is important to note that selection of border values for the different features strongly influences the elements used in the HMU survey and thereby the possible outcomes of scaling or habitat assessment. The values are obviously subject of strong discussion, but since the method is designed for general use, it should incorporate species or location specific elements as little as possible. As shown above, border criteria dividing each feature into two groups is somewhat arbitrary in a sense that the values do not incorporate real habitat information, but they incorporate general eco-hydraulic sense. It has to be noted that the values selected are mentioned in connection with salmonid species. Different target species might require different HMU border criteria as well.

HMU proximity, longitudinal accumulation (Figure 2.3) of the separate types and basic statistical analysis of HMU areas are calculated to provide input for a fish population model. HMUs are then aggregated according to fish sample results (Figure 2.4) and the aggregated entities are analysed by meso- or microhabitat means. Results of the meso- or microhabitat analyses are extended to the studied river reach by means of the aggregated HMU map. River reaches as in Frissell et al. (1986) on macro-scale, are separated according to the needs of the actual project (e.g. fish densities) and accumulation charts of HMU areas (Figure 2.3).

One of the ultimate goals of the Mesohabitat project (Appendix A.2.2) is to present a practically applicable interaction between a population model for production of juveniles and the means of physical habitat modelling, the NMCM. In order to achieve this goal, NORSALMOD, the Norwegian population model for Atlantic salmon was used. Appendix A.3.1 provides a short description of the population model illuminating its use and data needs.

2.1.2 Pilot study of the NMCM – Lower Nidelva

This pilot study started during autumn 2000 and was the first practical test after the theoretical preparation of the method summarized in section 2.1.1.4. The purposes were to verify if (1) the eight HMU types cover all mesohabitats on this reach, (2) separate surveyors end up with similar HMU maps and (3) estimation of HMU features are feasible in practise. The HMU survey covered an approximately 4 km long reach of Nidelva starting from the outlet of the two lowest hydropower plants, Nedre Leirfoss and Bratsberg and reaching down to the estuary in Trondheim harbour. See section A.1.1 for an overview of Nea-Nidelva catchment and Figure A.1.4 for a scheme of the hydropower system. This reach is regulated and upstream inflow arrives through the hydropower system, either through the turbines or at the spillway. There are minor creeks adding small amount of water to the study reach further downstream, but these are neglected in our survey. Two flows (plant operation schemes) were selected which covered the usual daily operation ranges between 30 m^3/s and 133 m^3/s. The two HMU maps were then compared regarding how total surveyed area was divided among the HMU types, how their total and mean areas relate to each other and how areas within each HMU type vary.

The study discovered discrepancies between the theoretical model and its practical application. The originally planned eight HMU types had to be extended to ten, splitting types B (glide) and G (splash) into two. The nomenclature was accordingly altered in such a way, that new HMU types were B1, B2 and G1, G2 instead of the original B and G types. The refined system was used in the second run of the mapping at low flow, close to 30 m^3/s (as reflected on Figure 2.6).

In addition, some minor differences were encountered between results of the two surveying teams, which demonstrated the need of common training and discussion of survey results after they are sketched on the map. These were mainly slightly different placement of dividing cross sections and longitudinal divisions, which remained under error limits that did not exceed the expectations. Different classification of actually similar HMUs occurred very few times. This was caused by inattention for some of the classification features and was easily clarified later. These problems were expected to disappear in the future, as both groups were to gain more experience and additional reaches were planned to be surveyed by more than one team.

A common problem in both teams regarding slope-estimations arose as well. None of the groups was able to estimate 4% of slope, however both were confident of being able to distinguish between steep and moderate HMU types. On the other hand, both teams felt that the 4% limit is probably too steep to classify such estuary-close streams as lower Nidelva and recommended a lower value. Additional layers of habitat related data, like substrate, cover, fish densities, etc were not collected during this study. Figure 2.6 shows HMU maps after the teams combined their results at low (approximately 30 m^3/s) and high (approximately 120 m^3/s) flows.

Comparing HMU maps of the two flows, a higher fragmentation of the reach at low flow can be noted. Certain HMU boundaries "remained stable", that is, when a borderline between HMUs on the two maps showing different flows appear at the same place. The borders observed at high flow (less fragmented domain) seem to remain when discharge is reduced, but as additional ones appear, the HMU map at low flow becomes more fragmented. It must be noted, that more HMU types were utilized for the low flow survey, which fact alone increases fragmentation. On the other hand, certain HMU types, which did not appear at high flow, were registered at low flow (D, F and G1-G2). Please note that the differences between the two maps regarding wetted widths of the rivers are only based on estimations, not measured values. For this reason the absolute areas on the distribution charts are not fully accurate either.

Figure 2.7 shows HMU distributions at the two flows. The distribution shows how summed area values of various HMUs compose the surveyed reach of river. The percent values are based on areas of HMUs measured from the maps utilizing GIS functions. It has to be mentioned that no measurement was carried out to verify actual river sizes (especially widths) on the map. This fact leads to uncertainties when comparing total surveyed areas at different flows and thereby such a comparison table is not presented here. The reduced width at low flow that is shown on the map (Figure 2.6) is an estimation in relation to the high flow map.

HMU type C clearly dominates both high and low flow distributions with 55% and 54% respectively and that its proportion remains approximately the same in both cases. HMU types B (later B1 and B2) and E also cover approximately similar proportions in both cases. Type H is reduced in size at low flow from 5% to 2% and type A is mainly being divided among all new HMU types (F, G1 and G2) at low flow. Deeper HMU types dominate at high flow (A, B, C and E), while shallow (B2, D) and riffling classes (F, G2) appear at low flow.

Figure 2.8 shows average, maximum and minimum sizes of HMU types at both flows expressed in square meters. In cases of both flows, type C has the largest average area but the largest variation, especially at low flow. The same effect is noted at other large types, such as E at high flow and F at low flow. It is also clear that at high flow all HMU types has larger average areas than at low flow. Some types are under-represented (see the N numbers on the figure) and therefore should be considered with caution (e.g. type H at high flow and B2 or G1 at low flow). More thorough statistical analyses seems little meaningful based on such small amount of data and is therefore not carried out in this case.

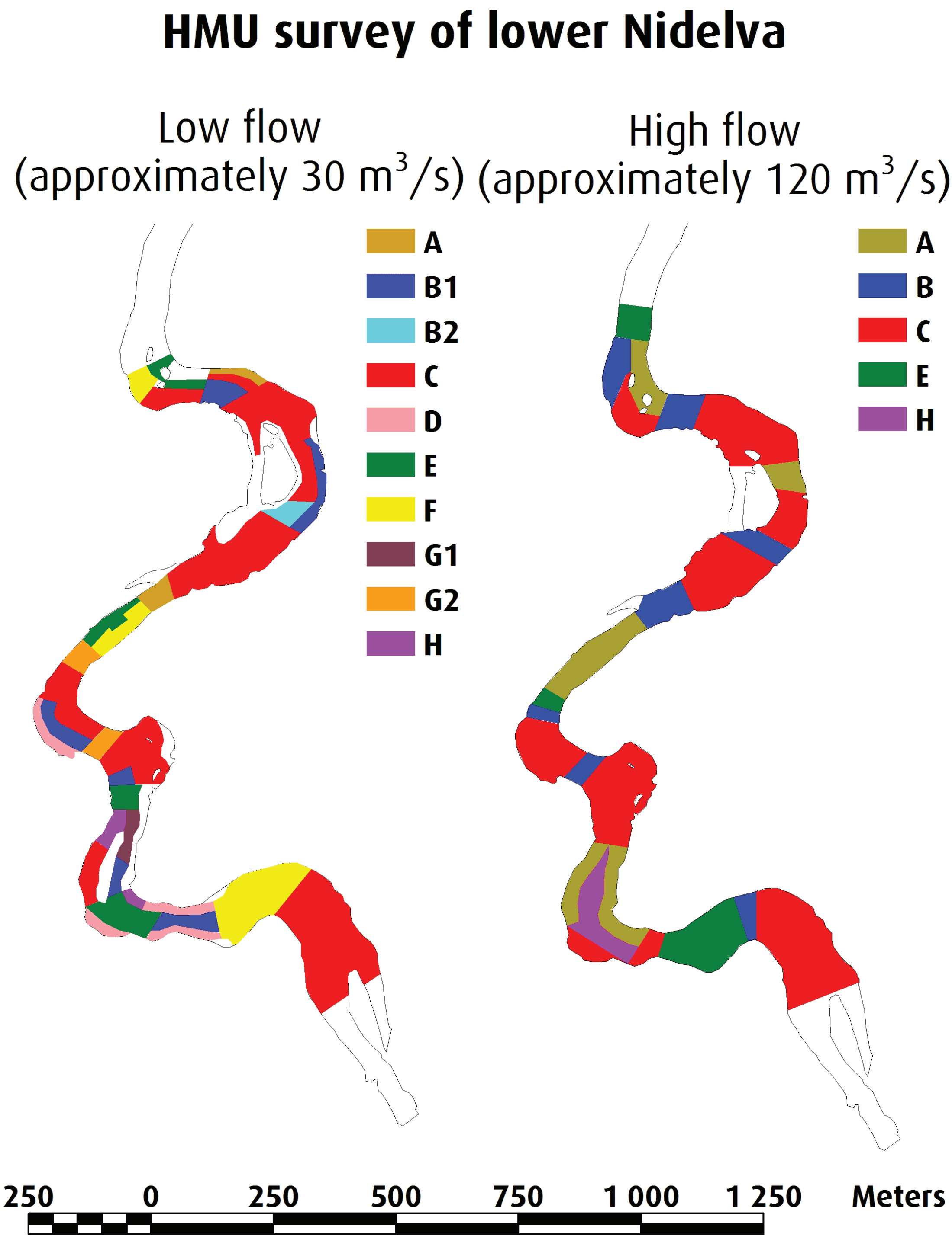


Figure 2.6: First application of the NMCM on Nidelva at low (approximately 30 m³/s) and high (approximately 120 m³/s) flows

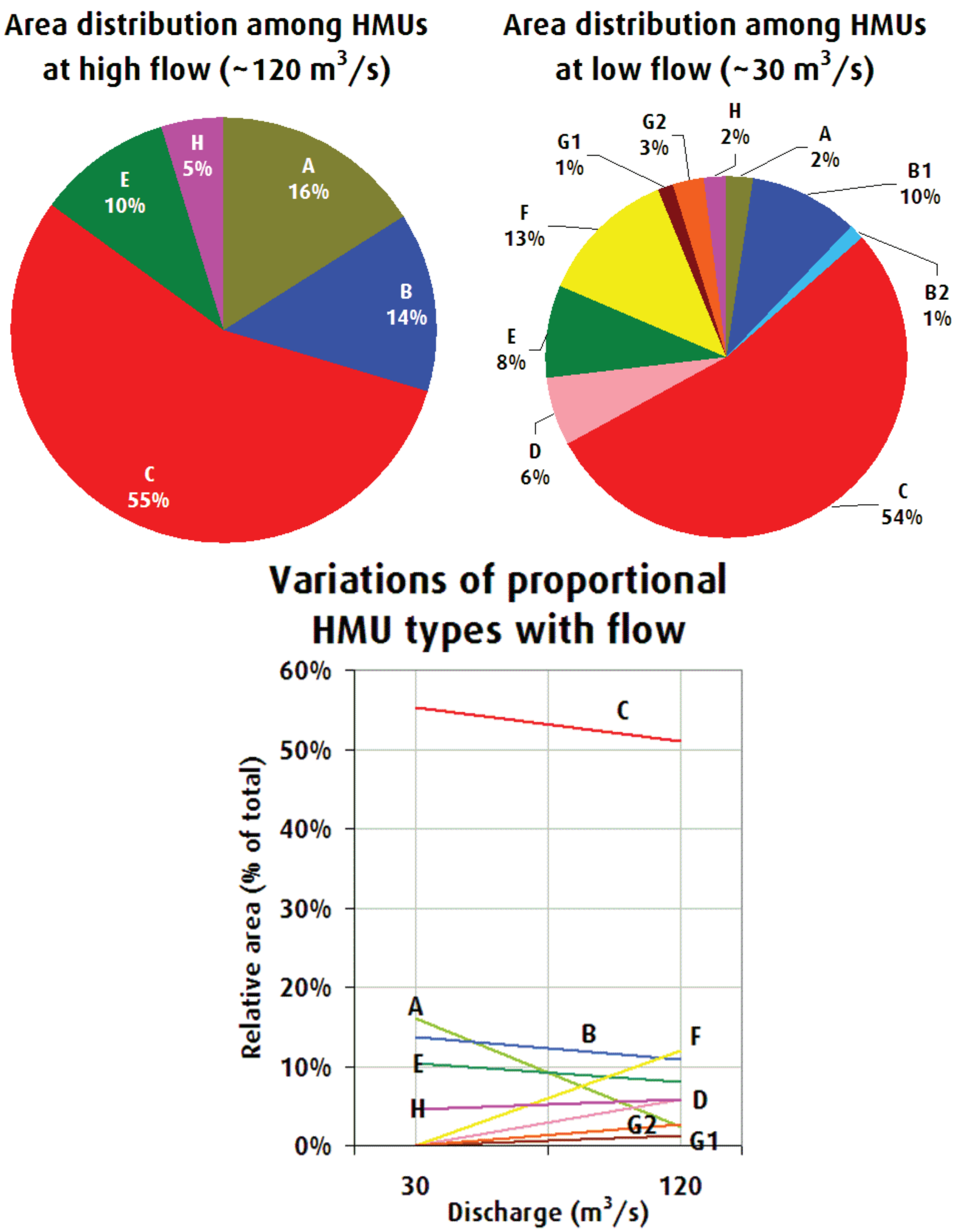


Figure 2.7: HMU distribution charts on Nidelva at low (~30 m³/s, top left) and high (~120 m³/s, top right) flows and HMU interpolation graphs for non-surveyed flows (bottom). Values show percentages of total surveyed area

Summarizing the results of the first case, it was decided to

1. Increase the number of HMU types from eight to ten, splitting types B and G into both deep and shallow types and noting these as B1, B2 and G1, G2;
2. Conduct a joint field training for those carrying out the HMU survey in order to ensure minimal differences in results;
3. Try to find means or simple tools to be used for slope estimations or measurements, as this feature is hard to estimate;

It has been shown that:

4. Variation in wetted area is not noted in the HMU maps and is a new feature to be included in future variants if necessary;
5. In order to exploit more features of the GIS, much longer reaches need to be mapped and additional functions must be included in the analyses.

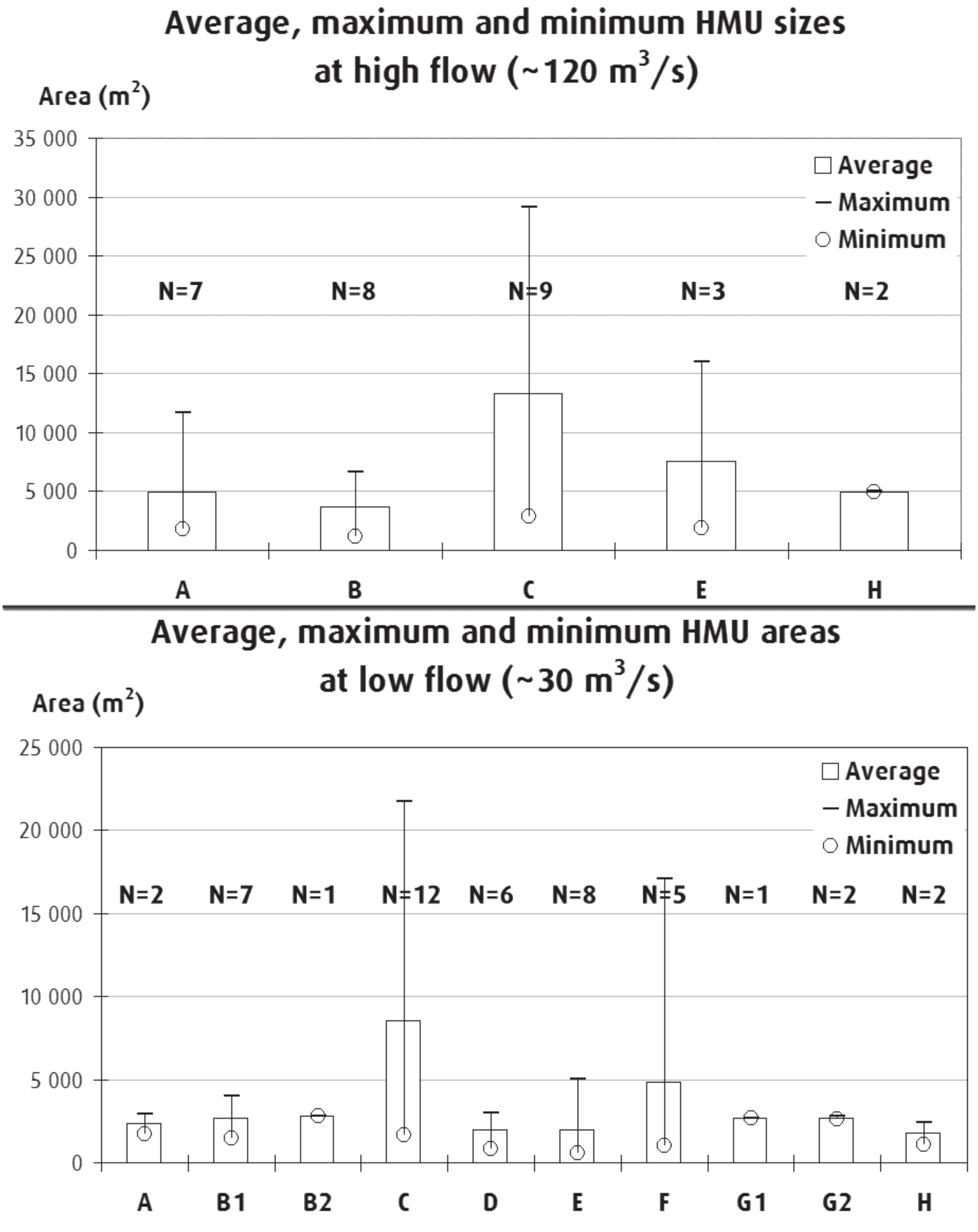


Figure 2.8: Average, minimum and maximum HMU sizes at low (approximately 30 m³/s) and high (approximately 120 m³/s) flows.

2.1.3 Refining the NMCM – Orkla and Ingdalselva

In the previous section, the pilot version of the NMCM was tested for the first time in practise. The test has highlighted several problems and showed where the method needed to be refined. These refinements included the extension of the number of HMU prototypes from eight to ten. Table 2.3 shows the new classification scheme.

Table 2.3: Second version of HMU classification decision tree in the NMCM

surface pattern	surface gradient	surface velocity	water depth	Code	NMCM name
smooth / rippled	steep	fast	deep	A	Run
			shallow		Non existing combinations
		slow	deep		
			shallow		
	mild	fast	deep	B1	Deep glide
			shallow	B2	Shallow glide
		slow	deep	C	Pool
			shallow	D	Walk
broken / unbroken standing waves	steep	fast	deep	E	Rapid
			shallow	F	Cascade
		slow	deep		Non existing combinations
			shallow		
	mild	fast	deep	G1	Deep splash
			shallow	G2	Shallow splash
		slow	deep		
			shallow	H	Rill

2.1.3.1 Length of study reaches

Another issue that arose in the pilot study on Nidelva was the short length of the study reach in Nidelva, which did not allow using the spatial analytical capabilities of the GIS created for this purpose. Therefore two study reaches in rivers Orkla and Ingdalselva were investigated, that are longer than the previously shown reach in River Nidelva. The two rivers were selected to test the sensitivity of the NMCM to river "size" and their locations. General descriptions of the rivers are presented in Appendix A.1.2 (Orkla) and A.1.3 (Ingdalselva).

Ingdalselva was surveyed at low medium (~0.9 m^3/s = 33% of MAF) and medium (~2.4 m^3/s = 92% of MAF) flows on 8 May and 13 June 2002. A study reach with a length of approximately 12 km in this river was selected. Figure 2.9 and Figure 2.10 show the complete and Figure 2.12 extracts of the HMU maps at both flows on Ingdalselva. Note the appearance of the side arm at medium flow at about 1 km north from the middle of the study reach compared to the low medium-flow situation. The river flows from right (upstream) to left (downstream) direction.
A ~20 km long reach of River Orkla was surveyed during low medium (~24 m^3/s = 36% of MAF) flow and a ~46 km long reach at medium (~65 m^3/s = 97% of MAF) flow on 27-28 May 2002 and 25 June 2003. Figure 2.11 shows the two complete and Figure 2.13 extracts of the HMU maps from Orkla. Note the difference between the lengths of the reaches surveyed at the two flows. The left picture shows not only a map of a shorter reach but a different flow as well on Figure 2.11.

2.1.3.2 Estimation of surface gradient

The discussions of the two teams after surveying the Nidelva pilot study has shown the higher uncertainty related to estimation of longitudinal surface gradient than to the other classification parameters. Both teams found it hard to estimate absolute values of gradients as defined in the classification scheme, however they affirmed their ability to classify HMUs into steep and mild categories. During the HMU surveys of Orkla and Ingdalselva, we therefore attempted to measure the actual gradients in a way that would support the quick and effective philosophy behind NMCM. For this purpose a clinometer, a simple instrument incorporating a gauging vertical and a rotating scale bar was used. The readings give 1-degree accuracy.
Without noting measurement values, it was found that gradients varied a lot and that it was not possible to identify a border value for slope between steep and mild gradient HMUs. However, the lengths (longitudinally along the rivers) of HMUs often made it difficult to measure the actual slope, because the shorter the HMU was, the more uncertain and sensitive the measurement became. Even though the measurement technique was not satisfactory, the use of higher accuracy instrumentation was not considered, because the measurements suggested a necessary change in the classification criteria.
It was found that the surface gradient classification criterion was not independent of the other criteria (pattern, depth or velocity). In fact there has always appeared another HMU border in addition to the slope as well. This suggested that surface slope on its own should not be used for dividing the water body into HMUs, instead, after finding borders looking at the other characteristics, the two following HMU may be distinguished according to the difference in their surface slopes additionally. Thereby in the new criteria, two classes for surface gradient were still kept, but their actual (absolute) slope values were neglected. Instead, it was decided to compare slopes of consecutive HMUs classified already by other parameters and separate them to steep or mild classes in relation with each

other. Thereby the parameter of surface gradient is dependent on the three other parameters in a way that its change in the river never occurs alone, but always in combination with some of the others.

2.1.3.3 Surveying substrate

During the preparation of the classification system, it was decided to note substrate information along with the HMU types as well (see section 2.1.1.4). The importance of substrate information is shown by the fact that some classification systems such as Bisson and Montgomery (1996) are primarily based on sediment and substrate data. Beyond the HMU classification purpose the importance from the habitat point of view is also noted by e.g. Bovee (1982, 1986).
Substrate was preliminarily classified into three subgroups, but this layer of information was not collected during the pilot study of river Nidelva (see section 2.1.2). Further on, during the first field trip, this method was found hard to apply, because it was difficult to group substrate into the arbitrarily created three classes. Substrate features recorded were confusing, thus providing little information regarding substrate variation and composition. This method also slowed down the surveying process. Therefore substrate data was decided not to be collected in this manner and it became clear that a more informative and convenient method should be found. Three options were considered for this purpose. The first was further dividing the HMU classification scheme with substrate data included and thereby increasing the number of HMU prototypes, as well as collecting substrate data for all surveyed HMU entities (method 1). The second option was noting substrate sizes separately, regardless of the actual HMU map, but covering the whole study reach (method 2). The third method was to collect samples of substrate after the HMU survey from a limited number of HMUs but including all HMU prototypes. This data could then be generalized assuming similar distribution of substrate within similar HMU types (method 3). All three methods were tested with varying success as shown below.

Substrate mapping method 1 – increased number of classes

In order to avoid the increase of the number of HMU prototypes to e.g. 8 HMU × 10 substrate = 80 theoretical classes, it was decided to record only special classes where substrate disturbed any of the previously defined classification features (such as depth, surface flow pattern, surface velocity or surface slope). "Disturbance" here meant in-HMU class alteration, which causes confusion when classifying the actual HMU. For example a large number of slow flow features are observed around boulders in an otherwise fast flowing (and thereby classified as "fast") HMU type. The HMU maps of both rivers and flows (Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.12 and Figure 2.13) show an additional HMU type marked G2WR. This category was added to the scheme during the survey of Ingdalselva showing a special HMU type typical for this river. In HMU type G2WR the original G2 (shallow splash) type is found in combination with boulders or large pebbles ("WR" in the name stands for "With Rocks"). However, besides G2WR, no other new HMU type in either rivers was found and thus it can be concluded that this method provides limited usability regarding overall substrate composition.

Substrate mapping method 2 – individual substrate maps

It was also planned to create a separate substrate map of the river regardless of the HMU maps. It was assumed that substrate features remain mostly stable in the flow ranges surveyed and so such a substrate map can be combined with any HMU maps covering different flows by means of GIS functions. Therefore, during the surveys, estimated sizes of dominant substrate were recorded, and it was noticed that its spatial variation followed HMU variations. This way, there remained no reason to separate substrate maps from HMU maps (creating two separately and combine them later) and so it was decided to record dominant substrate sizes for all surveyed HMUs. This method was found relatively fast and effective, providing relevant and more-or-less accurate information on substrate distribution on the study reach.

Substrate mapping using method 3 – sampling and generalization

The third method assumes similarity within each HMU type and variations between rivers regarding substrate. Selected HMUs were sampled in both rivers and substrate was classified into 15 classes according to Table 2.4. Regardless of the actual extent or dominance, each class that was represented (found), was also recorded.

Table 2.5 and Table 2.6 show the results. Each column represent one HMU (a region in the river with explicit extent), and each row a substrate class. Their marked meshes show that a particular substrate size (class) was represented in that particular HMU. In Table 2.5 the columns marked with "B1/C" and "C/D" note that these particular sampling regions changed HMU types with flow.

Table 2.4: Substrate classification scheme

Dominant substrate	Diameter (mm)	Class code
Fine organic material		1
Coarse organic material		2
Clay, silt	0.004 - 0.006	3
Sand	0.006 - 2	4
Coarse sand	2 - 8	5
Fine gravel	8 - 16	6
Gravel	16 - 32	7
Coarse gravel	32 - 64	8
Small pebble	64 - 128	9
Pebble	128 - 256	10
Cobble	256 - 384	11
Small boulder	384 - 512	12
Large boulder	> 512	13
Rough surface rock		14
Smooth surface rock		15

The tables show that not all HMU types were sampled. One can also note that distribution of substrate classes among the various HMU types do not follow a clear, easy to identify rule. The number of samples obviously does not allow performing even simple statistical analyses and thereby drawing sophisticated conclusions. The increase of the number of our samples was not considered, firstly because the necessary amount of samples was not possible to collect with the available means (time and labour). Therefore, the results could not be improved. Secondly the rapidity of the survey method would then be lost. Instead it was assumed that substrate composition followed other factors as well, not only HMU types, but e.g. macro-topographical and geological features of the river.

Concluding substrate sampling, it is shown that distribution of dominant substrate follows HMU distribution to some extent, but no direct link can be found between HMU types and substrate sizes (at least with our limited number of samples). Most effective and still representative method for substrate survey seems the recording of one or two dominant sizes or classes to each HMU on the whole study reach and collect more detailed information such as substrate distribution, embeddedness, roughness etc. in case it was necessary.

Table 2.5: Substrate samples from Ingdalselva

	B1	B1	B1/C	B2	B2	B2	C/D	D	D	D	D	G2	G2	G2
1														
2							X						X	
3						X	X							
4							X							
5														
6			X										X	
7				X		X			X					X
8			X	X		X	X	X	X	X	X	X		X
9			X	X	X	X	X	X	X	X	X	X	X	X
10	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	X	X		X	X	X		X	X	X	X	X	X	X
12	X	X		X		X			X		X	X		
13	X	X		X	X	X	X						X	X
14							X							
15	X	X												

Table 2.6: Substrate samples from Orkla

	B2	B2	B2	F	F	F	G2
1	X						
2							
3							
4		X	X				
5							
6			X				
7							X
8			X				X
9	X		X	X	X	X	X
10	X	X	X	X	X	X	X
11	X			X	X		X
12							X
13							
14							
15							

Figure 2.9: HMU maps at 0.8 (33% of MAF) and 2.4 m^3/s (92% of MAF) of Ingdalselva, upstream part

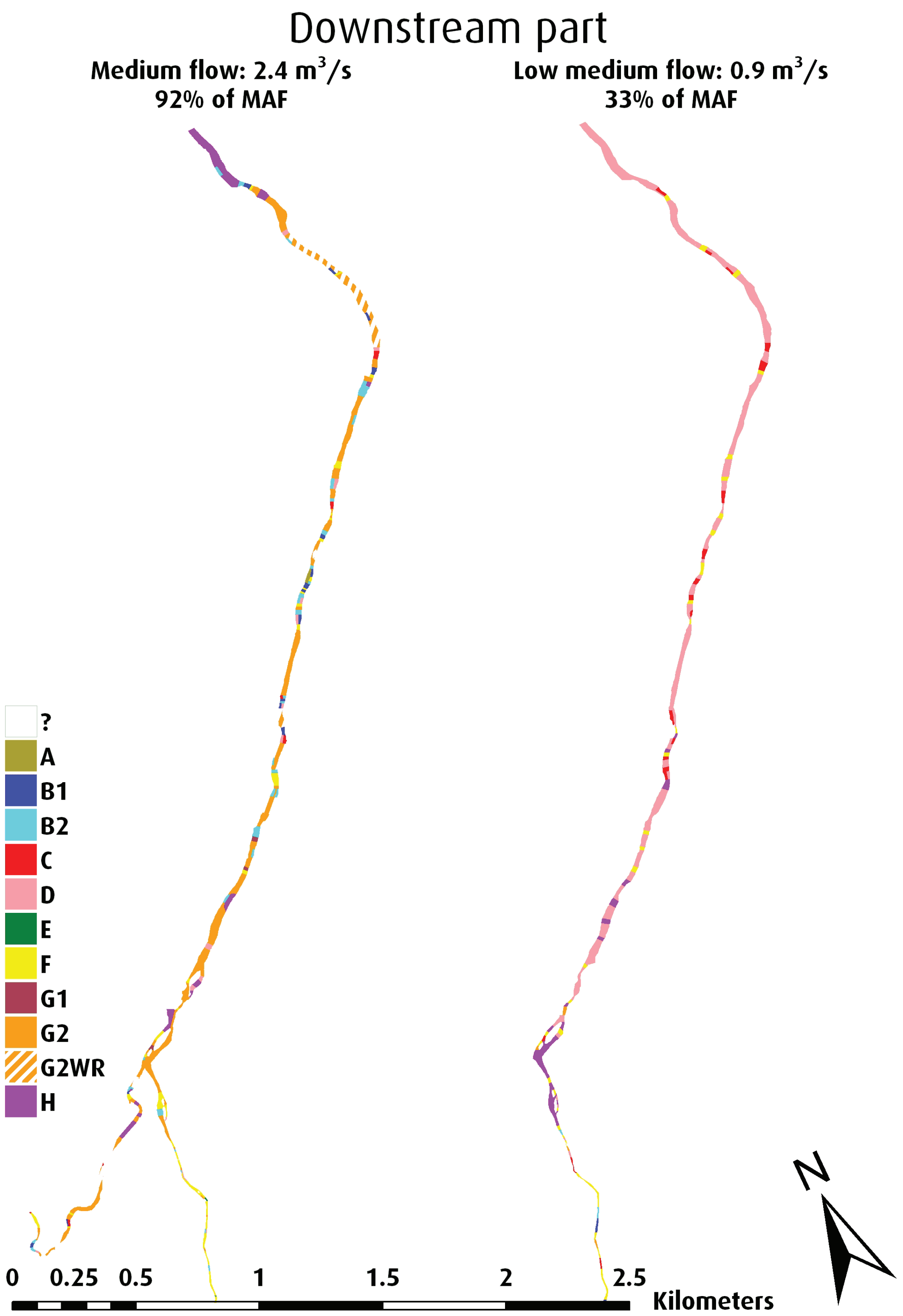


Figure 2.10: HMU maps at 0.8 (33% of MAF) and 2.4 m³/s (92% of MAF) of Ingdalselva, downstream part

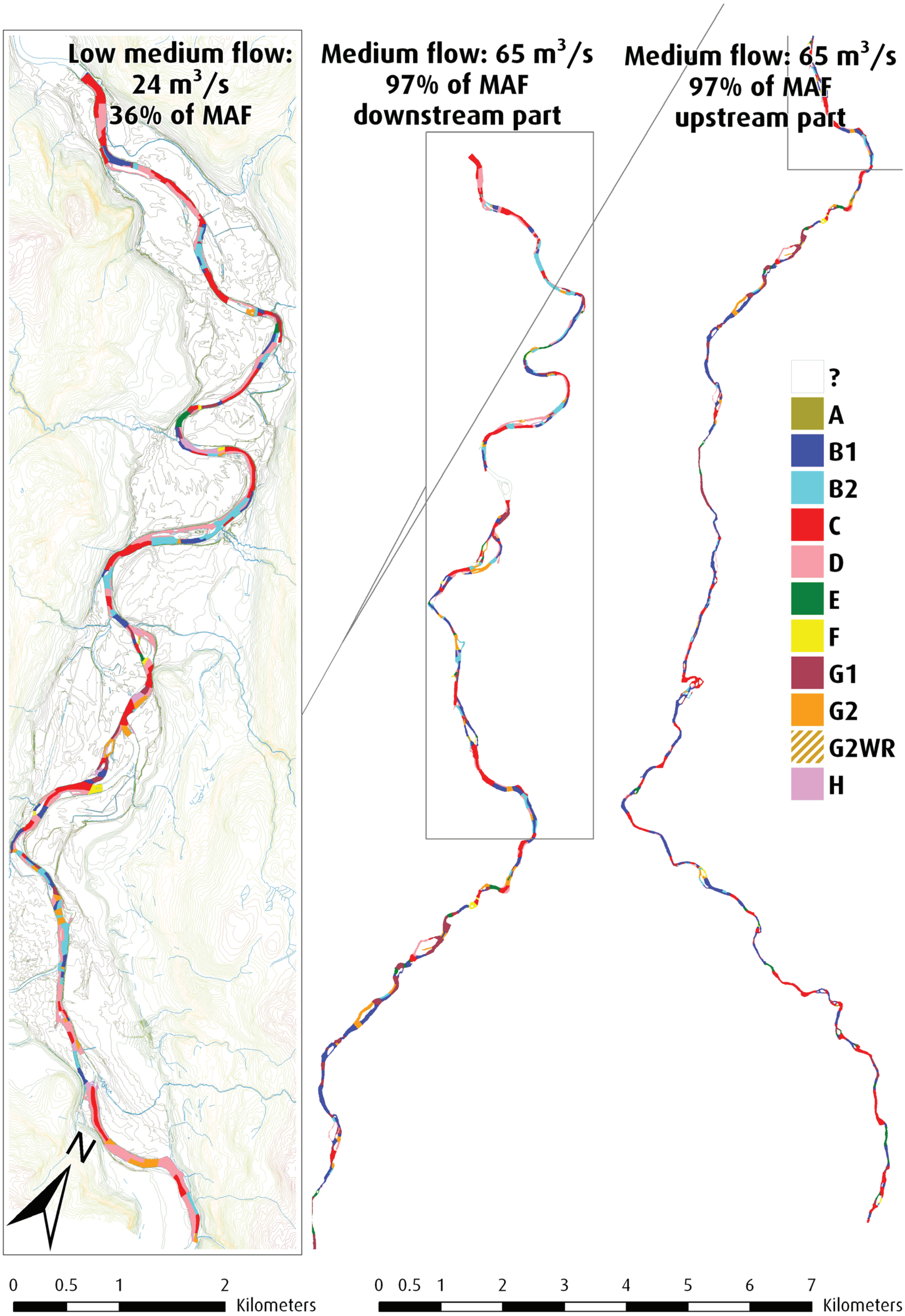


Figure 2.11: HMU maps of Orkla at medium low (24 m³/s ~36% MAF) and medium (65 m³/s ~97% of MAF) flows

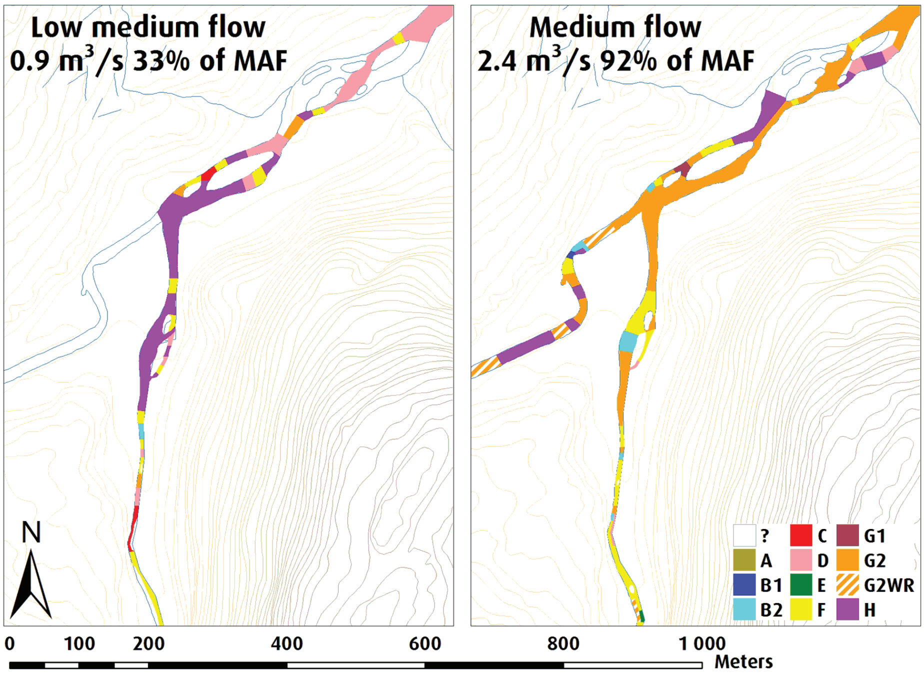


Figure 2.12: Extract of HMU survey maps from Ingdalselva at low medium (0.9 m^3/s) and medium (2.4 m^3/s) flows

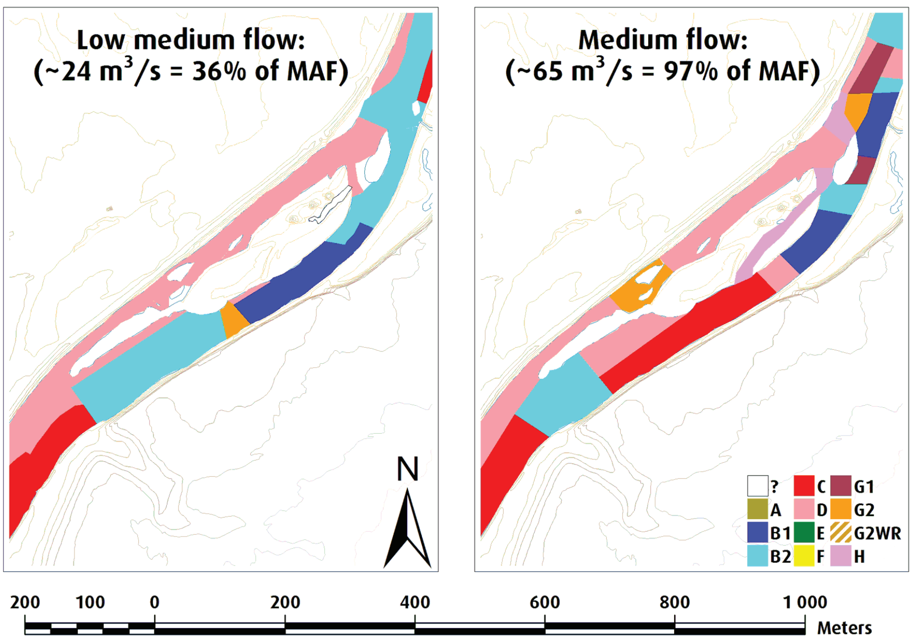


Figure 2.13: Extract of HMU survey maps of Orkla at medium low (24 m^3/s ~36% MAF) and medium (65 m^3/s ~97% of MAF) flows

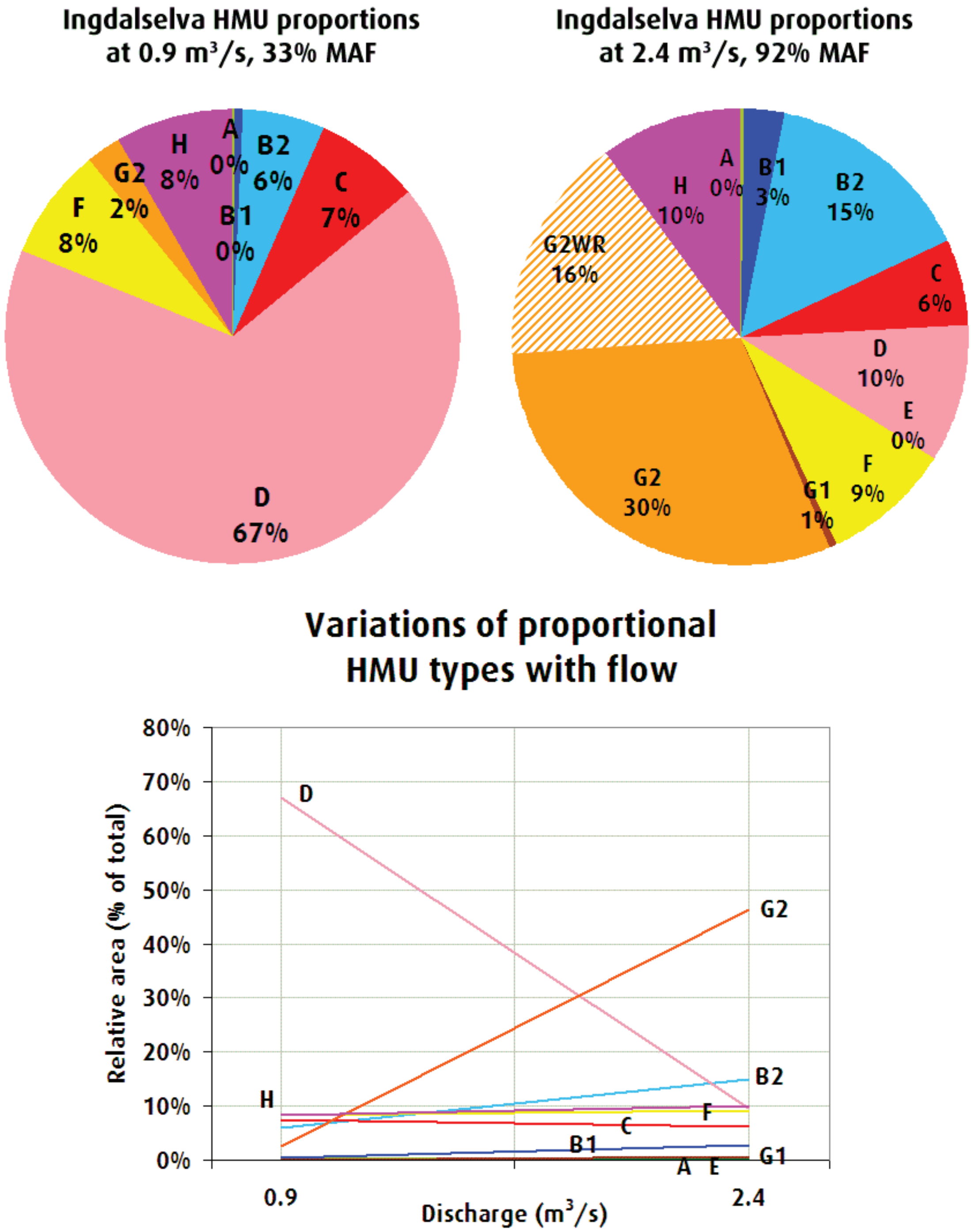


Figure 2.14: HMU distribution charts on Ingdalselva at low medium (0.9 m³/s, top left) and medium (2.4 m³/s, top right) flows, HMU area interpolation graphs for non-surveyed flows (bottom).

2.1.3.4 Spatial variations among HMUs

HMU type distribution separating types G2 from G2WR is shown on Figure 2.14 for Ingdalselva and on Figure 2.15 for Orkla. The percent values show the proportions that each HMU type covers on the surveyed study reach, calculated from horizontally projected areas. By means of these charts, the dominating or the opposite, the completely missing HMU types can be easily identifed at each reach. Just by comparison of the information from the same rivers at different flows, it is possible to identify shifts in domination, appearance or disappearance of the different HMU types.

In cases of Orkla and Ingdalselva, we estimated the alteration in wetted areas during the HMU surveys. We measured river widths by means of measuring tape or laser distance meter at several locations and these measurements were incorporated during digitising of the maps. This way wetted areas on HMU maps reflect reality, which used to be a problem in the Nidelva pilot study case in section 2.1.2.

Note the difference in domination between the two charts of Figure 2.14. At low medium flow (left picture), there is a clear dominance of HMU type D (shallow, smooth, slow, moderate) on the study reach, while most other types seem to cover relatively equal proportions of the remaining 1/3rd of the total surveyed area. This distribution dramatically changes with the increase of flow close to mean annual level. Here, HMU type G2 (shallow, broken, fast, moderate) dominates the reach, suggesting that a large portion of low-flow D-s turn into G2-s at higher flows. It was noticed that HMU type A (deep, smooth, fast, steep) is completely missing at both flows on this river, suggesting that some HMU types vanish at certain river types or sizes.

Further, comparing Ingdalselva with Orkla the same difference was found between dominating HMU types. Orkla has a more balanced HMU distribution at both flows than Ingdalselva, while at low-medium flow HMU type D dominates at Orkla as well (closely followed by type C). At medium flow the dominating HMU types are B1 (deep, smooth, fast, moderate) and C (deep, smooth, slow, moderate). Note that while in case of Ingdalselva shallow-broken classes dominate medium flow maps (E, F, G2, H), at Orkla mostly deep-smooth classes appear at medium flow (B1, C).

Figure 2.16 and Figure 2.17 show the size variation within each HMU type for both flows on Ingdalselva and Orkla respectively. The range (maximum and minimum), median and mean of areas of HMU type are shown. When HMU types were not found in the actual group, they are presented with zero values on the charts and only shown for convenience when comparing the different figures. The number of samples in the different groups varies. It is important to note that the wide ranges in almost all cases make it difficult to compare the graphs with each other. Table 2.7 shows mean, standard deviation, minimum, maximum of HMU areas and number of samples grouped by HMU types at the two rivers in order to have a better overview of the figures. A number of

HMUs were impossible to identify after the survey was carried out and these are marked with "?". The table and the figures highlight the large variability among and within areas of HMU types in all four cases. Note the large variation among number of HMUs in each group ("N" in the table): some types were not even present once (for example E and G1 on Ingdalselva at low-medium flow), others are surveyed in large numbers (for example D in the same case). It can be seen, that large average areas are coupled with large standard deviation ("St. Dev" in the table, see type C at Orkla medium and low-medium flows or D at Ingdalselva low-medium flow). Comparing average areas with each other except the largest ones, it is shown that at Ingdalselva, these are approximately similar (see for example mean areas at all HMU types except D at Ingdalselva low-medium flow), whereas at Orkla they vary with larger extent (see for example mean areas at all HMU types except C at Orkla medium flow).
Concluding the area-analysis of the individual HMUs, no relation between HMU type and HMU size, size distribution or size range was found. However, it seems that larger average sizes come with larger variation as well. A HMU size-river size relation is found: at Orkla (which is a larger river than Ingdalselva) all mean HMU sizes are larger too. In addition, some classes are completely missing from Ingdalselva, while all types were surveyed at Orkla, with varying frequency though. It is clear, that certain HMU types are consistently under-represented in all cases (type A), but on the other hand, the survey covered only two rivers and four (or rather two: medium and low medium) flows, which cannot be understood as basis for generalization in this matter.

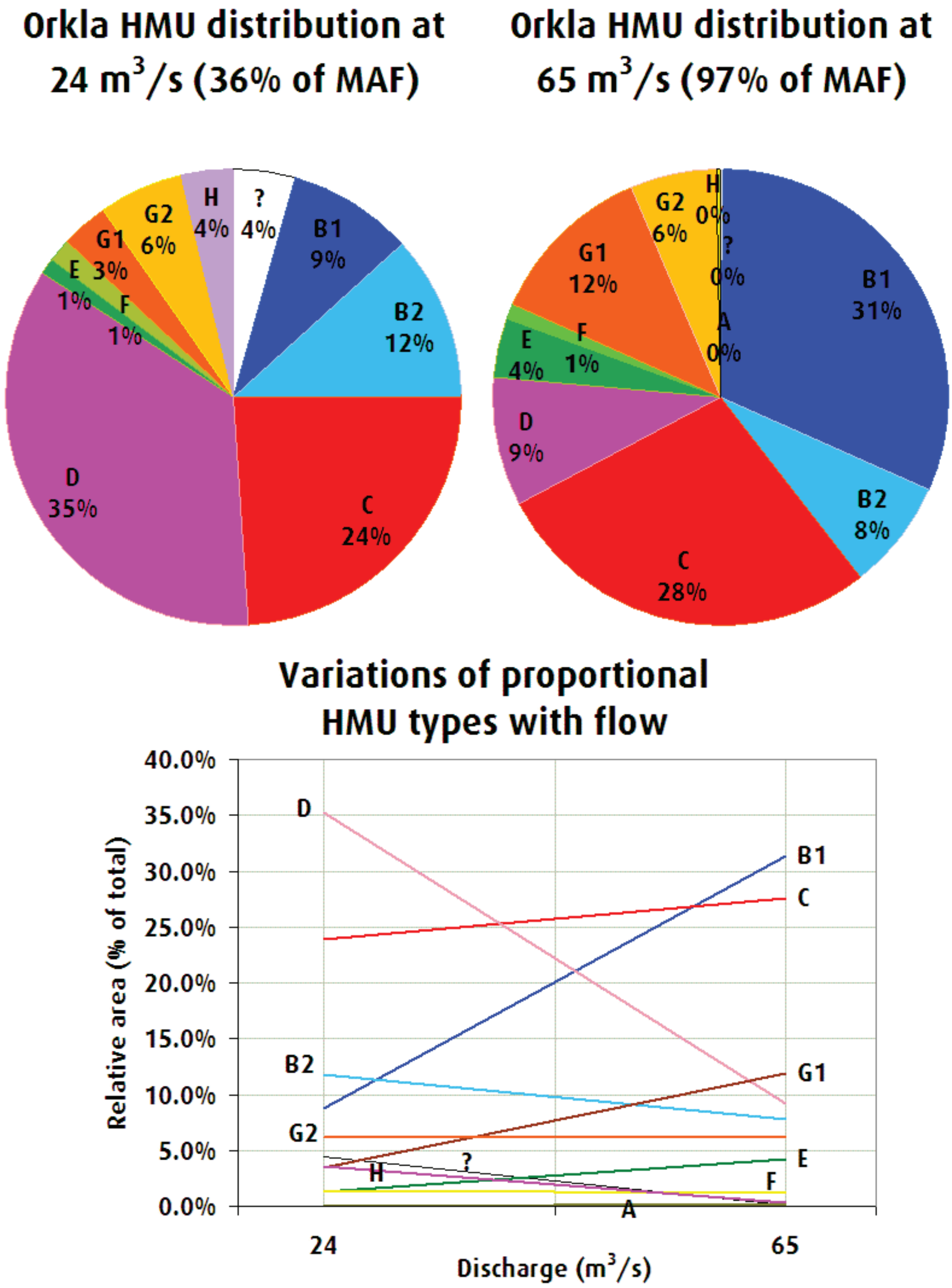


Figure 2.15: HMU distribution charts on Orkla at medium low (24 m³/s ~36% MAF, top left) and medium (65 m³/s ~97% of MAF, top right) flows, HMU area interpolation graphs for non-surveyed flows (bottom).

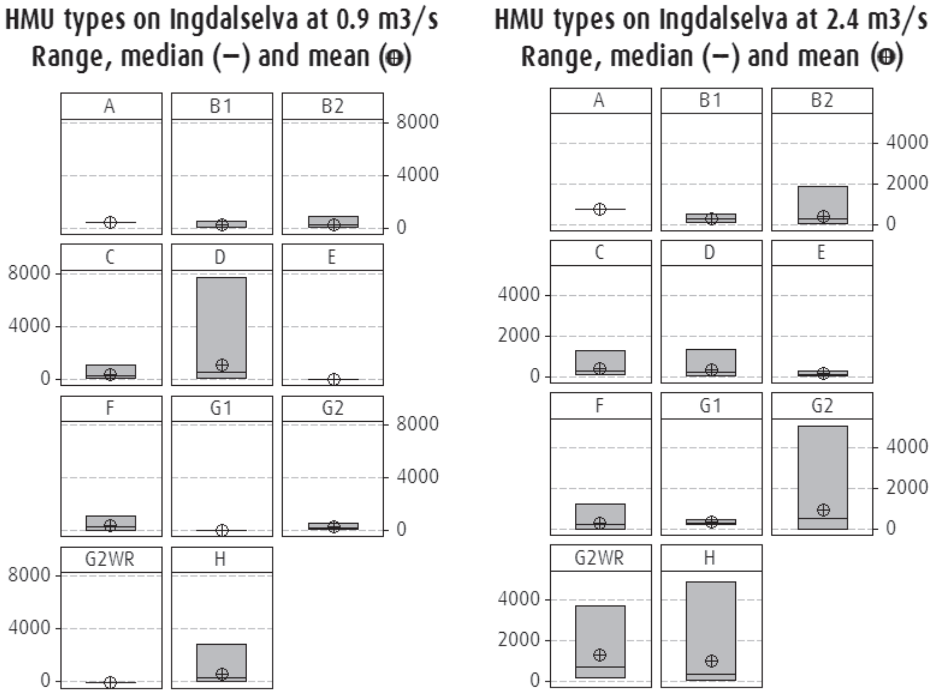


Figure 2.16: HMU area averages, ranges and medians on Ingdalselva at low medium (0.9 m^3/s) and medium (2.4 m^3/s) flows. All units are in m^2

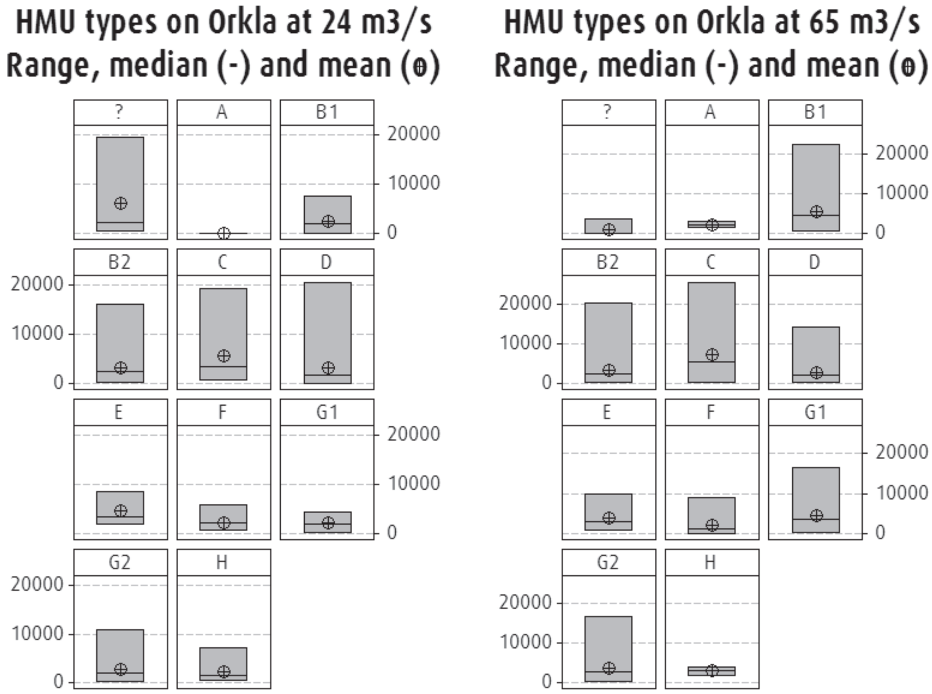


Figure 2.17: HMU area averages, ranges and medians on Orkla at medium low (24 m^3/s ~36% MAF) and medium (65 m^3/s ~97% of MAF) flows. All units are in m^2

Table 2.7: Statistical description of surveyed HMU areas at Orkla and Ingdalselva at both flows. All units are in m²

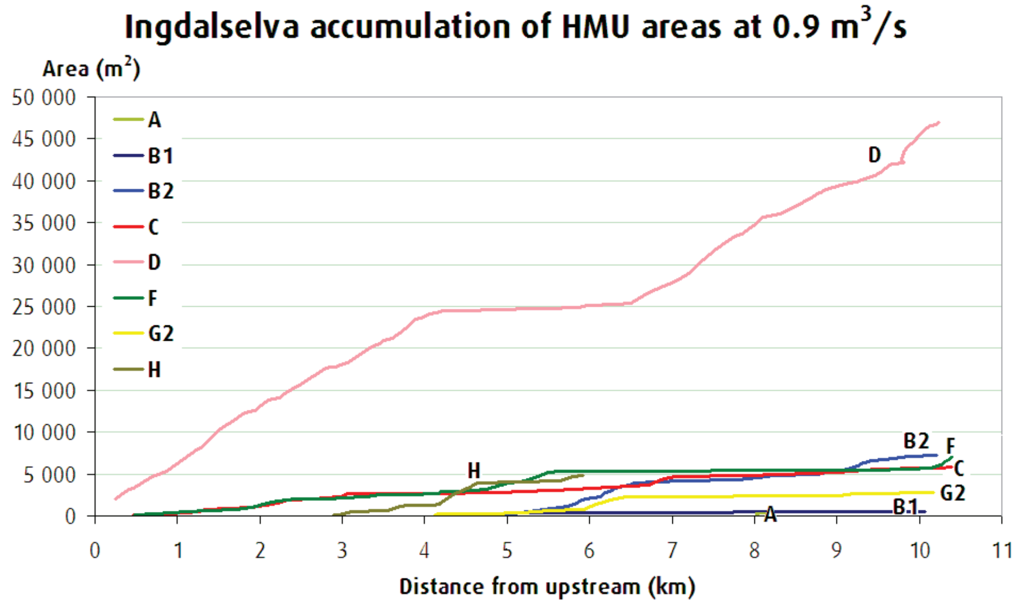
Orkla	Mean 24 m^3/s	St. Dev 24 m^3/s	Min 24 m^3/s	Max 24 m^3/s	N 24 m^3/s	Mean 65 m^3/s	St. Dev 65 m^3/s	Min 65 m^3/s	Max 65 m^3/s	N 65 m^3/s
?	6221	7484	571	19619	8	901	1531	30	3535	5
A	-	-	-	-	0	2166	746	1475	2957	3
B1	2389	1768	60	7667	41	5543	4461	478	22405	160
B2	3268	2854	303	16332	40	3372	3605	269	20205	65
C	5648	5574	715	19493	47	7290	6446	243	25612	107
D	3246	3383	50	20710	121	2675	2412	217	14267	97
E	4652	3408	1980	8490	3	3944	2824	985	10145	30
F	2271	1739	637	5921	7	1980	2434	124	9165	17
G1	2273	1371	207	4455	17	4583	3906	175	16662	73
G2	2751	2421	171	10883	25	3768	3384	327	16771	46
H	2305	2102	430	7106	17	2932	948	1983	3879	3

Ingdalselva	Mean 0.9 m^3/s	St. Dev 0.9 m^3/s	Min 0.9 m^3/s	Max 0.9 m^3/s	N 0.9 m^3/s	Mean 2.4 m^3/s	St. Dev 2.4 m^3/s	Min 2.4 m^3/s	Max 2.4 m^3/s	N 2.4 m^3/s
A	458	-	458	458	1	710	-	710	710	1
B1	224	235	73	495	3	261	135	54	509	20
B2	277	165	62	930	34	369	382	35	1831	75
C	373	242	42	1073	32	336	299	37	1227	34
D	1063	1393	54	7812	101	297	297	32	1317	60
E	-	-	-	-	0	125	130	23	272	3
F	314	243	50	1060	42	308	240	17	1273	55
G1	-	-	-	-	0	351	117	268	485	3
G2	235	140	73	585	17	932	1146	37	5116	60
G2WR	-	-	-	-	0	1314	1119	189	3718	23
H	629	698	49	2897	21	1034	1397	95	4941	18

2.1.3.5 Longitudinal HMU accumulation

The study reaches of Ingdalselva and Orkla are long enough to study longitudinal accumulation of each HMU type. Sums of upstream HMU areas grouped by HMU types for each surveyed flow along the whole study reach is shown on Figure 2.18 for both survey flows on Ingdalselva and for medium flow on Figure 2.19 for Orkla (it was not possible to carry out a complete survey at low flow situation). The figures show the separate HMU type areas as a function of river length.

We already noticed how HMU types relate to each other regarding their overall proportions at the different flows and reaches. Now, we see how these proportions develop along the rivers. This way, we expect to identify sub-reaches, between which the HMU composition and thereby functional habitat structure differs.



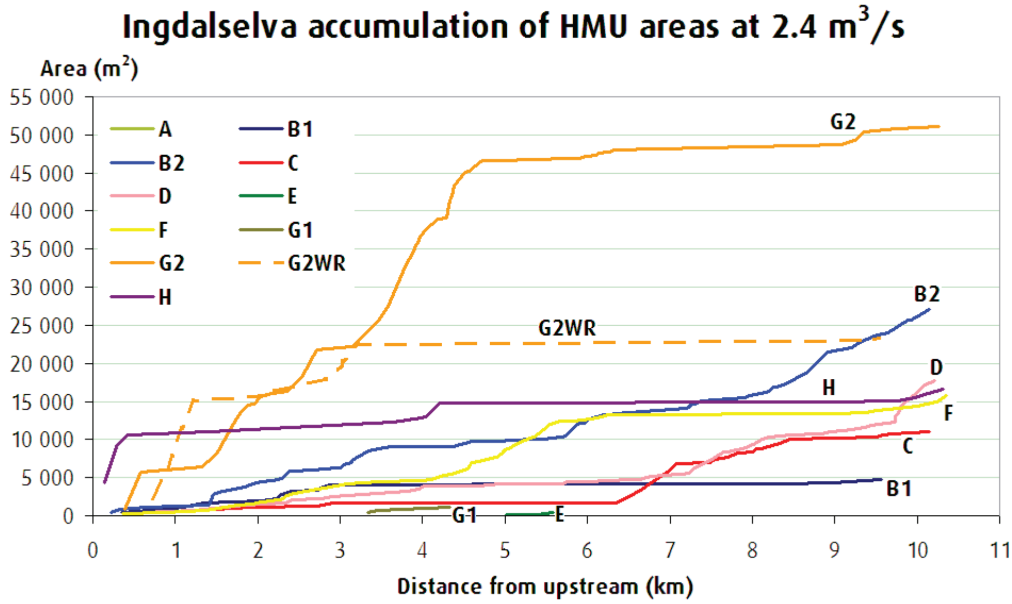


Figure 2.18: Accumulation of HMU areas at Ingdalselva at low medium (0.9 m³/s) and medium (2.4 m³/s) flows

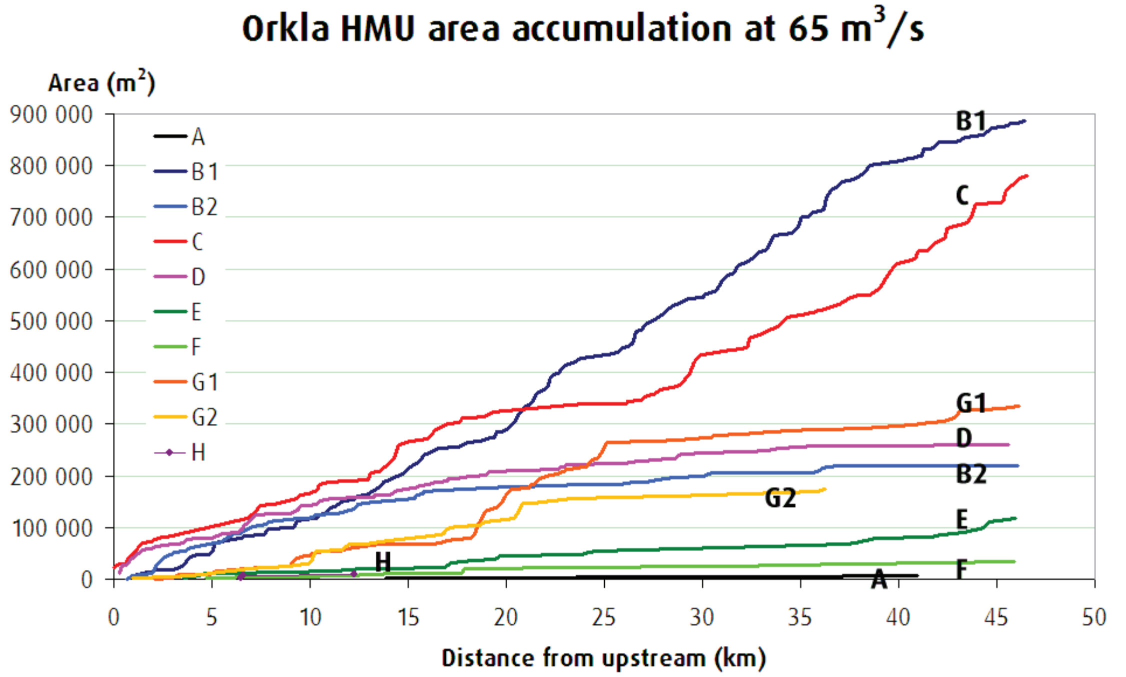


Figure 2.19 Accumulation of HMU areas on Orkla at medium (65 m³/s ~97% of MAF) flow

Comparing the two HMU area accumulation charts on Figure 2.18 (Ingdalselva) the difference between dominating HMU types appears again: type D at low medium and type G2 (G2WR) close to the downstream end of the study reach. Similarly, on Figure 2.19 (Orkla) types B1 and C cover larger areas than any other types by the end of the study reach. The new information these charts provide is the possibility of identifying section breakpoints within our study reach.

Taking low medium flow on Ingdalselva as example and looking at the upper chart on Figure 2.18 the two breakpoints on the accumulation graph of HMU type D at approximately 4 and 6.5 km downstream from the beginning of the study reach are found. These divide the reach into three sections. The same breakpoints, though less obvious, may be noted on the lower graph of the same figure. Here functions of HMU types G2 and C break, in addition others. Fish sampling carried out later by fish biologist experts verifies our suspicion, that there exist breakpoints in habitat structure in this river, but details of this study are not presented here.

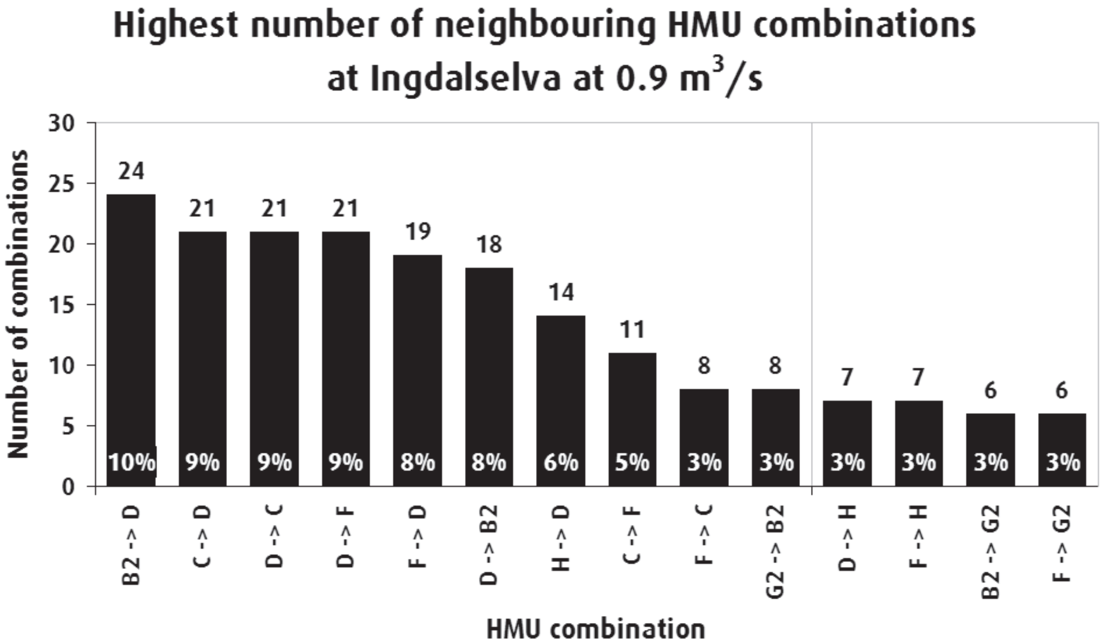
In case of Orkla on Figure 2.19 it is harder to identify strong breakpoints. Nevertheless, HMU types B1 and C do show some variation, which also corresponds to other, less dominating HMU types (like B2 and G1). Breakpoints are found at about 15 km, 18 km and 26 km downstream from the beginning of the study reach. No investigations of habitat distribution were carried out in Orkla, therefore the findings regarding the HMU breakpoints cannot be verified. However in a study on this river presented by Ureña (1999), a hydrology, topography and geology based division of this river defines approximately similar borders. This reference neglects biological classification criteria though.

Comparing the charts of the two rivers it is found, that Orkla shows a less scattered, more balanced picture of HMU distribution than Ingdalselva, where a few HMU types seem to play much more important roles than the remaining others (HMU type D and G2 vs. all other types).
Summarizing the work regarding area accumulation charts of HMU types, the functions were found useful but hard to verify without any biological information collected from the reaches. Nevertheless no reason was found to neglect these functions from future versions of the NMCM (see section 2.1.1.4 for related literature).

2.1.3.6 HMU proximity

Many ecologists, such as Kocik and Ferreri (1998) or Lonzarich et al. (2000) argue for the use of complex (combined) HMU types, which can be defined as e.g. combinations of those applied in the NMCM (a review of these articles is presented in section 1.2.7.3). By looking at the amount of (physically) neighbouring class combinations, the most often occurring sequences may be identified. Figure 2.20 and Figure 2.21 show these sequences for both surveyed flows at both Ingdalselva and at Orkla. The graphs show both numbers of sequences observed and the percentages showing the amount a particular combination contributes to all observed combinations. The graphs show sequences only with the highest numbers. The missing columns are sequences of the same HMU type (such as type D followed by type D for example). These are not shown in the study.
Looking at low medium flow at Ingdalselva on Figure 2.20 (upper graph), it is found that the most often observed one-way proximity is HMU types B2-s followed by D-s. This sequence is observed 24 times, which accounts for 10% of all observed sequences at this river and flow. However, if the two-way proximities are also taken into account, the largest number of sequences are found as C types in the proximity of D types, because C-s are followed 21 times by D-s and D-s are followed an additional 21 times by C-s. These two sequences contribute 18% (9% + 9%) to all sequences observed, which is higher than the 10% of B2->D sequences.
With rising flow (Figure 2.20, lower graph), the picture dramatically changes. Both B2->D and D->C disappear from the top of the list, while C->D remains at 10%. The new largest contributors are F->G2 and B2->G2 with 10% and 9% respectively, previously represented by 3% - 3% in the low medium flow case.
A more balanced frequency of sequences is shown on Figure 2.21 for Orkla. Here we often see a sequence close to its invert (see the first four bars at low-medium flow, on the upper graph). This simply means that types of HMU sequences in Orkla are spatially more clumped than those at Ingdalselva. In other words, if one particular sequence is observed at a certain part of Orkla, it is likely to find its invert sequence in its close proximity, while at Ingdalselva, invert sequences occur farther away and less often. It is shown that Ingdalselva has a more scattered HMU (and thereby habitat) structure than Orkla and that certain HMU sequences appear more independently from each other.

By counting frequencies of certain HMU sequences, it is possible to describe quality of complex habitat types, where such information is needed. For example if in Ingdalselva a survey of salmon spawning and nursery areas showed that most HMU type F-s are important spawning grounds and that most HMU type G2-s are important nursery areas, it would be desireable to find how often these appear in the proximity of each other. The more often this sequence observed, the better habitat for these life stages is provided in Ingdalselva. This may be relevant for habitat restoration, identification of bottlenecks in population development, or simple habitat surveys. Thereby, the importance and relevance of this analysis is shown.



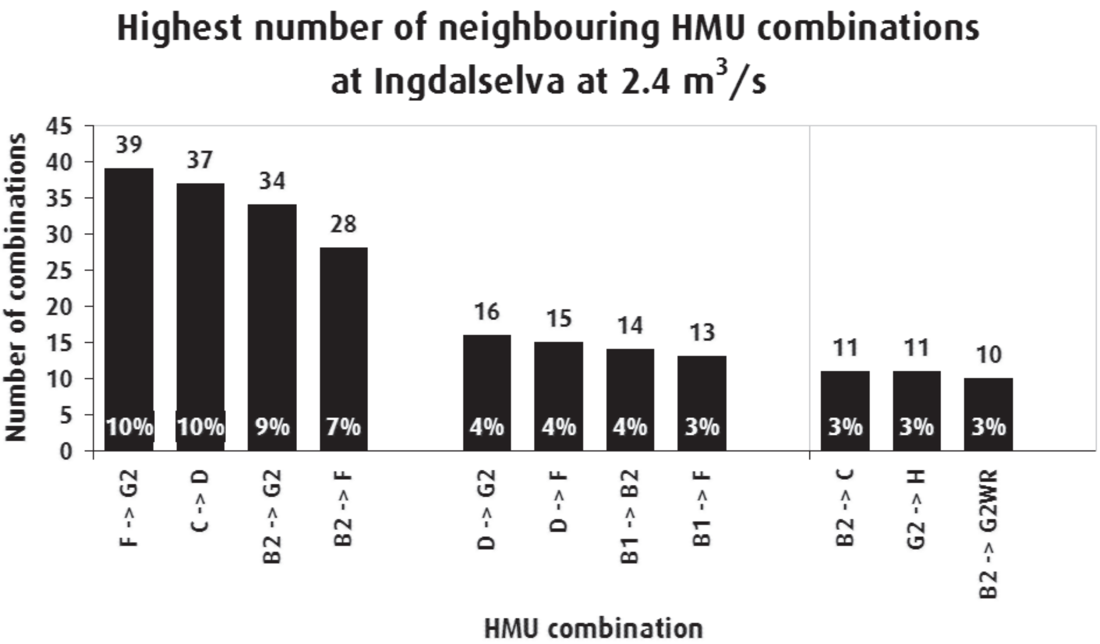


Figure 2.20: Proximity of HMU types on Ingdalselva at low medium (0.9 m³/s) and at medium (2.4 m³/s) flow

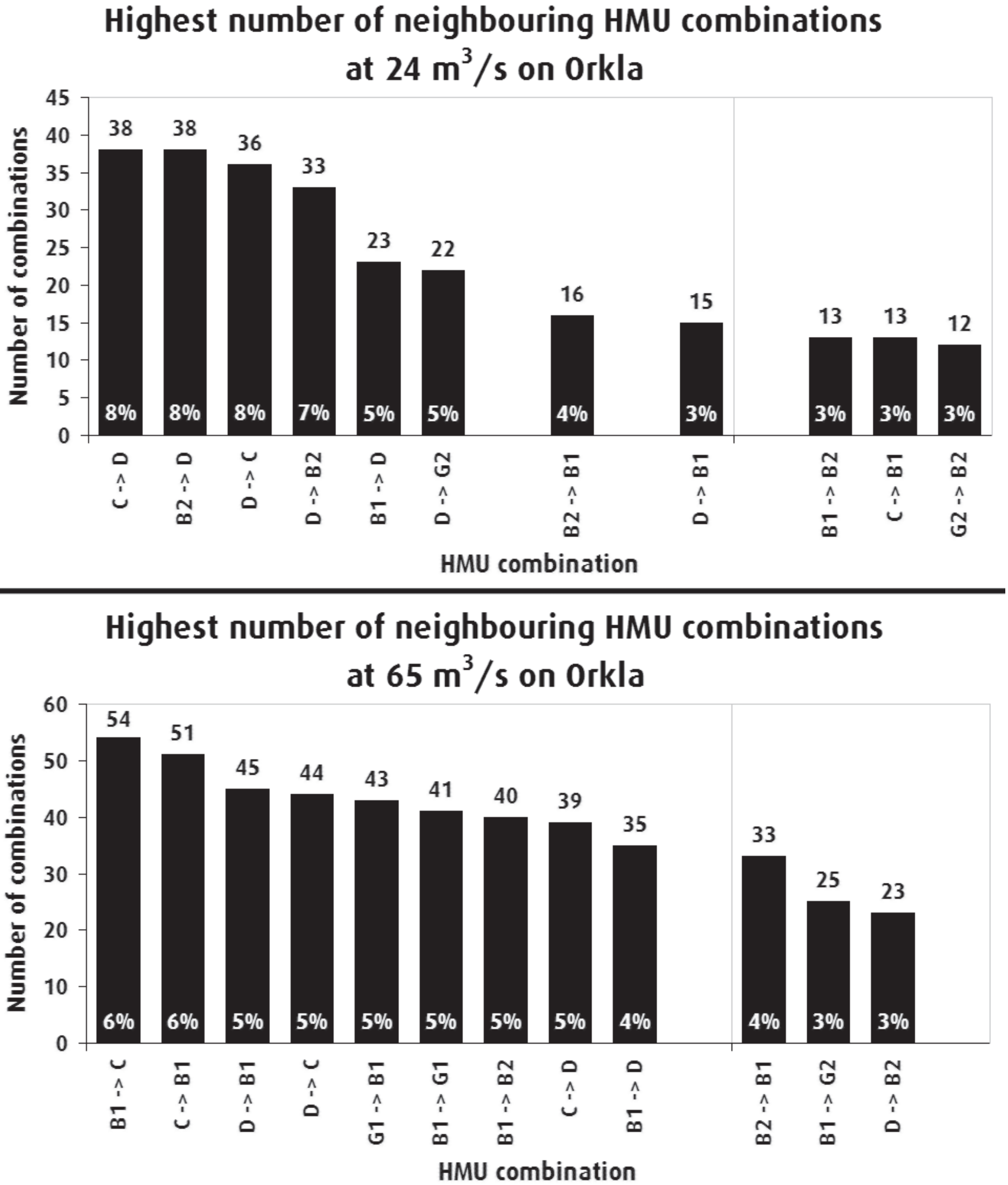


Figure 2.21: Proximity of HMU types on Orkla at low medium (24 m³/s) and at medium (65 m³/s) flow

2.1.4 Temporal variation of HMUs – River Surna

HMUs change with time and, at the same time, HMU-linked habitats as well. If the same spot in a river is observed at two different flows, different HMUs are observed there in most cases due to the changes in discharge and consequently in surface flow type, gradient, water depth or velocity, as shown in the studies above. In order to employ HMU maps representing functional mesohabitats for scaling purposes, the temporal variation of HMUs need to be addressed. Stability of and variations between HMU types following the variations of flow have to be examined. Thus for first, several HMU maps are prepared of the same reach for different flows. The flow variations preferably cover the range of flows of interest for the study.

A more accurate dynamic HMU map may be gained using dynamic or semi-dynamic hydraulic models that are able to calculate depth and velocity distribution over longer study reaches. Practically this would be a 2D or 3D dynamic hydraulic model incorporating hydraulic roughness information to estimate surface flow types as well. These models are available and tested for short or laboratory cases, but are less used in long natural rivers due to technical limitations inherent in necessary input data and in some cases computing power. Therefore today these are not applicable for the present purposes.

The study related to River Surna served as a subsidiary project under the umbrella of a larger program aiming at finding sensitive habitat stretches likely to be affected by a proposed new power generation scheme. A general description of the river is shown in section A.1.4. It was required to apply the NMCM for this study, even though the method was still in its development phase. We had the opportunity to investigate different parts of Surna from beginning during early winter 2000 and the last HMU survey was carried out during summer 2003. In this period, the NMCM has changed (see sections 2.1.2 and 2.1.3) and therefore the presented HMU maps are not fully consistent with each other. The most important difference is the absence of HMU types G1 and G2 from the early map because by that time only type G was used. Here, an extract of this series of projects is presented keeping the focus on issues relevant for the development of the NMCM. The NMCM was planned to serve as a tool to identify reaches where specific habitat types are especially sensitive to flow variation and provide guidelines to establish ecologically feasible flows. Evaluation of the results of the larger project is not complete yet.

Two surveys were carried out: one at low flow (present regulated minimum flow, surveyed during winter 2000) and another at high flow (somewhat close to the flow the hydropower station releases at maximum power generation, surveyed during spring 2003). Figure 2.22 shows two HMU maps of the approximately 20 km long reach starting from the outlet of the power station at Solemshølen and ending at Øye Bridge at Skei. The two maps show the same reach in two different flow situations, one at about 40 m^3/s (Figure 2.22, upper map), the other at about 15 m^3/s (Figure 2.22, lower map). In the period between the two surveys, a flooding and an ice-jam had altered the topography at some parts of the study reach, but the majority of the channel – after visual investigations – was assumed to remain mostly similar to the pre-flood situation.

For the ease of understanding, the majority of the methods presented above in sections 2.1.2 and 2.1.3 are used further on and the regular description of the river is presented. The results are shown without further details on the methods themselves, because they are similar to those shown in the previous sections.

Figure 2.23 shows HMU area distribution charts. These help identifying dominating and less dominating HMU types on the study reach. Note the shift in dominance from HMU type C at minimum flow to B1 at production flow on Figure 2.23. Further, we see the relative little presence of steep HMU types A, E and F and the relative abundance of HMU types with smooth surface (B1, B2, C and D) at both surveyed flows. This corresponds to our general vision of the study reach, showing geomorphological features of lower river parts with large number of meanders, traces of cutoff bends.

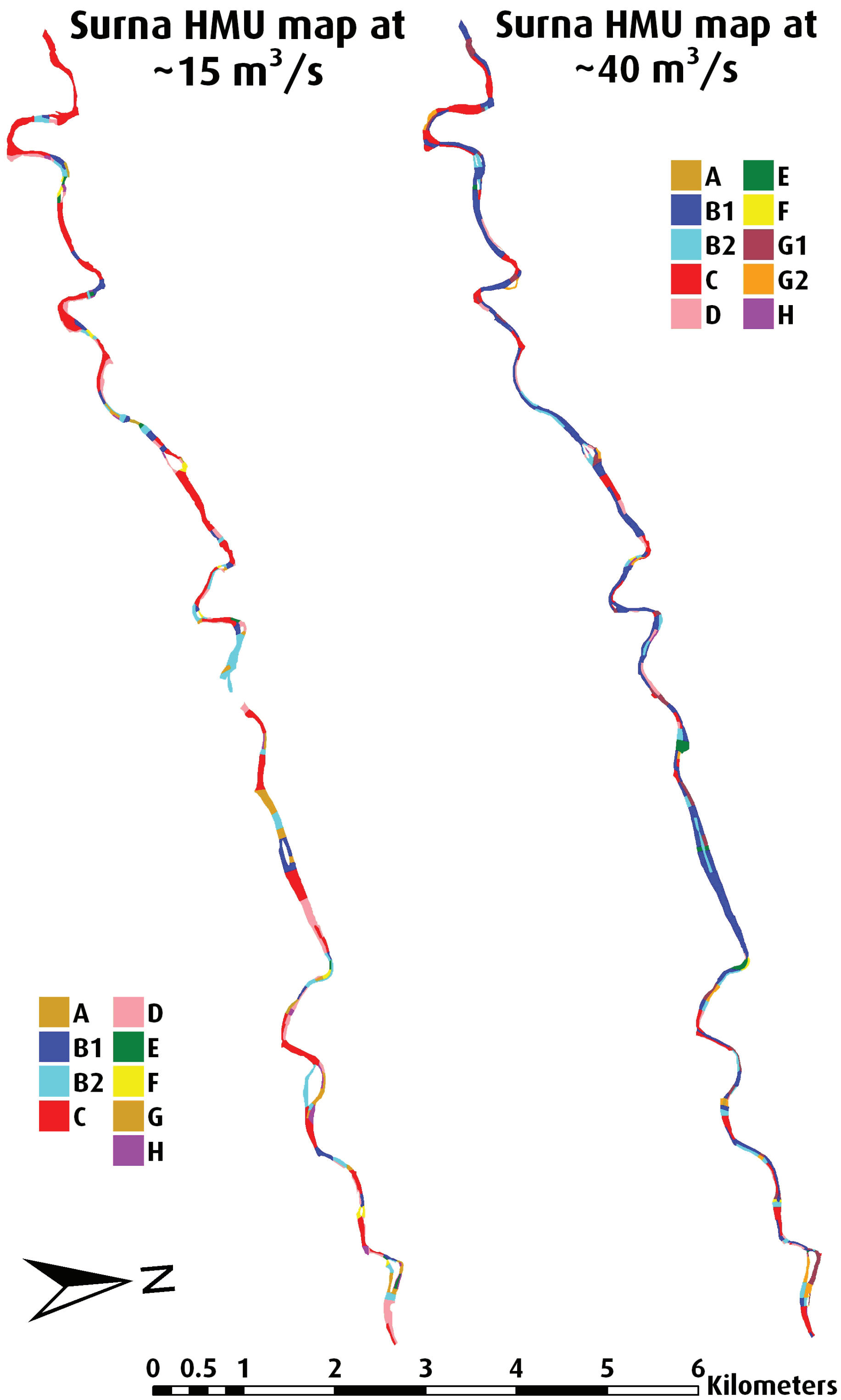


Figure 2.22: HMU maps on River Surna at low (15 m^3/s) and at high (40 m^3/s) flow

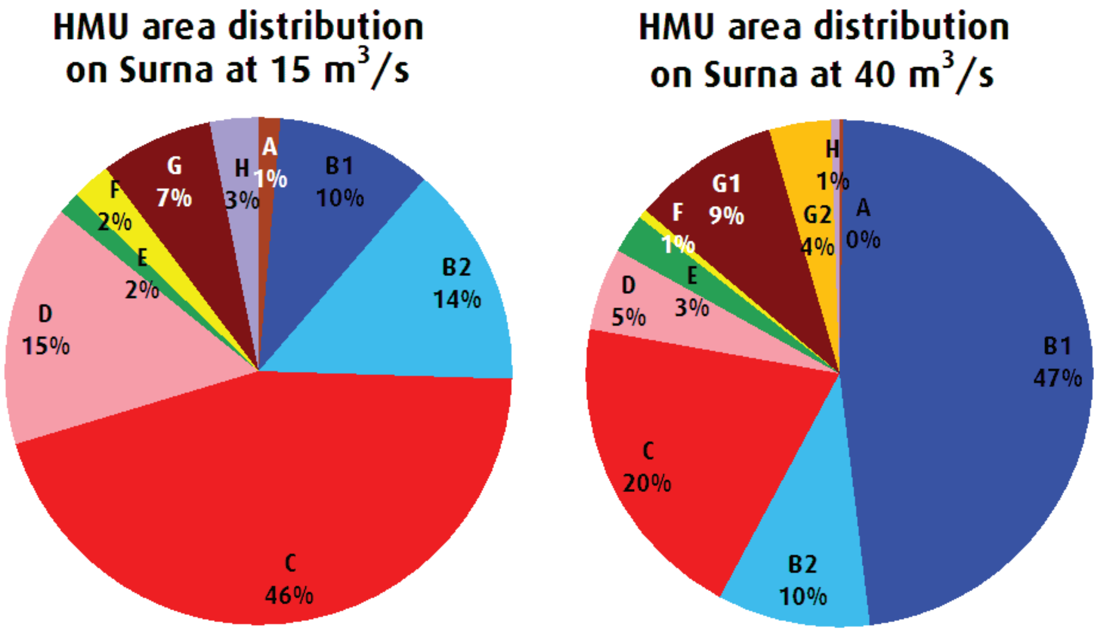


Figure 2.23: HMU area distribution charts at Surna at 15 m³/s and 40 m³/s

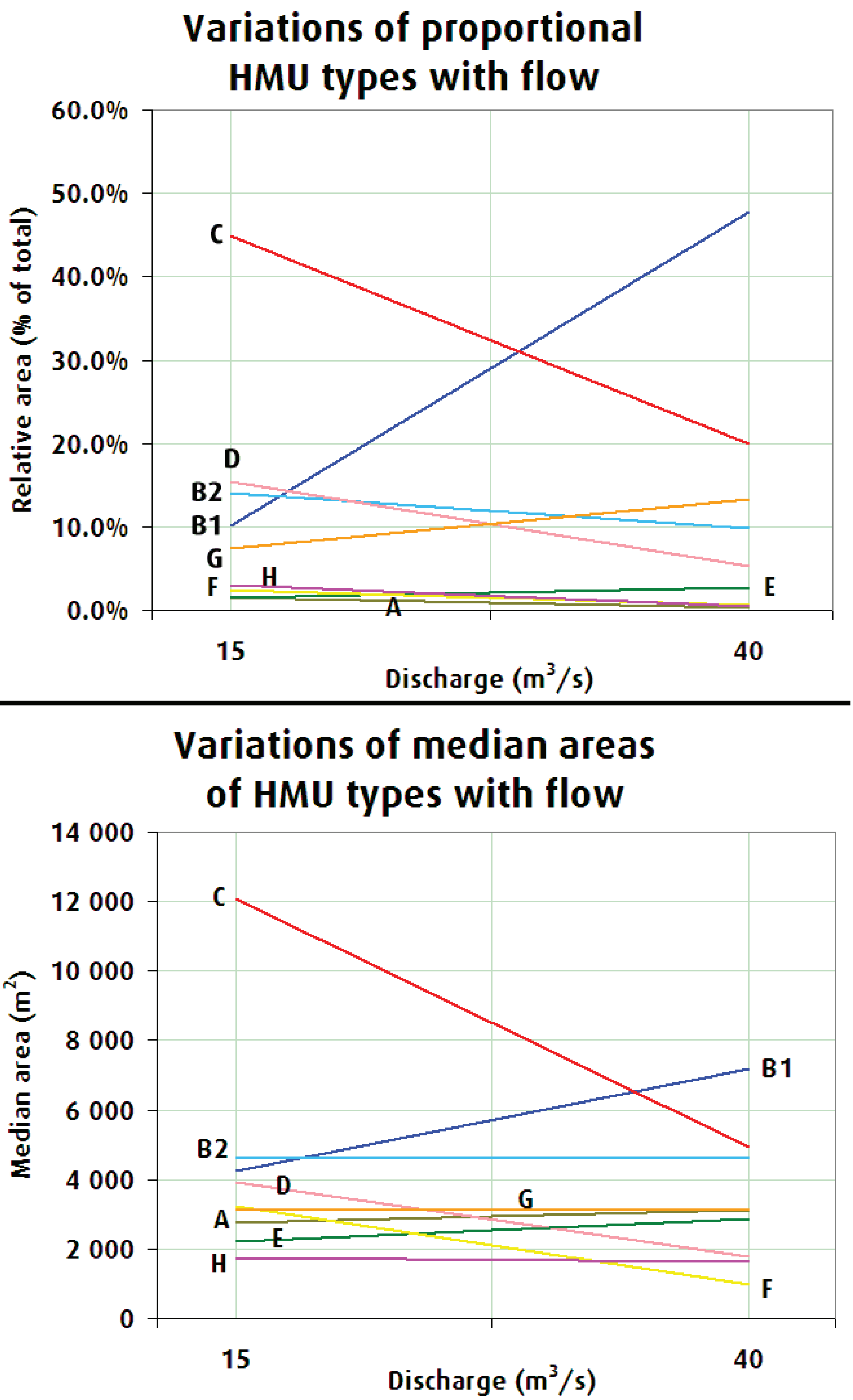


Figure 2.24: Total (top) and median (bottom) HMU area interpolation graphs for non-surveyed flows on Surna

Figure 2.25 and Table 2.8 show basic statistical analysis related to areas of individual HMUs at both flows. Note the apparent covariance between average sizes (column "Mean" in Table 2.8) and related standard deviations (column "St. Dev" in Table 2.8) as well as the high variation in the number of samples between the different HMUs (e.g. compare HMU type A with one sample with B1 with 64 samples at 40 m^3/s). Certain HMU types apparently are usually smaller than others in general. Types B1, B2 and C have generally the largest areas at both flows, while type H has generally small. Types A, E and G (G1 and G2 at 40 m^3/s) have somewhat unaltered sizes in the middle range of all median sizes at both flows, while a decrease of median areas of types D and F with increasing flow can be observed.
Table 2.8 allows the construction of HMU interpolation graphs for non-surveyed flows. The graphs may be based on proportional areas as shown before (Figure 2.7, Figure 2.14 and Figure 2.15) or we may include any other of the statistical variables as well

Table 2.8: Basic statistical description of HMU types at Surna at 15 m^3/s and 40 m^3/s

	HMU	Mean	St. Dev	Median	Sum	Min.	Max.	N
15 m^3/s	A	3064	2103	2757	18386	962	6076	6
	B1	6367	6868	4230	127339	1569	32876	20
	B2	6844	8903	4621	177931	989	45938	26
	C	17213	16255	12078	568029	2959	73140	33
	D	5570	5838	3929	194947	572	27402	35
	E	2423	907	2227	19387	1122	4065	8
	F	2998	1520	3231	29977	945	5655	10
	G	5164	5959	3168	92946	971	26821	18
	H	2528	1939	1733	37913	735	8253	15
40 m^3/s	A	3137	-	3137	3137	3137	3137	1
	B1	9793	11755	7181	626740	151	82313	64
	B2	4437	2704	4636	128665	308	9980	29
	C	7682	7908	4929	261181	360	34689	34
	D	2489	2287	1782	69705	81	8727	28
	E	5878	6412	2876	35265	563	17537	6
	F	1258	1208	982	7548	253	3391	6
	G1	4034	3901	2848	121034	669	17239	30
	G2	4409	3108	3427	52903	354	9380	12
	H	1678	958	1640	6710	797	2633	4

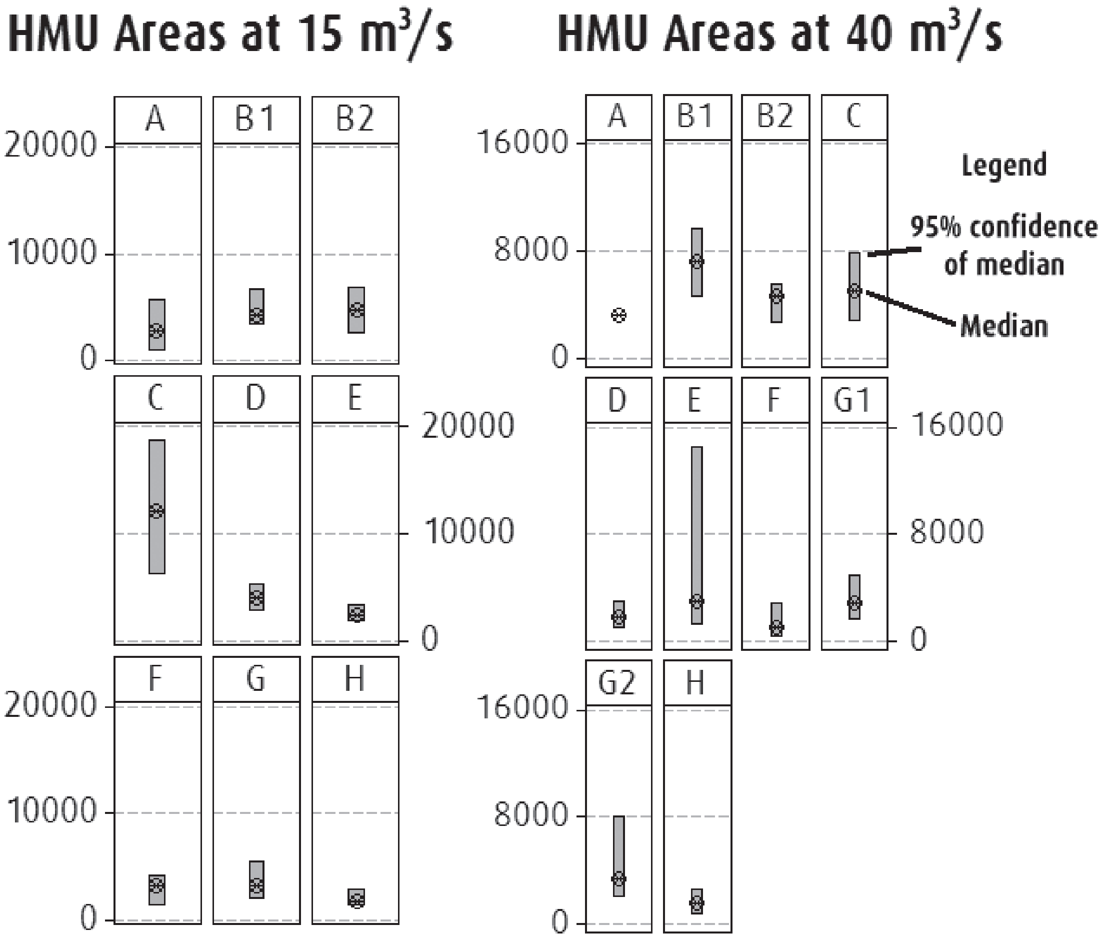
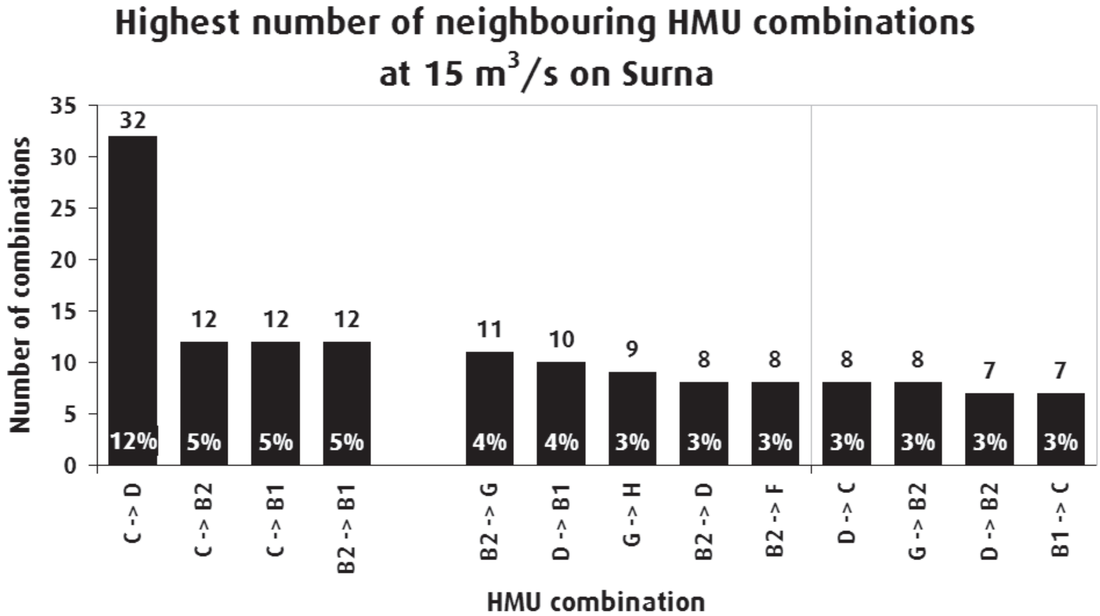


Figure 2.25: Median and 95% confidence of median areas of HMUs at Surna at 15 m^3/s and 40 m^3/s

HMU accumulation was not tested at Surna and therefore the accumulation charts like in the ones section 2.1.3.5 are not presented here. However, HMU proximities are shown on Figure 2.26. Note the highly dominating sequence of HMU type C followed by D ("C->D") at 15 m^3/s compared to the other observed HMU sequences and how this particular sequence looses its importance at 40 m^3/s. In the first case C->D sequence is observed in 12% of all sequences (32 times, upper graph on Figure 2.26), whereas in only 2% in the second case (8 times, lower graph on Figure 2.26). Note that combinations of HMU types B1, B2 and C either preceding or following one another provide the majority of sequences at both flows. At minimum flow C->B2, C-> B1 and B2->B1 takes 15% (3×5%) of all observed sequences and at production flow B1->B2, B1->C, C->B1 and B2->B1 takes 29% (8%+8%+7%+6%) of all sequences.

It was previously noted that HMU types D and F are flow-sensitive because these decrease both in individual and sum area when flow increases. Their related sequences show the types of neighbouring HMUs that benefit from their reduction. First looking at HMU types D it is shown that at minimum flow these are most often preceded by type C and followed by B1. Second most often C

B2 followed by C. At production flow the situation only slightly changes, as D-s both preceded and followed by type B1 mostly and by C second mostly. Thereby it is shown that when HMU type D looses, mostly types B1, B2 and C gain areas (with increase of flow). The proximity charts only show the 15 most often observed HMU sequences for the ease of presenting the graphs. However, it is believed that less frequent sequences play little role in habitat diversity and variation. For this reason HMU type F is only shown on the minimum flow chart, being preceded by type B2. Other sequences in which F is present are less in number than those shown on Figure 2.26.



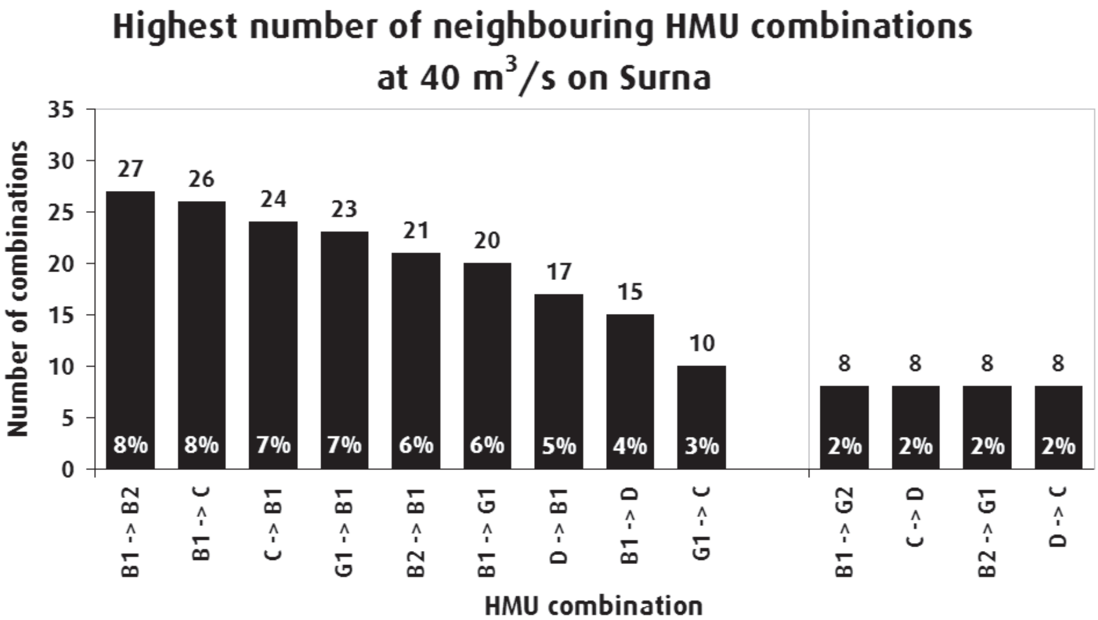


Figure 2.26: Proximity of HMUs at Surna at 15 m^3/s and 40 m^3/s

Figure 2.27 shows HMU surveys of the same part of the study reach at both flows separately (upper maps) and together, overlaid them on each other (lower map). The combined map is gained by intersecting the individual HMU entities observed at minimum and production flows. This way a map that shows how each arbitrarily selected point in the river changes its features in a meso-scale context with flow is prepared. On this combined map areas with striped pattern indicate areas where HMU type changes with flow, while areas with single colour fill indicate areas where the same HMU type was observed at both flows. Such a map is useful for studying HMU type variations at selected specific locations in the river. The site is situated on the upper end of the study reach. It has to be noted, that the analysis and the further calculations are based on the theoretical intersection of the two HMU maps and so areas where only one flow is mapped are excluded from the analysis (see for example the side channels on the maps).

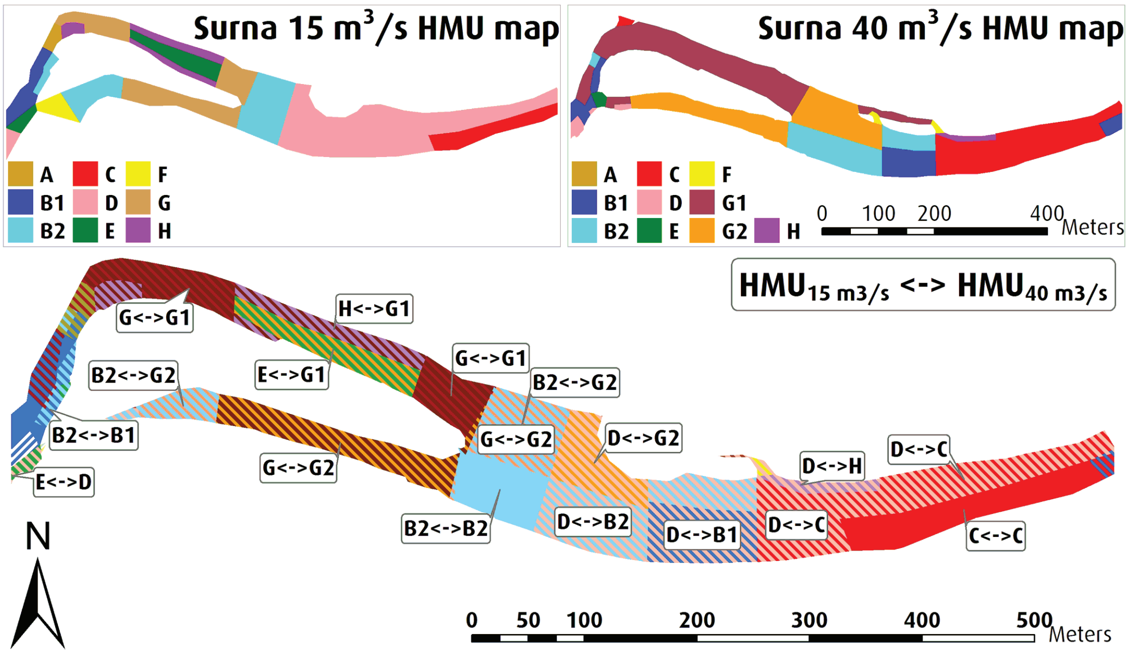
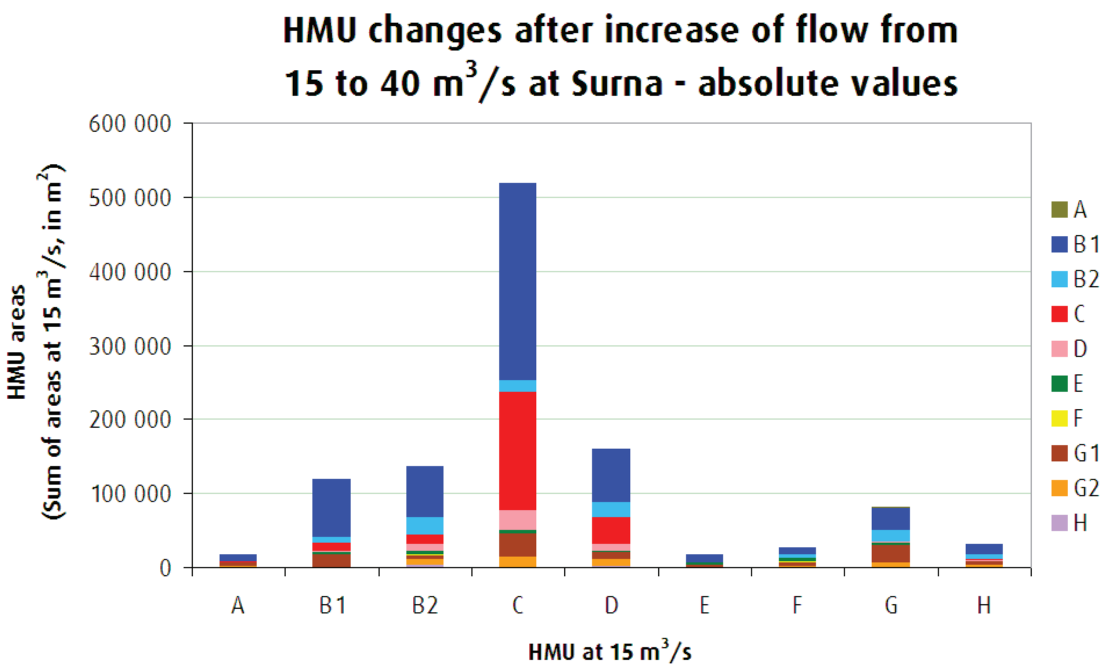


Figure 2.27: Combination of HMU maps at 15 m³/s and 40 m³/s on Surna

Further, a statistical analysis of the data from the combined map provides additional information on HMU variations with flow. If the map entities are grouped by their minimum flow HMU, it shows what other HMU types these turn into and what their relative and absolute ratios are related to the original HMU group or to the whole study reach. It is shown on Figure 2.23 that HMU types C, D, B1 and B2 cover the largest parts of the study reach at minimum flow. The same ratio between HMU types is shown on the upper chart of Figure 2.28, only here the sum areas are shown for each bar. These bars are then further divided according to the areas each HMU group at production flow gained from them. For example looking at bar no. 4, counting from left that represents the sum area of all HMU type C-s at minimum flow, it can be seen that this type takes about 520000 m² of surveyed area. At production flow, these C areas are divided among many HMUs, but roughly half of them turned into type B1-s (dark blue section of bar no. 4) and another approximately 1/3rd of C areas remain C at the higher flow situation as well. This chart however does not show HMUs covering smaller areas related to the dominating ones. Therefore on the lower part of Figure 2.28, the same division of HMU types is shown with percent values, related to their varying minimum flow areas. This way, division of all minimum flow HMU types is presented with 100% on each bar. However 100% in these cases mean different extents of HMUs. Looking at for example HMU type A on the upper chart, we only see the relative small area this HMU type covers in relation with the larger types, such as C or D. But on the lower chart, it is possible to identify further details as well. Keeping HMU type A as example we see, that at 40 m^3/s flow, most of the previous A type areas are turning into B1-s and G1-s (dark blue and brown stripes on the lower chart of Figure 2.28). The actual areas of the combined area analysis are shown in Table 2.9 and the percent values in Table 2.10.



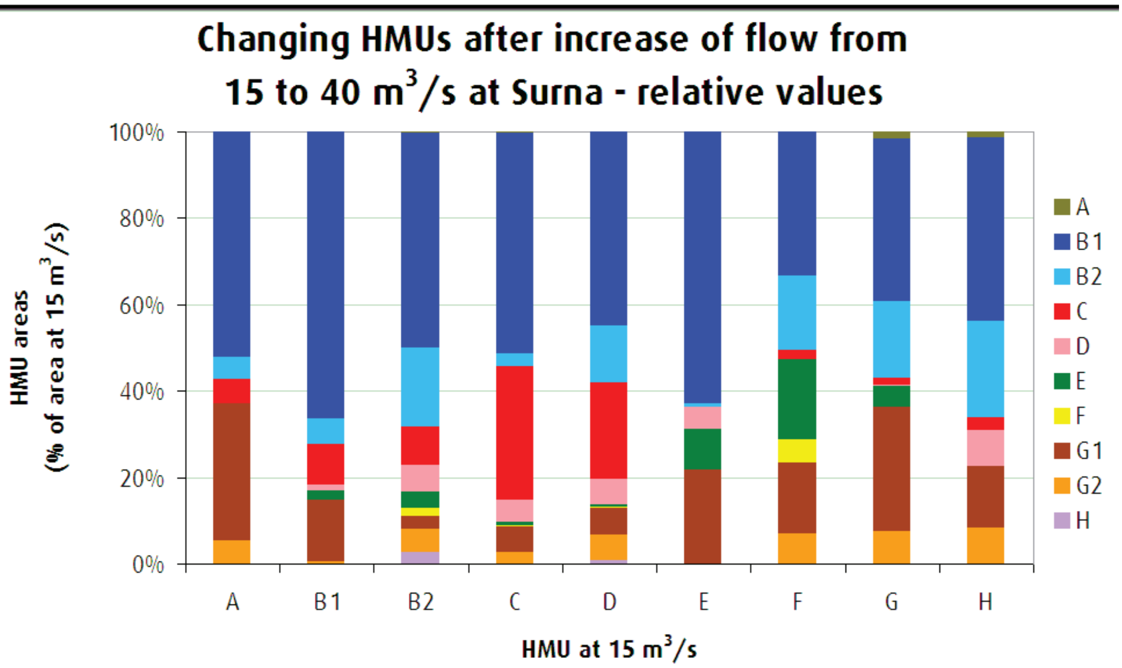


Figure 2.28: Ratios of HMU areas at 15 m³/s (minimum flow) among HMU areas at 40 m³/s (production flow)

Table 2.9: Distribution of divided HMU areas. Rows show HMU types at 15 m³/s and columns at 40 m³/s

	HMU types at 40 m³/s									
	A	B1	B2	C	D	E	F	G1	G2	H
A	0	8941	888	968	1	0	0	5416	925	0
B1	0	79114	7015	11296	1617	2780	0	16937	543	0
B2	509	67505	24784	12135	8518	5007	2452	4095	7521	3508
C	919	265478	15734	160385	26297	4508	1010	31492	13351	0
D	0	71614	20970	36028	9473	728	219	9983	9480	1315
E	0	11211	139	36	894	1680	0	3892	0	0
F	0	8703	4524	565	14	4799	1450	4264	1831	0
G	1420	30637	14413	1226	137	4118	0	23330	6132	0
H	418	13370	7035	935	2643	0	0	4471	2648	0

Table 2.10: Percents of rows of Table 2.9

% of row	A	B1	B2	C	D	E	F	G1	G2	H
A	0%	52%	5%	6%	0%	0%	0%	32%	5%	0%
B1	0%	66%	6%	9%	1%	2%	0%	14%	0%	0%
B2	0%	50%	18%	9%	6%	4%	2%	3%	6%	3%
C	0%	51%	3%	31%	5%	1%	0%	6%	3%	0%
D	0%	45%	13%	23%	6%	0%	0%	6%	6%	1%
E	0%	63%	1%	0%	5%	9%	0%	22%	0%	0%
F	0%	33%	17%	2%	0%	18%	6%	16%	7%	0%
G	2%	38%	18%	2%	0%	5%	0%	29%	8%	0%
H	1%	42%	22%	3%	8%	0%	0%	14%	8%	0%

In order to analyse stability of each HMU type and trends of change regarding flow variation, each value from Table 2.9 was ranked in decreasing order in Table 2.11. The largest values show variations involving largest amount of HMU areas. If a value is found in a mesh of similar HMU types in Table 2.9, then that portion of the particular HMU type remains the same if flow changes. If a value is found in a mesh of two different HMU types in Table 2.9, then a major trend of changes of those particular HMUs can be seen. For convenience, only the 20 largest areas are shown of all 70 combinations generated.

Table 2.11 shows that the largest shift when flow increases from minimum to production level are related to HMU type C-s turning into B1-s. In other words it means that flow velocities become faster and that a large portion of minimum flow pools become deep glides at production flow. Checking below in the table, we find other HMUs contributing to B1 at production flow: HMU types surveyed as D and B2 at minimum flow give additional 12% (6%+6%) to B1-s. Further, it is shown that HMU type C and B1 are also the most stable HMU types on the study reach for this particular flow range, providing 21% (14% + 7%) of non-changing HMU areas in the river.

Table 2.11: The 20 largest sum areas of all HMU combinations in decreasing order

HMU combination ($15\ m^3/s$<->$40\ m^3/s$)	N	Sum area (m^2)	% of total river area
C<->B1	67	265478	24%
C<->C	46	160385	14%
B1<->B1	41	79114	7%
D<->B1	39	71614	6%
B2<->B1	49	67505	6%
D<->C	32	36028	3%
C<->G1	10	31492	3%
G<->B1	19	30637	3%
C<->D	28	26297	2%
B2<->B2	23	24784	2%
G<->G1	12	23330	2%
D<->B2	19	20970	2%
B1<->G1	12	16937	2%
C<->B2	11	15734	1%
G<->B2	15	14413	1%
H<->B1	17	13370	1%
C<->G2	4	13351	1%
B2<->C	6	12135	1%
B1<->C	8	11296	1%
E<->B1	11	11211	1%

Another reason causing HMU changes due to varying flow occurs when the flow reaches a certain bed moving magnitude. Actually, this did happen between the two surveys of Surna. In this case, the bed shape is altered and the configuration of the HMU-s as well. Unfortunately, there was no possibility to carry out measurements regarding the magnitude of this process, as bathymetry was not measured neither other detailed maps of the channel before and after the flood event occured. But it is understood that, above a certain threshold of discharge, the river bed is likely to reconfigure and in extreme cases completely changes.

Frissell et al. (1986) describe a hierarchical framework for stream habitat classification. This work is referred above in section 2.1 in a different context. They present "potential persistence" classes for "reach levels", which are river reaches with a length in the order of ten to hundred meters in case of a second or third order stream. These persistence classes are derived from erosional, morphogenic and substrate features, stating the facts that river beds vary in time and that the grade of variation is changing along the channel. Potential persistence varies

from <20 years (short term) through 20-100 years (moderate term) to >100 years (long term). Stepping one level lower in their system, to the “pool/riffle” level, which are river reaches with a length in the order of one to ten meters in case of a second or third order stream, they show the development of longitudinal channel slope of a hypothetical reach system. Such a development changes the actual sequence and position of riffle and pool elements, while keeping the overall frequency (area or volume) of those unaltered within the reach.
It is therefore assumed that major river segments (identified by class accumulation) would not change even in cases of major floods, since they are organized according to the energy-loss gradient of each river. Even during large floods, the macro characteristics of rivers remain mostly intact and that includes energy-loss gradients or average slopes as well. So, if the spatial distribution of HMU-s would change, their overall accumulated composition is expected to remain the same (related to flow of course). This assumes that each HMU type represents a unique energy loss amount.
Engineering or other anthropogenic constructions may also alter the HMU distribution. Depending on the extent of such an alteration, the effects can be local or extended, in this latter case, reconstruction of the HMU maps may also become necessary.

2.1.5 The hydromorphological picture of HMUs

The previous sections presented development steps that were focusing mostly on practical application and technical issues related to the NMCM. At the same time, we were looking for proof through the physical parameters of HMUs that our surveying strategy is feasible. These parameters should allow explicit description of each HMU type. During the surveys it was noticed that the four parameters used in the NMCM (surface pattern, relative gradient, depth and surface velocity) vary within each HMU to some accepted extent and these variations differ in magnitude from each other in the different HMU types.
The different magnitudes of variation imply different data density needs in case in-HMU habitat use is analysed. This finding implies that different minimal resolution for each HMU type is required. Such an analysis is relevant for previously noted plans to use the HMU surveys for scaling purposes, where HMUs are analysed by, for example, microhabitat methods.
It was decided to take point samples of the four selected parameters from HMUs and analyse them. By such an analysis, it should be possible to show the accuracy of the strategy using estimation of parameters and the accepted level of variation of describing parameters within and between HMUs. It was assumed that describing parameters in complex flow patterns (in “rough” HMUs) vary with greater extent than in moderate areas (in “calm” HMUs). Data was collected during several field campaigns in numerous rivers. The means, equipment, methods, time and labour varied between these, and therefore, the results are presented separately for each study.

At first, rivers Orkla and Ingdalselva were sampled in combination with the studies presented in section 2.1.3. A general description of the rivers is presented in sections A.1.2 and A.1.3. Appointed HMUs were sampled in these rivers and this way the sampling was biased by the actual HMU layout. The sampling followed a semi-regular structure.

The second and more intensive campaign was carried out in combination with an internal Centre for Ecology and Hydrology (CEH) project, under the umbrella of a COST Action 626 Short Term Scientific Mission (STSM) in 2002. Two small rivers were selected in the UK by CEH and one in Norway. The UK sites were studied by the Banchory branch of CEH as part of a project comparing salmon productivity in upland and lowland rivers. The Wallingford branch of CEH provided hydromorphology and hydraulics related support in the project. Section A.1.5 provides a general description of the sites. The Norwegian river was actually a side channel of River Nidelva, in Trondheim (described in section A.1.1). The sampling strategy in these rivers was meant to cover a whole river reach in a partly structured, partly unstructured way. The samples were collected independently from the actual HMU layout.

The third and fourth campaigns took place at River Surna in mid-west Norway and at River Nausta, west Norway, both in 2003. Data collected in Surna was primarily used in other investigations related to environmental flows and hydropeaking (see section 2.1.4 for our other activities on this river and section A.1.4 for a description of the study site). The Nausta project investigated mitigation possibilities to maintain and improve salmon production. This project is presented in more details among the applications of the NMCM in section 3.1 and a project description is given in appendix A.2. Data collected in Surna and Nausta came from selected fish sampling sites. Sampling was not meant to cover the whole width of the river, the complete reach or a whole HMU.

2.1.5.1 HMU sampling in Orkla and Ingdalselva

Orkla and Ingdalselva were selected test rivers for the development of the NMCM as described above. Besides other development steps, it was intended to verify the estimating capabilities of the surveyors and to test new discharge measuring instruments. Therefore, a series of discharge measurements were carried out in both rivers at different sites in the same period when the rivers were HMU mapped. The instruments used in this campaign were:

1. Ott C2 current meter (classical propeller type): this device has exchangeable propeller heads for different flow velocities. During measurement, the propeller is aligned with flow direction, adjusted to the proper depth (depending on the total depth at the vertical of measurement) and it counts the rotations for some arbitrary time. 40 s for were used in all cases. Each propeller head is laboratory calibrated and formulae are provided to calculate flow velocities from the number of rotations. Measurement limits ranged from 0.025 m/s to 3 m/s.

2. Sontek Flow Tracker, a handheld acoustic Doppler velocimeter (ADV): this device uses acoustic Doppler technology to measure multi-dimensional flow in a sampling volume 10 cm away from the sensor. The sound generated and emitted by the transmitter unit is reflected from suspended particles or air-bubbles in the water. The reflected sound is then received by the sensors of the device and averaged in each second of measurement. The built-in processor converts the averaged signal to water velocities. Measurement limits ranged from 0.001 m/s to 5 m/s.
3. Nortek Aquadopp Profiler, an acoustic Doppler current profiler (ADCP) adjusted on a float: the device is an experimental version of a stationary sea-tested device, utilizing the same Doppler phenomena as the ADV, but equipped with three sound emitters and receivers. The combined use of the three heads enable sampling a complete column of water, at most 128 layers (cells). The layer height and thereby the vertical resolution of the sampled profile is adjustable. The device is equipped with an electronic compass and a built-in battery. The measurements are conducted from the shore through radio connection by means of a handheld computer. It provides 3D instantenous and time averaged velocities in each measuring vertical. Measurement limits ranged from 0.001 m/s to 5 m/s for velocity and from 0.3 m to 20 m for depth.

Using the three devices, several teams carried out discharge measurements and depth and velocity measurements in either regularly or irregularly distributed points. Only a part of the collected data was meant for the verification of the NMCM, the other part was related to other projects requiring discharge values. The sampling followed a regular structure otherwise: HMUs were selected and sampled one by one on a diverse reach (where many HMU types are found close to each other). The structured sampling followed apointed cross sections. Spacing of the sampling points were also regular. If this sampling was actually a case of a discharge measurement, if they were carried out by Ott propellers or handheld ADV, the mean column velocity was measured instead of the surface velocity. The sampling points in this latter case were distributed evenly across the river, in about 1/10th width from each other.

Table 2.12 shows averages of depths, mean column velocities and surface velocities (where available) grouped by HMU type and river, as a simple validation procedure for HMU classification. “Expected HMU” shows which HMU type was the point classified into. “Average” shows the average of the particular parameter (such as depth, Surface velocity or Mean column velocity) from all points in the particular HMU type and river. “Expected” shows reference values, which are expected from the HMU classification. For mean column velocities “?”-s stand only, because there are no expected values for this parameter in the NMCM (however the assumption of logarithmic velocity profile would give 15% difference). Each HMU represents only one sample of that particular type in each river (meaning that for example in Ingdalselva four HMUs were sampled: one B1 type, one B2 type, one D type and one G2 type, but each with several points).

Table 2.12: Averages of point measurements grouped by HMU and river on Orkla and Ingdalselva

River	Exp. HMU	Measured data	Avg.	Exp.	Result
Ingdalselva	B1	Avg. Depth (m)	0.39	>0.7	Incorrect
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.55	?	
	B2	Avg. Depth (m)	0.35	<0.7	Correct
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.33	?	
	D	Avg. Depth (m)	0.37	<0.7	Correct
		Avg. Surface velocity (m/s)		<0.5	
		Avg. Mean column velocity (m/s)	0.28	?	
	G2	Avg. Depth (m)	0.25	<0.7	Correct
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.40	?	
Orkla	B1	Avg. Depth (m)	1.42	>0.7	Correct
		Avg. Surface velocity (m/s)	0.56	>0.5	Correct
		Avg. Mean column velocity (m/s)	0.51	?	
	B2	Avg. Depth (m)	0.29	<0.7	Correct
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.36	?	
	C	Avg. Depth (m)	1.97	>0.7	Correct
		Avg. Surface velocity (m/s)	0.24	<0.5	Correct
		Avg. Mean column velocity (m/s)	0.25	?	
	F	Avg. Depth (m)	0.24	<0.7	Correct
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.55	?	
	G2	Avg. Depth (m)	0.20	<0.7	Correct
		Avg. Surface velocity (m/s)		>0.5	
		Avg. Mean column velocity (m/s)	0.43	?	

Table 2.13: Comparison of number of good and false classification results. Optimistic strategy, considering mean column velocities

River	Expected HMU	Correct	False
Ingdalselva	B1		36
	B2		57
	D	82	2
	G2		68
Ingdalselva Total		82	163
Orkla	B1	22	20
	B2		73
	C	15	6
	F		62
	G2		28
Orkla Total		37	189
Grand Total		119	352

Comparing the number of good and false guesses of points per HMU type and river, the startling facts show that of all 471 cases only 119 times (~25%) the expected HMU classification was verified (see Table 2.13). Looking at separate HMUs, it is found that in cases of types B2, F and G2 all points were incorrectly classified, in case of type B1 most points were incorrect, while in cases of types C and D most points were correctly classified. If looked at the two measurement parameters separately, it can be seen that depth is more often classified correctly, while velocity estimates seem to result more often in failure.

However, it is important to notice, that in Table 2.13 mean column velocities were included as well as surface velocities for verifying our classification, while in the NMCM only surface velocities are used. If the two types of velocity measurements were separated, the results would differ, as shown in Table 2.14. It is shown that in fact there are only two HMU types in one river, where surface velocities were measured, HMU types B1 and C in Orkla. B1-s were classified about 50-50% correct and false, while C-s were classified about 70% correct and 30% false. It must be noticed that the number of sampled HMUs by point measurements were far less than classified HMUs, taking Orkla as an example, 5 HMU-s were sampled, while on the shorter HMU survey carried out at 24 m^3/s 326 HMUs were mapped on that study reach.

Table 2.14: Comparison of number of good and false classification results. Careful strategy, separating mean column and surface velocities

River	Expected HMU	Correct	False	Uncertain
Ingdalselva	B1			36
	B2			57
	D			84
	G2			68
Ingdalselva Total				245
Orkla	B1	22	20	
	B2			73
	C	15	6	
	F			62
	G2			28
Orkla Total		37	26	163
Grand Total		37	26	408

Summarizing the first attempt to verify the validity of the survey, it is concluded that mean and surface velocities give different results in this test. It is shown that larger number of HMUs must be sampled in order to conduct a statistically significant test for the present purpose. The measured parameters seem to vary within HMUs, but this is expected because of the natural resolution of our HMU survey strategy. So far, no limitation was defined for lower size limits for HMUs, but we followed an implicit strategy of defining HMUs with longitudinal lengths of at least one river width (for example, if the river is 10 m wide at the spot of survey, the shortest HMU is 10 m long along the river). This strategy gives a good balance between picking up mesohabitat features while at the same time not producing over-fragmented HMU maps. However, it would be hard to verify this strategy.

2.1.5.2 Cruick Water, Water of Tarf and Trekanten reach, Nidelva

Investigations in these rivers were based on point sampling of the complete reaches regardless of the actual HMU positions, to collect enough data to carry out a series of statistical tests. The purposes of the tests were:

1. to show that all different HMU types (as in the NMCM, e.g. C, D, etc., all together 8 types) do differ,
2. to show that HMU surveys really identify different regions in the rivers (as in the NMCM) by comparing separate HMUs with the whole river body,
3. to show that similar HMU types in different rivers are similar to each other.

The investigations were carried out together with other projects and, for this purpose, data was collected from three different rivers. Previously collected data sets from Orkla and Ingdalselva were neglected, because these were not representative for our purposes.

The two rivers in Scotland were Cruick Water and Water of Tarf. The study section on Cruick Water lays by Newtonmill, SE Scotland and on Water of Tarf by Tarfside Farm, SE Scotland. Section A.1.5 shows some description of the rivers and the region. The sampling followed a regular random structure, meaning that the samples were taken from nodes of an imaginary grid stretched on the surface of water, which had no relation to HMU layout or other hydromorphological features. 5-8 points were sampled in cross sections following each other in regular distances of about 2-3 meters. In these nodes, surface flow type, bottom, mean and surface velocity, depth and substrate composition data were collected. Mean velocities in this case mean assumed values of mean column velocities. In case of water depths at most 0.75 m, these were assumed to be found at 40% of depth from the bed, whereas in case of deeper areas the averages of velocities measured at 20% and 80% of depth were taken as average of the water column. In addition to this, detailed topographical data (X, Y, Z bed, Z water level) were collected in an irregular manner, but on a much denser basis then the other set of points. The purpose of this second data set was to allow preparation of channel topography for a 3D hydraulic model over the reaches, which in turn (after calibration) would provide practically infinite amount of additional samples of velocities and depths. Unfortunately, the CFD models never reached a stage of development what would allow to use them for this purpose, and therefore, the statistical experiments were based only on directly collected data.

At Cruick altogether 1913 points of which 216 include velocity, surface flow type and substrate data were collected on a 150 m long and about 5-10 m wide river reach. At Tarf, 4788 points including 188 with velocity, surface flow type and substrate data were collected on a 200 m long and about 5-15 m wide stream reach.

The third river selected was Nidelva, already mentioned in section 2.1.2. Measurements at Nidelva were carried out during autumn 2002 and followed the same method of data collection as at the two rivers in Scotland. A short study site was selected at Trekanten reach on the lower part of Nidelva, in the Trondheim area where the main stem of river flows right to an island. The left side-arm was suitable for our study, providing roughly similar flow and depth ranges as Cruick and Tarf. Section A.1.1 provides some further details on the river and the study site. At Nidelva, the reach was about 70 m long and 5-10 m wide, and in 39 sampling points, velocity, surface flow type and substrate data were collected.

After collecting data from sampling points, the reaches were surveyed according to the NMCM. The samples were collected independently from the HMU survey and the positions of the sampling point were assigned to the HMUs later in a GIS. The maps of HMU surveys and positions of sampling data points on the three sites are shown on Figure 2.29.

Table 2.15 shows the data collected at Nidelva to explain its structure. The header "ID" shows a unique identification for each sampling point, "Dep" stands for depth, "Vbot", "Vmean" and "Vsurf" for bottom, mean and surface velocities respectively, "Subs" for substrate code and "Surf" stands for surface flow type. For this latter two, the categories from Raven et al. (1998) were used (this work commonly known as the RHS report in the UK). The categories are presented here for convenience in Table 2.16.

The values of bottom velocities are missing from this table because in Nidelva there was no capacity to collect those; however, they were measured in the two other rivers. Depth was measured to the closest centimetre by a measuring pole and velocities to the closest millimetre per second by propeller instruments.

Guidelines presented by and tools provided in the works of Gordon et al. (2004), Townend (2002) and Johnson and Kuby (2004) were used for assistance in statistical analyses. The calculations were carried out in Microsoft Excel 2003 and Minitab 14.

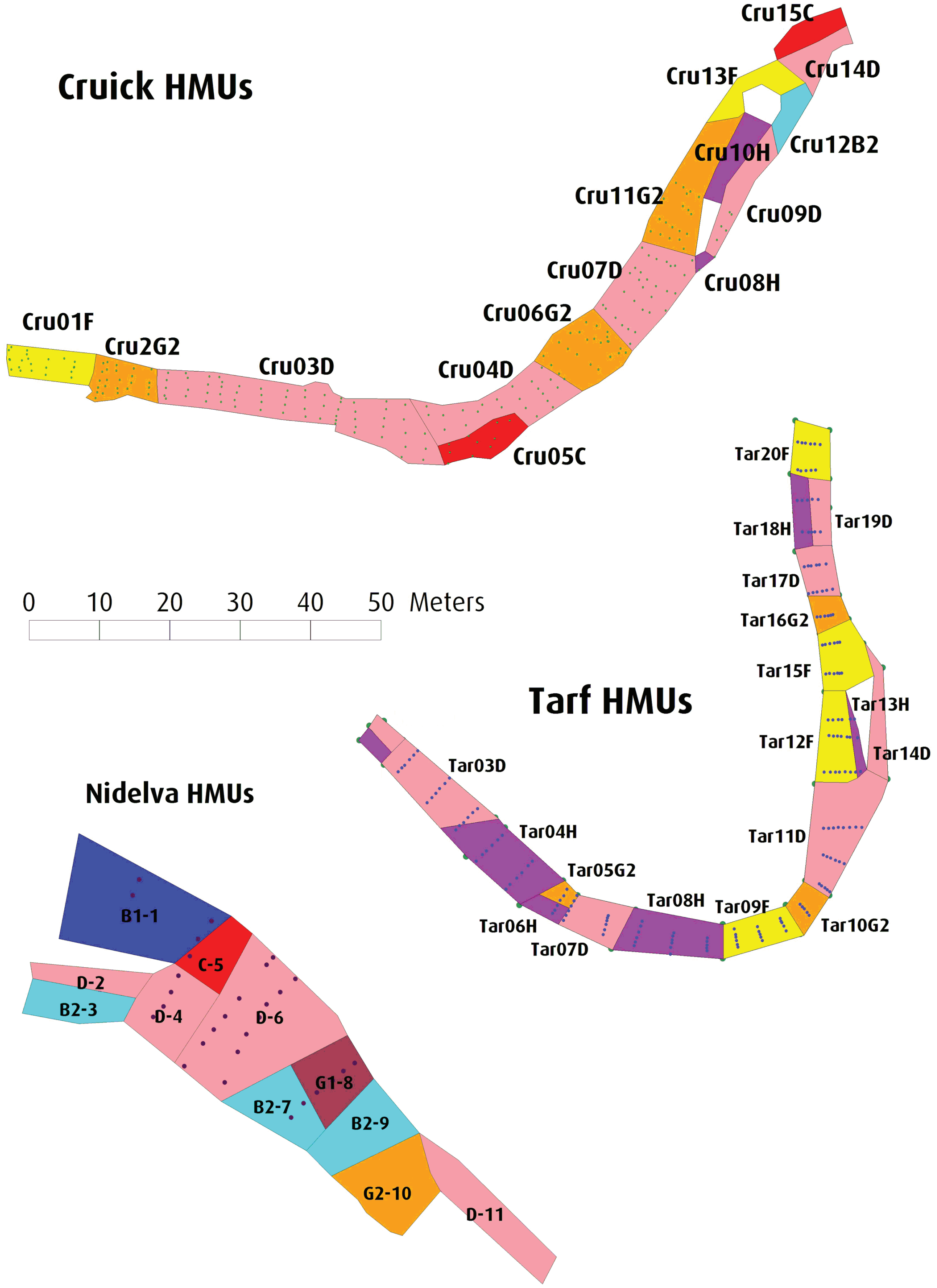


Figure 2.29: HMU survey map and sampling points of hydromorphological parameters on Cruick Water by Newtonmill, on Water of Tarf by Tarfside farm and on Nidelva Trekanten reach

Table 2.15: Example of collected data on Cruick, Tarf and Nidelva.

River	ID	X	Y	Z	Dep (m)	V_{bot} (m/s)	V_{mean} (m/s)	V_{surf} (m/s)	Subs	Surf	HMU
Nid	21	114.9	104.01	98.84	0.82	*	0.425	0.443	GR	RP	B1
Nid	22	112.99	101.43	98.85	0.82	*	0.789	0.789	GR	SM	B1
Nid	33	104.61	109.89	98.64	1.05	*	0.434	0.529	GR	RP	B1
Nid	34	103.69	107.65	98.63	1	*	0.542	0.568	GR	SM	B1
Nid	35	103.2	104.2	98.89	0.83	*	0.638	0.655	PB	RP	B1
Nid	11	126.19	76.07	99.02	0.6	*	0.703	1.132	GR	RP	B2
Nid	13	127.96	78.1	99.01	0.6	*	0.651	0.798	GR	RP	B2
Nid	23	111.78	99	98.95	0.7	*	0.807	0.763	GR	SM	C
Nid	25	110.17	96.22	99.3	0.32	*	0.282	0.382	GR	RP	D
Nid	26	109.14	93.89	98.98	0.68	*	0.339	0.408	GR	SM	D
Nid	29	108.04	91.87	99.05	0.58	*	0.391	0.399	PB	RP	D
Nid	30	106.59	90.36	99.13	0.55	*	0.074	0.044	PB	SM	D
Nid	1	126.81	95.79	98.86	0.7	*	0.122	0.213	SA	SM	D
Nid	2	124.64	93.91	98.88	0.76	*	0.495	0.499	GR	SM	D
Nid	3	122.7	92.17	98.96	0.7	*	0.499	0.681	GR	SM	D
Nid	4	121.7	90.3	98.85	0.81	*	0.46	0.694	PB	SM	D
Nid	5	123.62	98.85	99.08	0.53	*	0.209	0.161	GR	SM	D
Nid	6	119.82	87.92	99.08	0.57	*	0.542	0.664	GR	SM	D
Nid	7	118.61	85.41	98.96	0.73	*	0.443	0.43	CO	SM	D
Nid	8	122.69	97.78	98.95	0.65	*	0.303	0.426	PB	SM	D
Nid	9	116.74	81.08	99.28	0.31	*	0.391	0.399	GR	SM	D
Nid	10	118.82	92.99	98.99	0.74	*	0.722	0.698	GR	SM	D
Nid	14	129.85	79.64	99.06	0.52	*	0.382	0.677	BO	RP	G1
Nid	16	132.1	81.34	98.77	0.8	*	0.269	0.763	GR	RP	G1
Nid	17	133.62	82.69	98.71	0.8	*	0.521	0.88	GR	RP	G1
Nid	19	135.23	83.83	99.09	0.5	*	0.798	0.664	GR	RP	G1

Table 2.16: Codes and sizes for categorical variables used in the sampling and in the analysis. Extended from Raven et al. (1998)

Substrate diameter (mm)			
CL	code 1	Clay	<0.002
SI	code 2	Silt	<0.02
SA	code 3	Sand	<2
G	code 4	Gravel	<16
P	code 5	Pebble	<64
CO	code 6	Cobble	<256
BO	code 7	Boulder	>=256

Surface Flow Type		
BW	code 5	Broken Standing Waves
UW	code 4	Unbroken Standing Waves
RP	code 3	Rippled
SM	code 2	Smooth
NP	code 1	No Perceptible Flow

Table 2.17 summarizes the number of sampling points per river and per HMU where depths, surface and mean velocities, surface flow types and substrate composition were measured. Sampling points where any of these was missing are not included.

Table 2.17: Number of sampling points collected with complete set of data in Cruick, Nidelva and Tarf

River	HMU	Number of points with complete data
Cruick	C	10
	D	119
	F	22
	G2	67
	H	1
Cruick Total		219
Nidelva	B1	5
	B2	4
	C	1
	D	22
	G1	4
	G2	3
Nidelva Total		39
Tarf	D	67
	F	56
	G2	16
	H	49
Tarf Total		188
Grand Total		446

Table 2.17 shows that HMU types “A”, “B1”, “B2”, “C”, etc. are under- or not at all represented in the complete dataset. For example, in the case of type C, we see 10 sampling points from Cruick, one point from Nidelva and none from Tarf. There also seems to be little overlapping between HMU types on the three sites, as for example types B1 and B2 are only present in Nidelva, or type F mostly only in Tarf. Such distortions were expected to limit the possibilities to follow the original plans for the tests.

Searching for proof that the 8 HMU types do differ

First the objective to show that all different HMU types (as in the NMCM, e.g. C, D, etc., altogether 8 types) do differ from each other is aimed at. In order to do this, the trivial test of comparing the number of sample points classified correctly and incorrectly were repeated (based on the actual measured/observed values) in HMUs, like in the case of Orkla and Ingdalselva (see section 2.1.5.1). This way, an overview is provided showing whether some HMU types are easier to distinguish from the others and how good or bad the HMU survey results are reflected in the measured features.

Table 2.18 shows the results. In this test, the sampling points are linked with both the surveyed HMU type and with the expected HMU type (from the actual measurement/observation variables). The main diagonal (from top left to bottom right, greyed) shows the percent and number of correctly classified points during the surveys. The table also shows into which other HMUs the wrongly predicted points should have been classified.

For example in the first row we see that altogether 5 sampling points were surveyed to be present in HMU type B1, however, based on the depth, surface velocity, surface flow type and gradient, 4 (80%) confirmed the features of HMU type B1, one point (20%) actually had the characteristics of HMU type C.

Table 2.18: Comparison of surveyed and expected point-HMU relations. Numbers show the number of sampling points and percentages of the actual correct and wrong proportions for each surveyed HMU type.

Surveyed HMUs	Expected HMUs								
	B1	B2	C	D	E	F	G1	G2	H	Total
B1	80% 4		20% 1							100% 5
B2	0%	50% 2						25% 1	25% 1	100% 4
C	9% 1	0%	73% 8	18% 2						100% 11
D	1% 3	11% 23	3% 7	72% 149				1% 3	11% 23	100% 208
F					3% 2	41% 32			56% 44	100% 78
G1	50% 2	50% 2								100% 4
G2		28% 24		21% 18			1% 1	45% 39	5% 4	100% 86
H		24% 12		58% 29				6% 3	12% 6	100% 50

Table 2.18 shows that no HMU type A was either surveyed or expected in either of the three rivers (thus the row for type A is missing) and that even though no HMU type E was surveyed (row for type E is also missing), it was found in two sampling points wrongly classified as type F-s. HMU types B1, B2, C and D were mostly correct (or equally correct and wrong in case of B2). This is concluded because percentages in the diagonal of these types are higher than any other value in the same rows respectively. HMU types F, G1, G2 and H were mostly incorrectly classified. Note that all wrongly surveyed HMU types have broken surface. Looking at the row of type F for example, it is shown that out of 78 surveyed sampling points appointed to F type areas, only 32 (41%) had the characteristics of type F. 44 points (56%) had actually characteristics of type H. In case of G2 it is important to note, that even though points of this HMU type were mostly incorrectly surveyed to be G2 types (39 cases of 86 total or 45% of 100% correct), still among all the actual types the sample points fall in, the correct type dominated. 24 points had actually type B2, 18 points type D, 1 point type G1 and 4 points type H characteristics. Interestingly, the sampling points classified as points in HMU type H mostly showed characteristics of type D (29 cases of 50 total or 58% of 100%).

Summarizing the analysis of Table 2.18 we see that the HMU survey of the NMCM classifies areas in rivers into similar types that do not have exactly similar characteristics. The physical features of the different HMU types vary to some extent, and therefore, a simple comparison of their mean values seems to be insufficient to provide basis to distinguish between HMU types. Since here similarities/differences between HMU types are important, those with few samples should be excluded from further analysis. These are HMU types A, B1, B2, C, E and G1 and so this section focuses further on the comparison of HMU types D, F, G2 and H.

To continue with the analysis, it is necessary to carry out some exploratory data analysis. Four (three in case of Nidelva) numerical variables (depth and two or three velocity values) and two categorical variables (substrate class and surface flow type class) were collected. The latter two would limit the possibilities of applicable tests and therefore are converted to numerical categories. This is possible because classes of these variables actually represent gradually increasing substrate sizes and (sort of) wave heights or relative energy loss reflection on the water surface.

Normality of the data was tested by means of probability plots and the Anderson-Darling test for the three numerical variables registered in all three rivers per HMU types. The plots display the 95% confidence interval and the numerical values displayed are means, standard deviations, number of samples, Anderson-Darling values and probability values. Figure 2.30 shows analysis of depth samples ("Dep" on the plot), Figure 2.31 mean velocities ("Vmean") and Figure 2.32 surface velocities ("Vsurf").

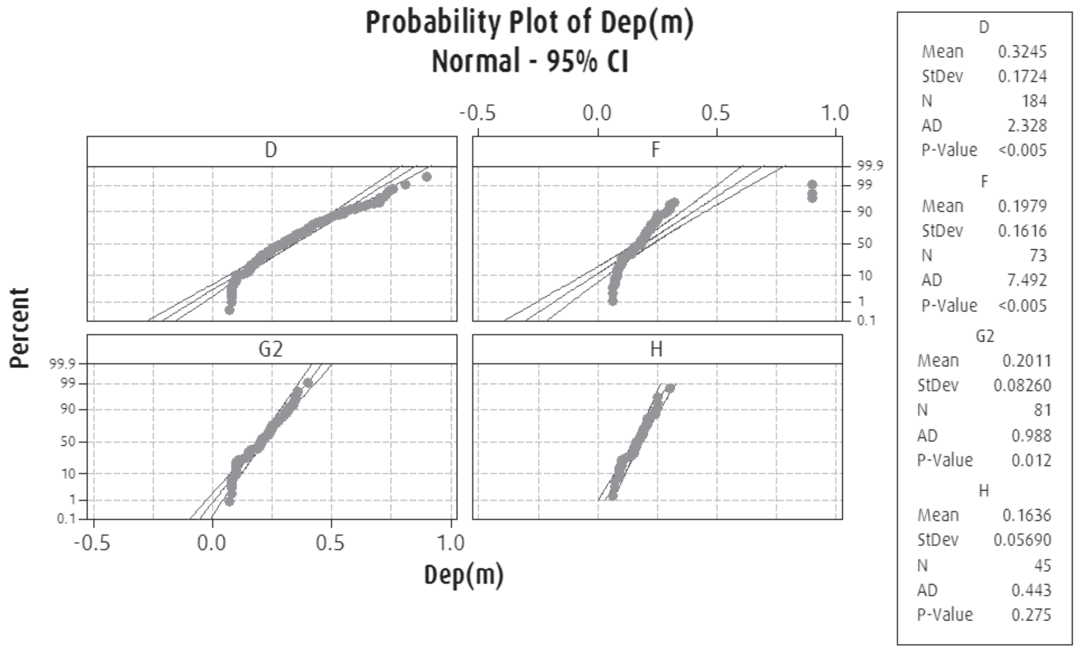


Figure 2.30: Normality test of depth samples in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

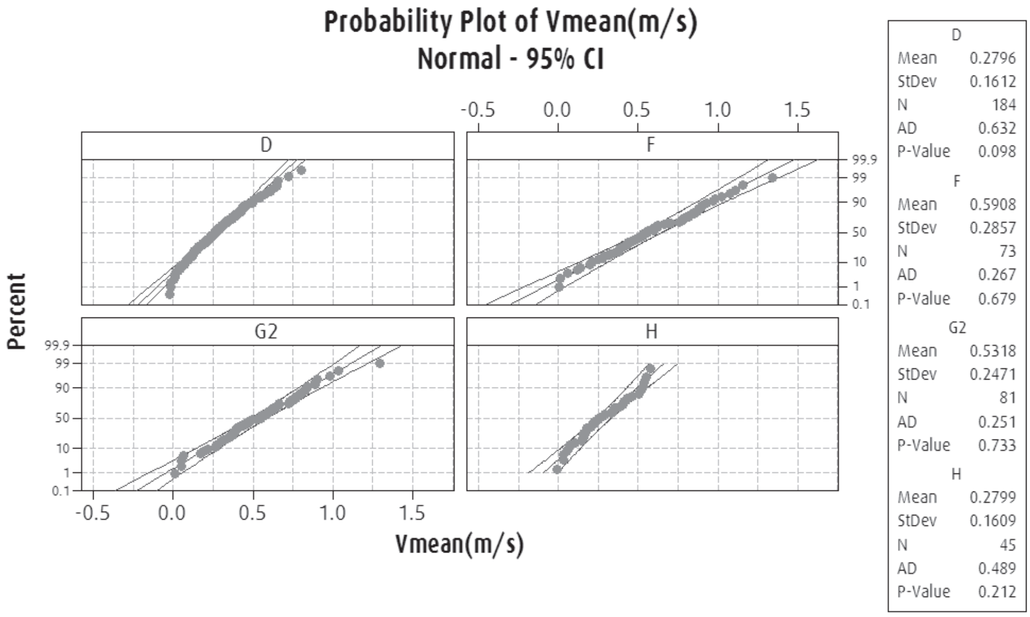


Figure 2.31: Normality test of mean velocity samples in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

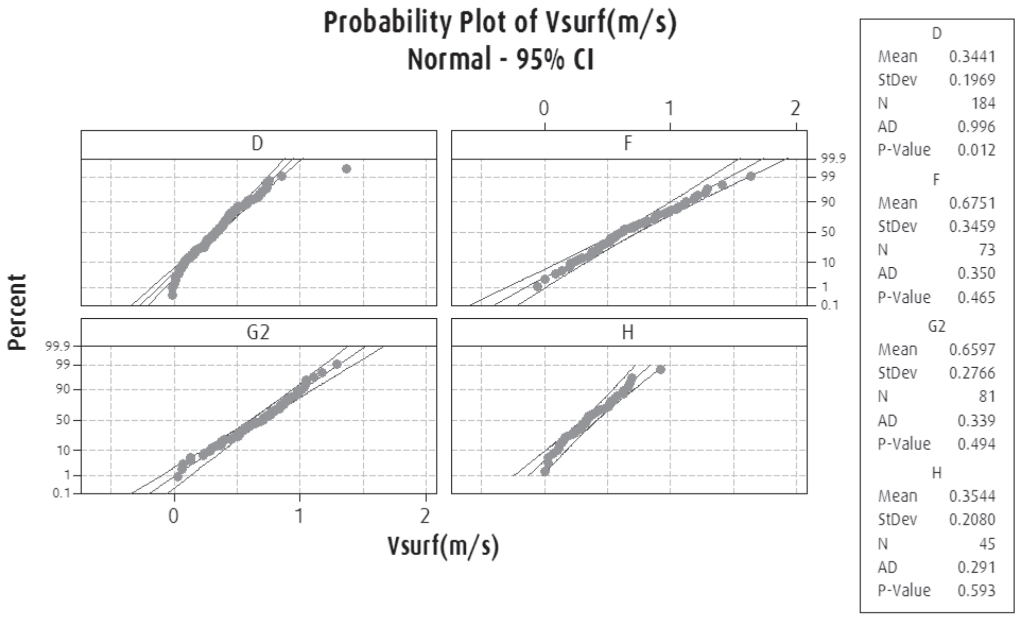


Figure 2.32: Normality test of surface velocity samples in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

Trying to keep the experiment simple, performing analysis of variances (one-way ANOVA) on the samples was aimed at. It is known that this test compares only the means of the populations and it was already suspected from the analysis of Table 2.18 that there are other statistics as well that might be important here. However, this test could serve as the first level of differentiating between HMU types.

In order to perform ANOVA the populations must be normally distributed and have equal variances. The plots and the numerical results above show that in case of depth samples, normality is probably not achieved in the sample from HMU types D, F and G2, as p-values here are below 0.05. All velocity samples are probably normally distributed except surface velocities from HMU type D.

Since it is desireable to use all five variables in the analysis and these are not all normally distributed or excluded so far from the analysis, principal components are sought. These may both reduce the number of variables to be used in the tests and thereby simplify our methods while at the same time keep the features of the original dataset. Principal component analysis (PCA) is performed on the complete set of the five variables, testing for correlation between them. The scree plot is shown on Figure 2.33. The scree plot displays the component number with the related eigenvalues (which are the variances of the principal components) of the correlation matrix.

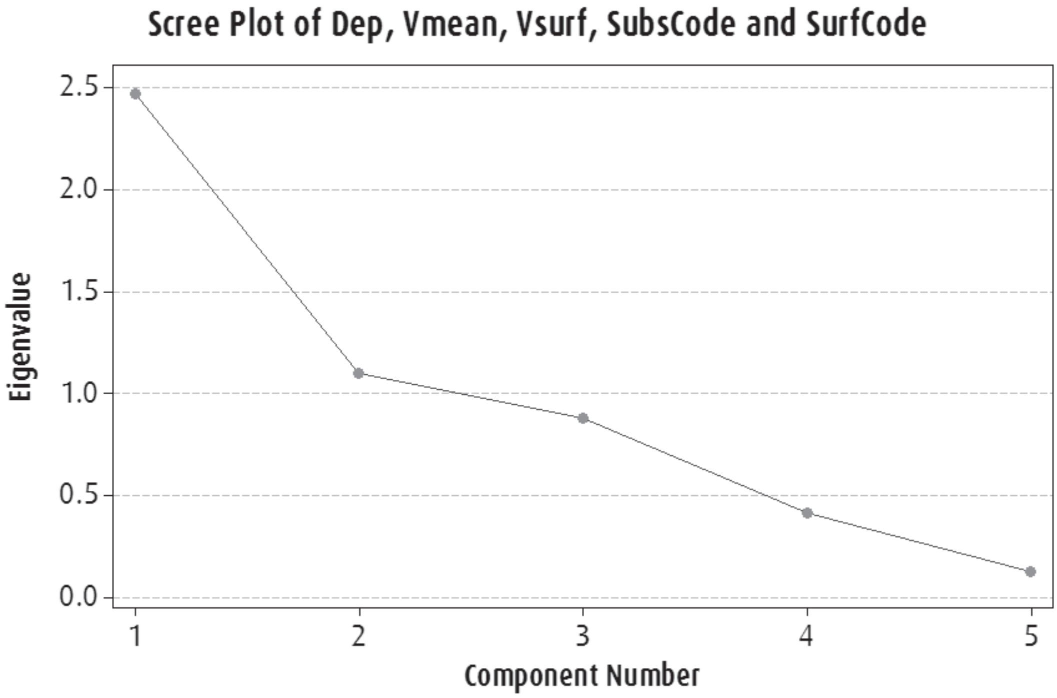


Figure 2.33: Scree plot of depth, mean and surface velocities, substrate code and surface code to determine the number of principal components for the PCA analysis

The plot does not show a clear flattening shape at higher principal component values. As epected, components 2 and 3 have almost similar effect on the data and 4 and 5 follows the descending trend of the graph. We could either select only one component (because only component no.1 provides clearly higher eigenvalue than value 1, or select three components, as they might divide the rapidly increasing and flattening parts of the graph. Normality tests carried out on the first three principal components show that component 1 is likely to provide normal distribution in all four HMU types (Figure 2.34), whereas components 2 (Figure 2.35) and 3 (Figure 2.36) are probably not normally distributed in HMU types D, F, G2 and D, H respectively. In order to maintain data integrity, we must use the same amount of principal components for all HMU types and therefore we must use only one, which is noted PCA1 further on. The coefficients are shown in Table 2.19.

Table 2.19: Coefficients of the PCA for calculation of the first three components

Variable	PC1	PC2	PC3
Dep	0.092	-0.853	-0.383
Vmean	-0.577	-0.214	0.095
Vsurf	-0.577	-0.255	0.099
SubsCode	-0.245	0.345	-0.902
SurfCode	-0.516	0.208	0.143

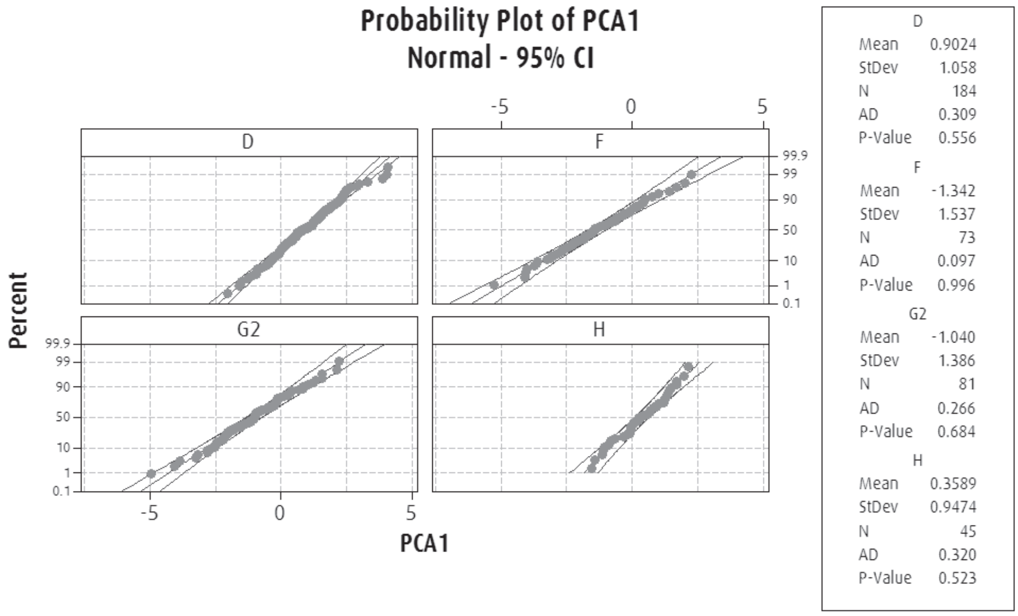


Figure 2.34: Normality test of component 1 in the PCA in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

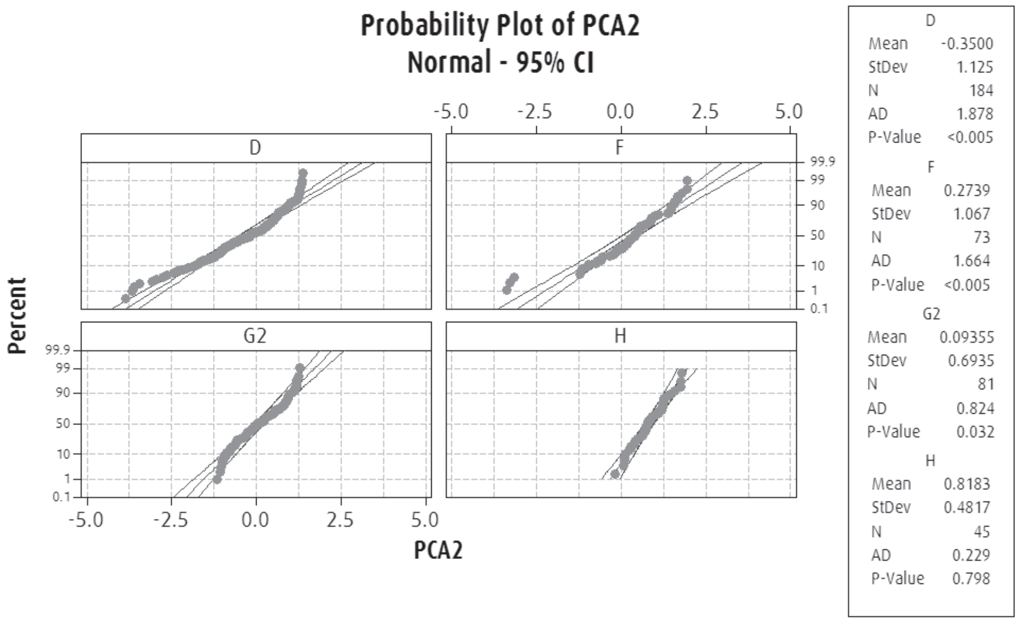


Figure 2.35: Normality test of component 2 in the PCA in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

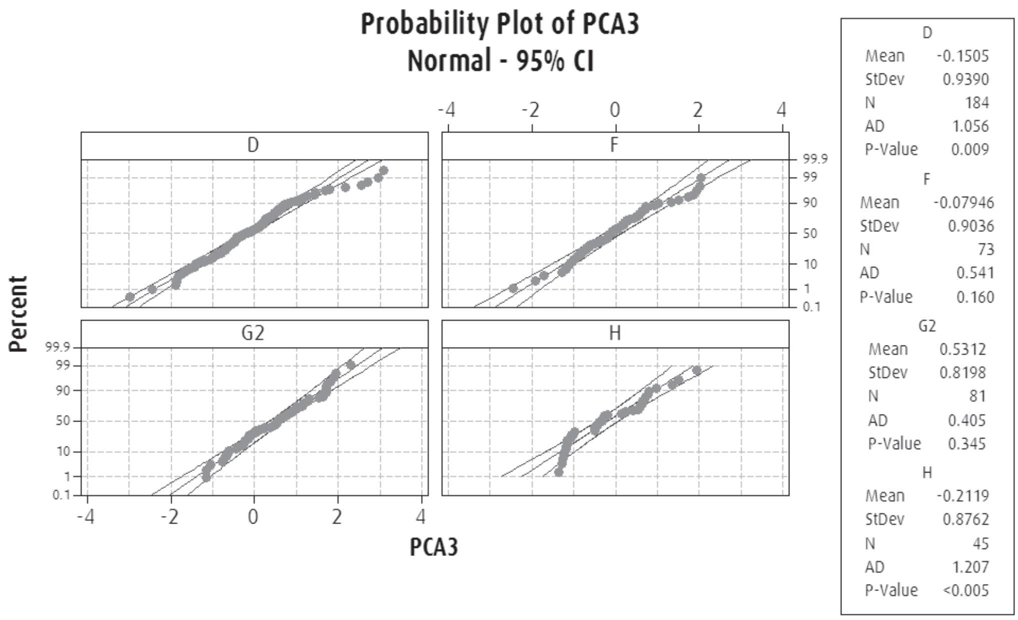


Figure 2.36: Normality test of component 3 in the PCA in HMU types D, F, G2 and H. Theoretical normal distribution and 95% confidence intervals (CI) are shown by lines, the samples by points. P-values are calculated by the Anderson-Darling test.

Besides normality, equal variances between the samples based on PCA1 must also be checked. PCA1 is a linear combination of the five original variables. This may be tested by the F-test. The null-hypothesis is that there is no difference between the variances of the populations where the samples came from. Pairwise checks of all possible combinations show that only samples from HMU types D-H and F-G2 have probably equal variances (Figure 2.37). In cases of D-F, D-G2, G2-H and F-H the p-values in the F-tests were below 0.05, hence in each comparison one of the populations has significantly larger variation than the other. The figure only shows tests for the groups with equal variances.

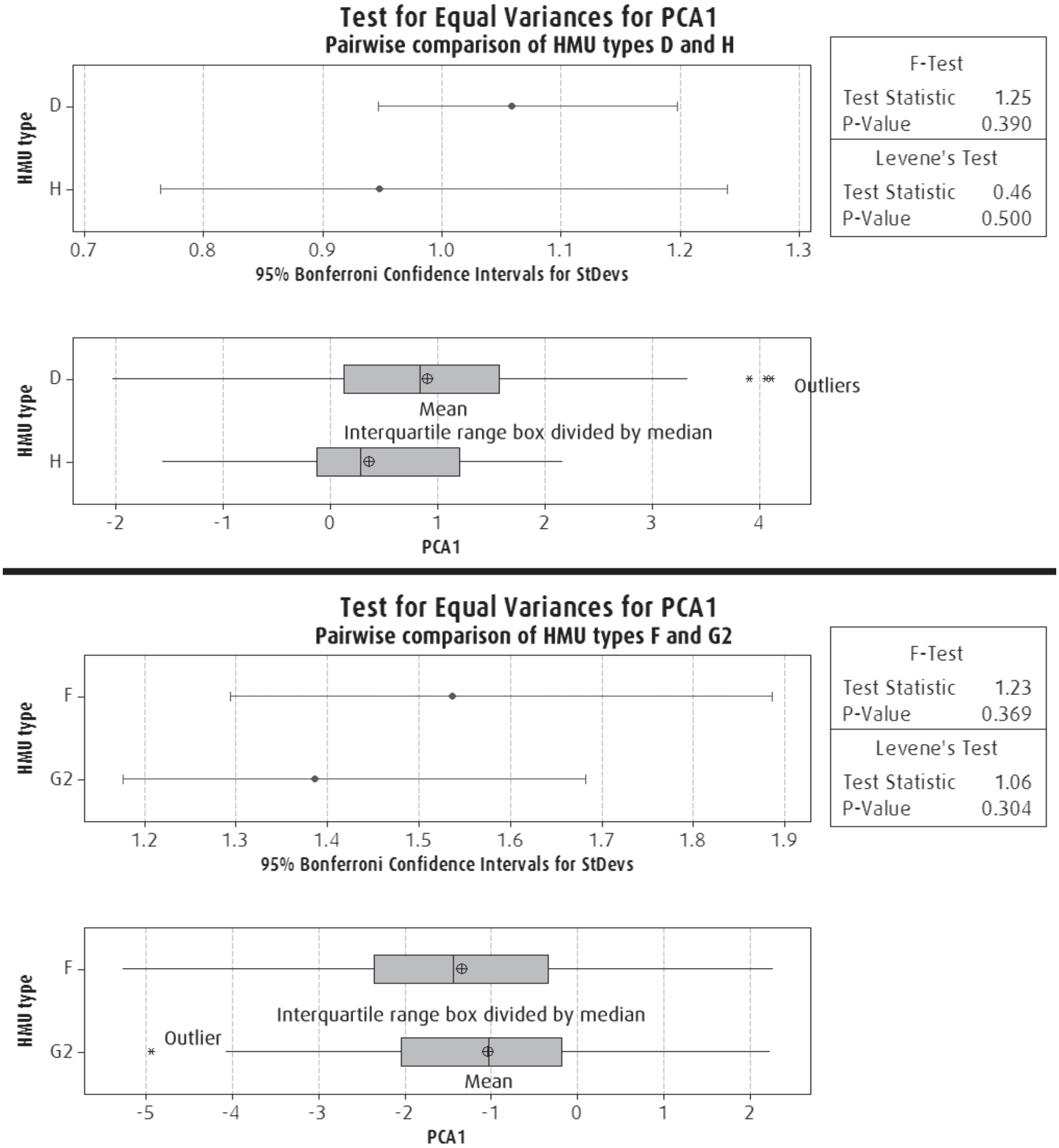


Figure 2.37: Tests for equal variances between HMU types D-H (above) and F-G2 (below)

Now we finally reached the stage where ANOVA can be performed, however our conclusions will be limited to comparisons of two pairs of HMU types instead of 64.

Table 2.20: Results for: F-G2 (One-way ANOVA: PCA1 versus HMU type)

Source of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P
Between groups	1	3.50	3.50	1.64	0.202
Within groups	152	323.78	2.13		
Total	153	327.28			

Table 2.21: Results for: D-H (One-way ANOVA: PCA1 versus HMU type)

Source of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P
Between groups	1	10.68	10.68	9.92	0.002
Within groups	227	244.39	1.08		
Total	228	255.07			

HMU type	N	Mean	Standard deviation
D	184	0.902	1.058
H	45	0.359	0.947

Table 2.20 tells that there is no significant difference between the means of populations F and G2 ($p > 0.05$). On the other hand Table 2.21 shows that the types D and H have significantly different means ($p < 0.05$). As a remainder it is noted that HMU type

- D has smooth surface, moderate gradient, slow flow and is shallow;
- F has broken surface, steep gradient, fast flow and is shallow;
- G2 broken surface, moderate gradient, fast flow and is shallow;
- H broken surface, moderate gradient, slow flow and is shallow

but in case of most HMU types it was not possible to show the differences due to lack of or incompatible data.

Concluding this limited series of tests aiming to prove the differences between the eight HMU types, it was found that based on the parameters of depth, surface flow type, surface and mean velocities and dominant substrate size (1) there are no differences between HMU types F and G2 and (2) there are differences between HMU types D and H.

These conclusions are not surprising because types F and G2 only differ in surface gradient, which parameter was excluded from the analysis and D and H differ in their surface flow types, which was included in the analysis. Unfortunately, our data does not allow drawing any further conclusions regarding the other HMU types.

Searching for proof that HMUs, as separate entities in the water body, do exist

This test needs a different approach than the previous, as the number of populations to compare is large and both the amount and quality of the describing data varies among these. On the Cruick samples by point measurements of 9 HMUs were collected, of which one is divided into two (Cru03D and Cru04D) to fulfil the predefined surveying requirements. On the Tarf, 14 HMUs were sampled, which are surveyed as 17 entities, and on Nidelva, 5 HMUs were sampled that are surveyed as 6 separate entities. A combined map of the three rivers is shown on Figure 2.29 (see above).
Cluster analysis of the observations seem to be a useful way to investigate this problem, because the theory does not build on prerequisites like normal or similar shaped distributions between the populations to compare, makes use of any number of parameters (multivariate) with the possibility of different types, such as numerical or categorical as well. For the sake of simplicity, it was decided to separate the data from the three reaches and instead of looking for 30 (9+15+6) HMUs among the clusters, separate analyses were carried out for each of them. Table 2.22 shows the number of sampling points per river, HMU type and HMU entity in order to have a better overview of the data.

Table 2.22: Number of sampling points per river, HMU type and HMU entity in Cruick, Nidelva and Tarf

River	HMU type	HMU entity	Number of sampling points
Cruick	C	Cru05C	10
	D	Cru03D	61
		Cru04D	22
		Cru07D	29
		Cru09D	6
	F	Cru01F	19
	G2	Cru02G2	24
		Cru06G2	24
		Cru11G2	18
	H	Cru08H	1
Cruick Total			214
Nidelva	B1	B1-1	5
	B2	B2-2	2
	C	C-5	1
	D	D-6	10
		D-4	4
	G1	G1-8	4
Nidelva Total			26
Tarf	D	Tar03D	7
		Tar07D	10
		Tar11D	19
		Tar17D	12
		Tar19D	4
	F	Tar09F	16
		Tar12F	15
		Tar15F	12
		Tar20F	11
	G2	Tar05G2	5
		Tar10G2	5
		Tar16G2	5
	H	Tar04H	14
		Tar06H	3
		Tar08H	17
		Tar13H	4
		Tar18H	6
Tarf Total			165
Grand Total			405

Cluster analysis of observations builds on the grade of similarity between the individual samples. The individual samples are grouped into larger and larger clusters based on their "distance" from each other. The distance (performing as similarity measure) method is to be selected by two functions. These are the distance measure and the points of the cluster between which the distance is measured. The selection of these two features may dramatically change the resulting cluster structure.

Therefore, two combinations of the clustering features were tested. Test 1 used "Single linkage" and "Manhattan" distance measure, while test 2 used "Centroid linkage" and Squared Pearson" distance measure. Table 2.23 provides a short overview of the measures and methods used in the analyses. The two tests reflect the different strategies of grouping. In case of "Single linkage", the distance between the closest neighbours does not change as the clusters are joined into fewer and fewer of groups, whereas in case of "Centroid linkage" the coordinates of the centroid continuously changes as new and new points get joined in the cluster.

"Manhattan" distance measure produces a value that incorporates the classical eucledian meaning of distance, but makes it less sensible to outliers. Squared Pearson measure standardizes the coordinates (variables) and therefore is not sensitive to differences in the data types. See Townend (2002) or Johnson and Kuby (2004) for further details about the methods.

In case of Cruick Water the number of clusters were set to 10, in case of Water of Tarf to 17 and in case of Nidelva to 6, similarly to the number of HMU entities shown in Table 2.22.

Table 2.23: Short description of distance measures and linkage methods used for Cluster analysis of observations

Distance measure	**Description**
Manhattan (or city block)	Calculated as the average distance of all dimensions (variables) between points and/or clusters
Squared Pearson	Calculated as sum of square distances divided by variances of all dimensions (variables) between points and/or clusters
Linkage method	
Single linkage (or nearest neighbour)	Takes the minimum distance between points of clusters
Centroid linkage	Takes the distance between cluster centroids The coordinates of the centroid is given by the mean of all separate coordinates (values of variables)

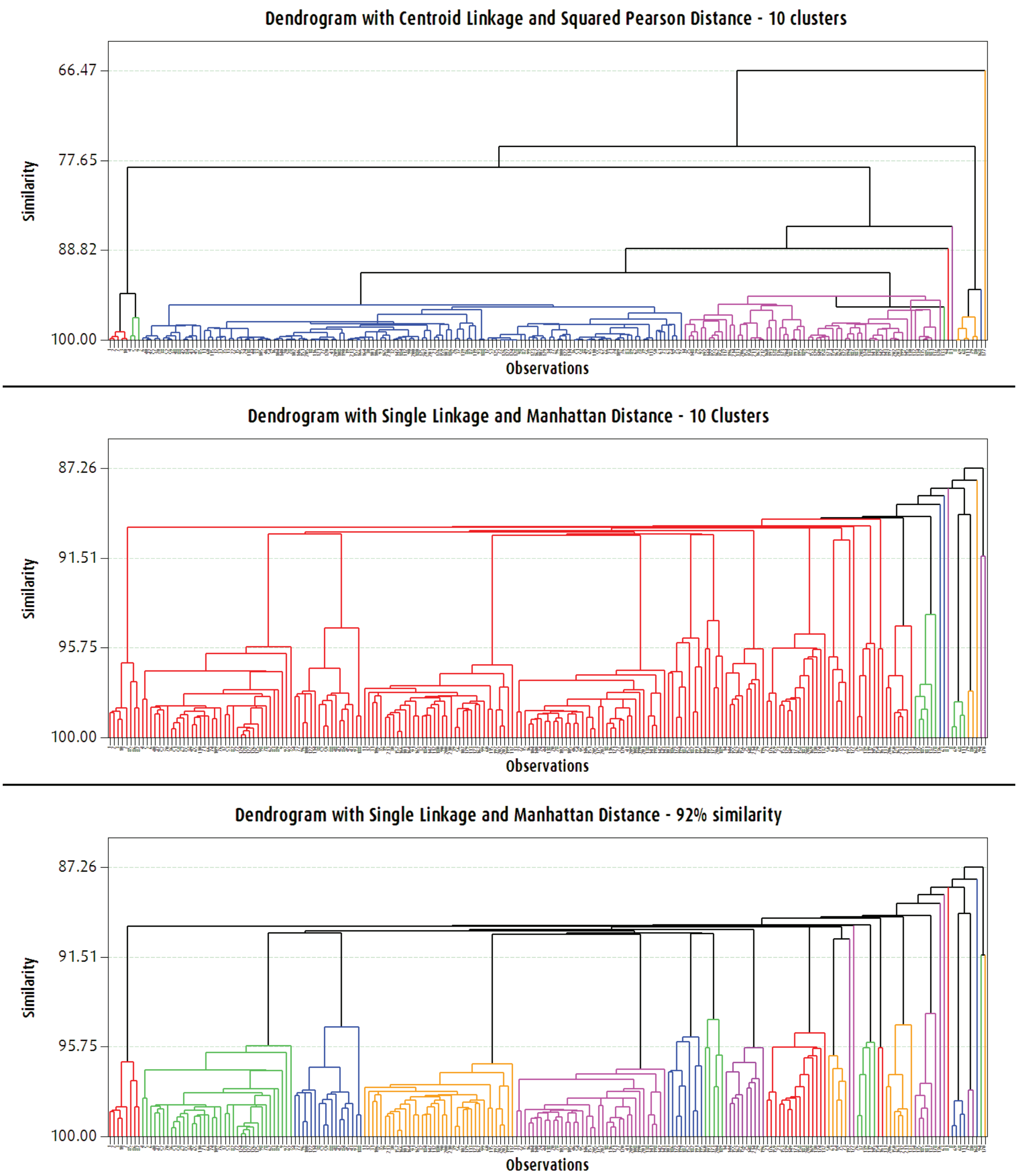


Figure 2.38: Dendrograms of different cluster analysis techniques applied on data collected at Cruick Water by Newtonmill

Figure 2.38 shows three dendrograms generated with data from Cruick. The first is generated using Centroid linkage and Squared Pearson distance measure to gain 10 clusters, the second and the third using Single linkage and Manhattan distance, to gain 10 clusters and to split clusters at 92% similarity respectively. This latter seemed useful, as the given number of 10 clusters did not seem to succeed splitting the data, only selecting the outliers. It is shown that most clusters are red on the middle graph, but at approximately 92% similarity, the number of clusters radically increases. This is the reason the third graph was generated, which resulted in 24 clusters.

Using Centroid linkage and Squared Pearson distance measure, the data is grouped into two larger clusters (blue and violet on the graph) and similarity between clusters increases about linearly stepwise. Using Single linkage and Manhattan distance in case of 92% similarity criterion give 7-10 large groups and the same amount of separate individuals and there seems to be two major steps in similarity differences in the cluster structure.

Figure 2.39 shows dendrograms generated with the Tarf data. In this case, both tests seemed to produce approximately balanced groups of data, being less sensible to outliers, and therefore, we did not consider using other clustering methods.

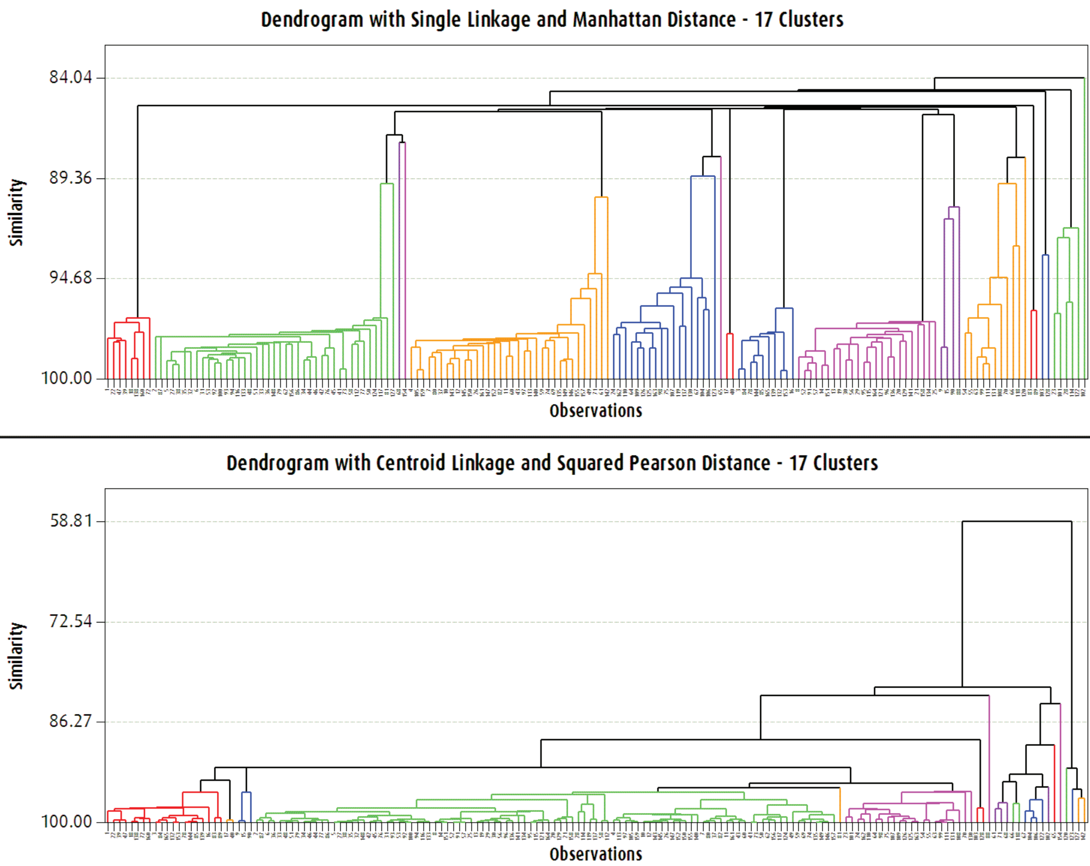
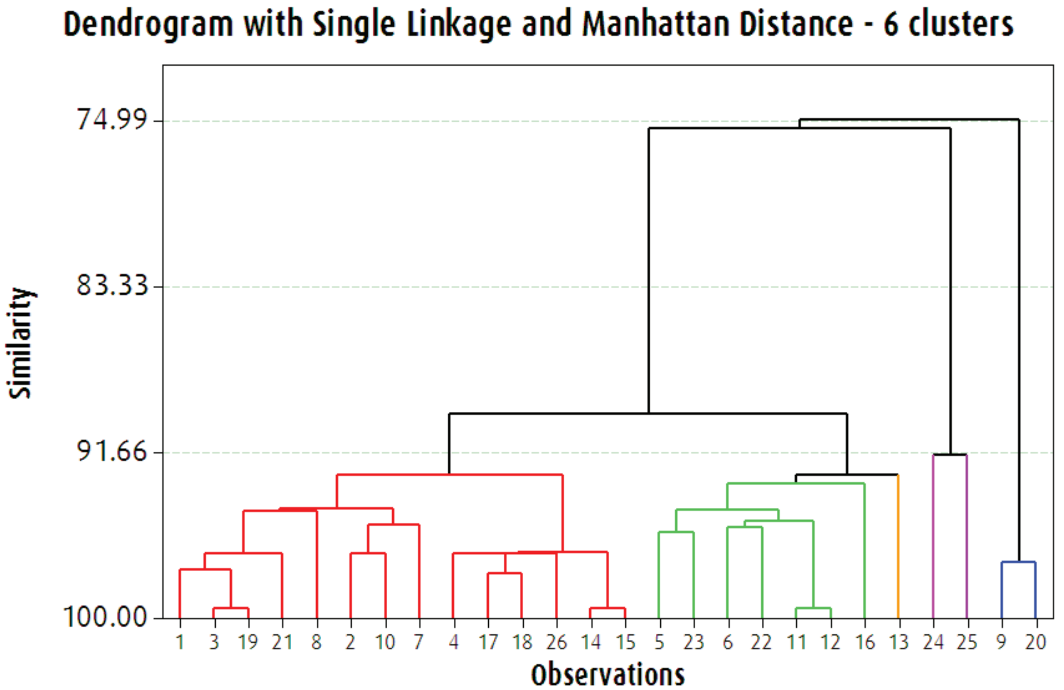


Figure 2.39: Dendrograms of different cluster analysis techniques applied on data collected at Water of Tarf by Tarfside farm

A similar stepwise structure on the Centroid-Squared Pearson test can be seen in case of Tarf as previously in case of Cruick. In case of Single-Manhattan test, there is also a noticeable two-level similarity structure, less obvious though as in the case of Cruick.



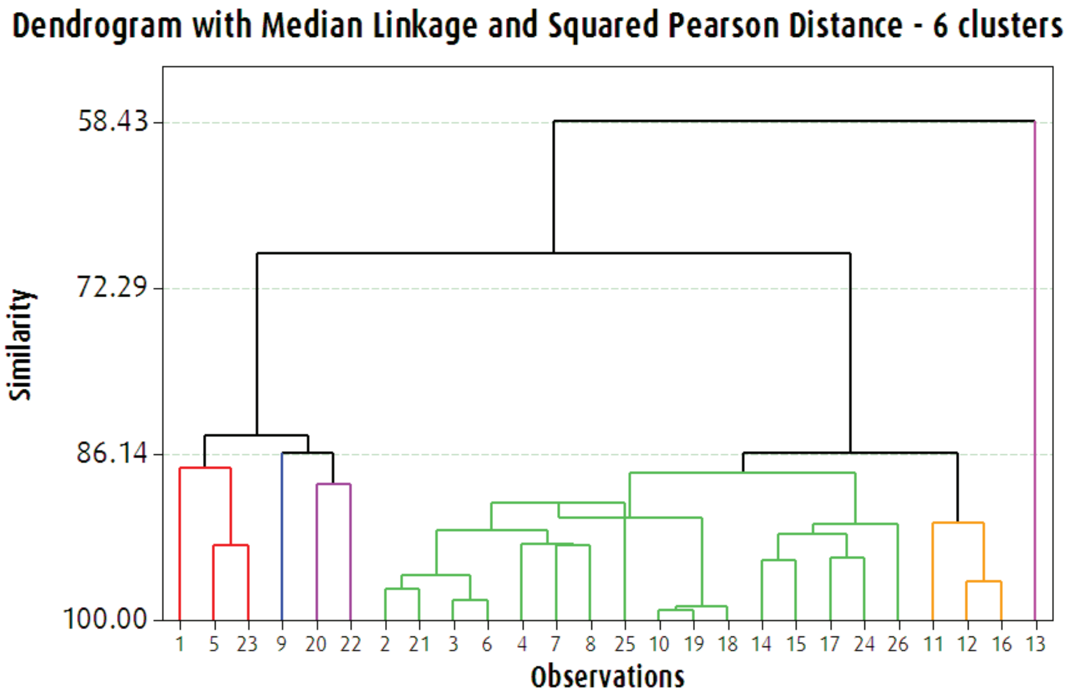


Figure 2.40: Dendrograms of different cluster analysis techniques applied on data collected at Nidelva Trekanten reach

Figure 2.40 shows dendrograms generated from the Nidelva data. Note the fewer sampling points in this case compared to Cruick or Tarf and also the slightly lower similarity in the data. The two-level vs. stepwise gradual similarity is noticeable here as well regarding the Single-Manhattan vs. Centroid-Squared Pearson approaches respectively.

Table 2.24: Clustering results of Cruick data, 10 clusters. Single linkage with Manhattan distance measure above, Centroid linkage with Squared Pearson distance measure below. The percent of number of data sampling points in HMUs are grouped by clusters (1-10, columns)

	Percent of points in rows in clusters 1-10 grouped by original HMUs (Single-Manhattan)									
HMU	1	2	3	4	5	6	7	8	9	10
Cru01F	68						11	16	5	
Cru02G2	83					4	8			4
Cru03D	95	3	2							
Cru04D	86			9	5					
Cru05C	90	10								
Cru06G2	88							13		
Cru07D	93	3				3				
Cru08H	100									
Cru09D	100									
Cru11G2	83						17			

	Percent of points in rows in clusters 1-10 grouped by original HMUs (Centroid-Squared Pearson)									
HMU	1	2	3	4	5	6	7	8	9	10
Cru01F			21		74			5		
Cru02G2			29		67				4	
Cru03D			90	3	7					
Cru04D			82	9	5	5				
Cru05C	50	30	10	10						
Cru06G2			33		63					4
Cru07D			90	3	3		3			
Cru08H					100					
Cru09D			100							
Cru11G2			39		61					

The cluster structure is presented in table form in all three cases and for both tests (three tests in case of Tarf). Table 2.24 and Table 2.25 shows clustering results of Cruick, Table 2.26 of Tarf and Table 2.27 of Nidelva. Ideally, all sample points in HMUs would fall into exactly one cluster and these points would provide the whole population of that cluster. On the other hand it is known, that HMUs are not homogeneous entities and variations within HMUs were expected. The clustering tables are ought to show the magnitude of the intra-HMU variation and frequent inter-HMU links (similarity). As certain HMUs happen to be similar HMU types, more similarity between these than between HMUs of different types were expected regarding the structure of clusters.

Looking at Table 2.24 and Figure 2.41 in case of Single-Manhattan test (upper) it is shown that the majority of the sample points regardless of the surveyed HMU falls into Cluster 1 (first column). However, points in the remaining clusters show some pattern: Cluster 2 gives points mostly to Cru05C, Cluster 4 to Cru04D, etc. What is shown here from the distribution of points between Clusters 2-10, is that Cru04D is very different from the other HMUs, the two other type D HMUs (Cru03D, Cru07D and Cru09D) are somewhat similar to each other as they include points from Cluster 2 and others, just as type G2 and F, which include points from Clusters 6, 7 and 8.

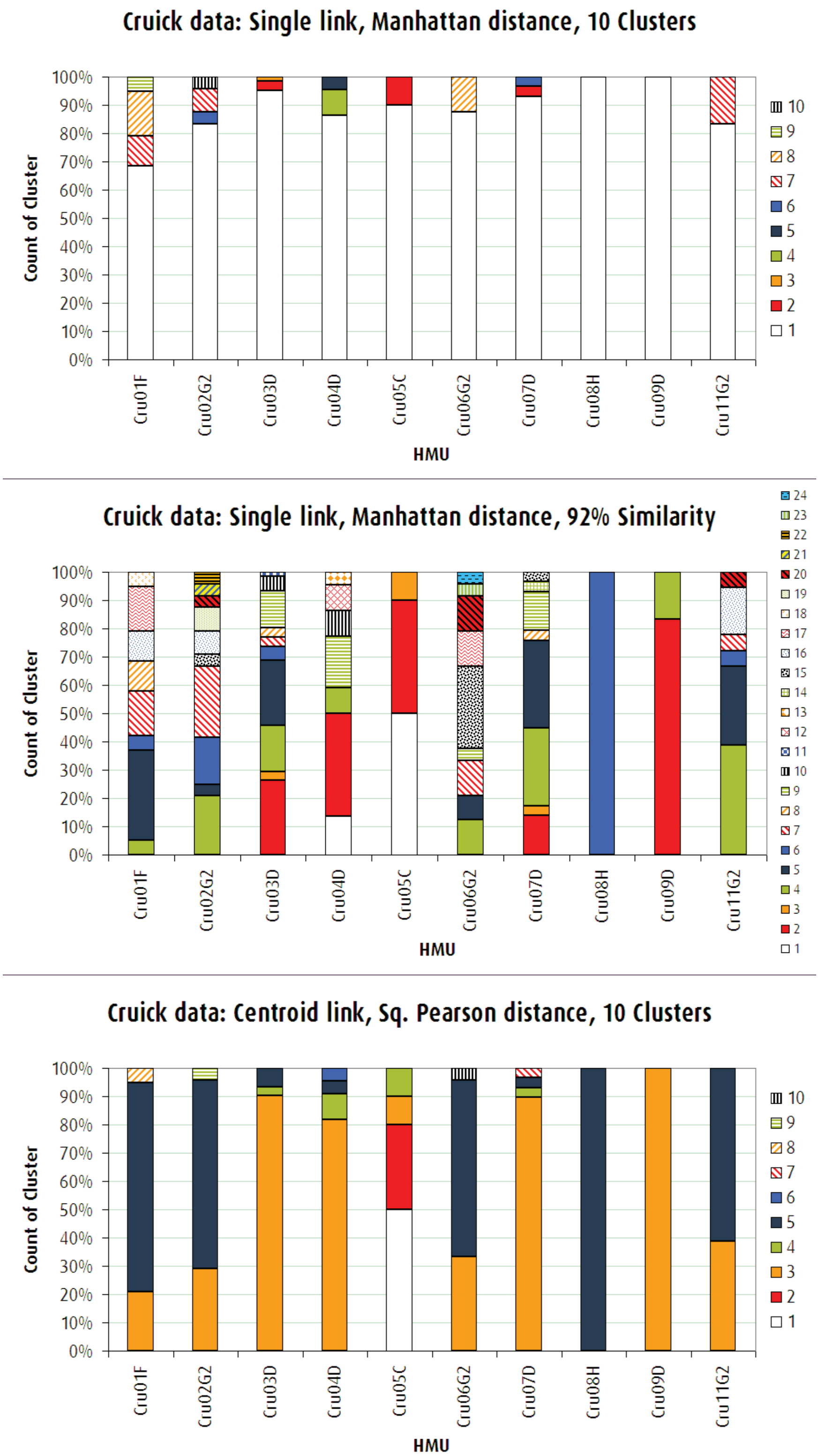


Figure 2.41: Proportional cluster structure for each HMU for Cruick. The graphical representation of Table 2.24.

Looking at the lower table that shows results from Centroid linkage with Squared Pearson distance measure, we note the relative dominance of Clusters 3 and 5. It is difficult to draw conclusions of the table, most data sampling points are grouped around Clusters 3-5, showing little variation. It is found however that while in case of HMU type D-s Cluster 3 dominates the pattern, then in case of HMU type G2-s and F Cluster 5 is more important. Types of F and G2 also include points of Clusters 8-10, which pattern is not found elsewhere. Also the only type C: Cru05C shows a different pattern than the other HMUs, being dominated by points in Cluster 1 and 2.

Table 2.25: Clustering results of Cruick data, 92% similarity (gave 24 clusters). Single linkage with Manhattan distance measure only. The percent of number of data sampling points in HMUs are grouped by clusters (1-24, columns)

Percent of points in rows in clusters with less than 92% similarity (giving 1-24 clusters) grouped by original HMUs (Single-Manhattan)

HMU	1	2	3	4	5	6	7	8	9	10	11	12
Cru01F				5	32	5	16	11				
Cru02G2				21	4	17	25					
Cru03D		26	3	16	23	5	3	3	13	5	2	
Cru04D	14	36		9					18	9		9
Cru05C	50	40	10									
Cru06G2				13	8		13		4			
Cru07D		14	3	28	31			3	14			
Cru08H						100						
Cru09D		83		17								
Cru11G2				39	28	6	6					

…	13	14	15	16	17	18	19	20	21	22	23	… 24
Cru01F				11	16	5						
Cru02G2			4	8			8	4	4	4		
Cru03D												
Cru04D	5											
Cru05C												
Cru06G2			29		13			13			4	4
Cru07D		3	3									
Cru08H												
Cru09D												
Cru11G2				17				6				

Table 2.25 and the middle chart on Figure 2.41 show the result of our attempt to refine the clusters presented in Table 2.24, above. The linkage and distance measures in these cases are similar, the difference is in the division criteria when

building clusters. While in the first case (Table 2.24) the number of final clusters are specified as 10, in the second case (Table 2.25) the grade of similarity as 92% is given. This second strategy results in 24 clusters, among which the sample points seem to be more distributed than in the 10-cluster case. The difference between the only HMU type C: Cru05C and D-s are noticeable, which difference was not obvious in the first approach, but was shown in the Centroid-Squared Pearson test. There is also a slight difference between the only F type: Cru01F and the G2-s: points in Clusters 8 and 18 are not repeated in G2-s. It is more difficult to interpret the increased amount of clusters, but the strategy successfully shows previously hidden features in the data.

The clusters of Tarf samples are presented in Table 2.26 and Figure 2.42. Surprisingly, the Centroid-Squared Pearson clustering provides more compact cluster structure than the Single-Manhattan test, which is opposite to the results from Cruick. Please note that there is a difference in relative data density between the rivers, as in Cruick generally, there are more sample points present in each HMU than in the Tarf. Fewer points may fail covering dominating features of HMUs, which features are more important in the Centroid-Squared Pearson clustering. It is shown that cluster structure from the Tarf data does reflect the HMU survey in a way. Even though choice of clustering parameters resulted in compacting most data points mainly to cluster 2 in the Centroid-Squared Pearson test, the remaining individual points show clear difference from each other. This finding supports our hypothesis, in an unexpected way though. That is, a large proportion of HMUs are somewhat similar to each other, but a few features make them notably different from each other (assuming of course that points represent portions of HMUs of comparable sizes). Whether this difference is statistically significant, is not tested here. Similarly to the Cruick conclusions, we see a slight difference between groups of HMU types C-D and G2-F in both cases of clustering.

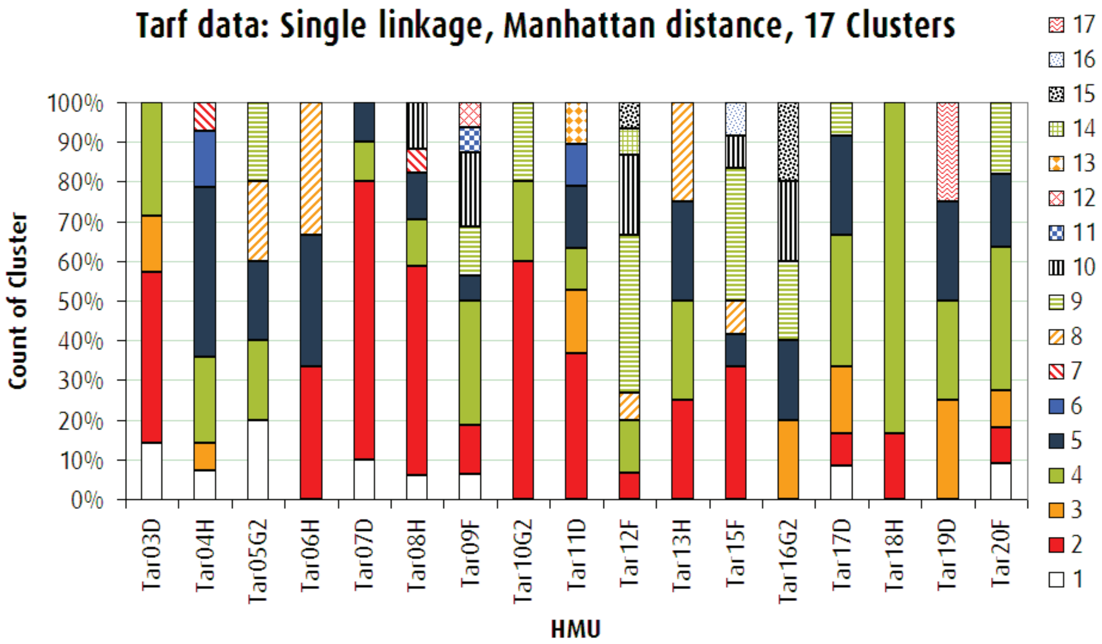
Table 2.26: Clustering results of Tarf data, 17 clusters. Centroid linkage with Squared Pearson distance measure on the top and Single linkage with Manhattan distance measure below. The percent of number of data sampling points in HMUs are grouped by clusters (1-17, columns)

Percent of points in rows in clusters 1-17 grouped by original HMUs (Centroid-Squared Pearson)

HMU	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Tar03D	29	71															
Tar04H	14	64	14	7													
Tar05G2	20	40			40												
Tar06H		100															
Tar07D	10	90															
Tar08H	6	76		6	12												
Tar09F	6	38			19	19	6	6	6								
Tar10G2		80			20												
Tar11D	26	58	5							5	5						
Tar12F		20			53				13			7	7				
Tar13H		100															
Tar15F		42			17			8	8					8	8	8	
Tar16G2	20	20			40								20				
Tar17D	25	67														8	
Tar18H		100															
Tar19D	25	50															25
Tar20F	18	64			18												

Percent of points in rows in clusters 1-17 grouped by original HMUs (Single-Manhattan)

HMU	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Tar03D	14	43	14	29													
Tar04H	7		7	21	43	14	7										
Tar05G2	20			20	20			20	20								
Tar06H		33			33			33									
Tar07D	10	70		10	10												
Tar08H	6	53		12	12		6			12							
Tar09F	6	13		31	6				13	19	6	6					
Tar10G2		60		20					20								
Tar11D		37	16	11	16	11							11				
Tar12F		7		13				7	40	20				7	7		
Tar13H		25		25	25			25									
Tar15F		33			8			8	33	8						8	
Tar16G2			20		20				20	20					20		
Tar17D	8	8	17	33	25				8								
Tar18H		17		83													
Tar19D			25	25	25												25
Tar20F	9	9	9	36	18				18								



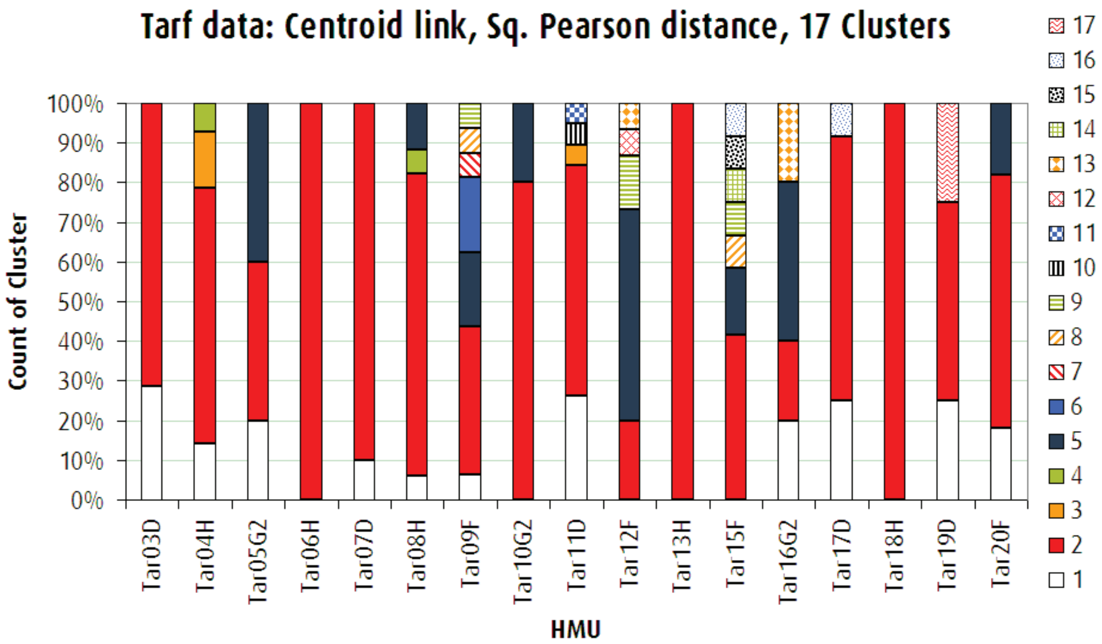


Figure 2.42: Proportional cluster structure for each HMU for Tarf. The graphical representation of Table 2.26

Table 2.27: Clustering results of Nidelva data, 6 clusters. Single linkage with Manhattan distance measure on the left and Centroid linkage with Squared Pearson distance measure on the right. The percent of number of data sampling points in HMUs are grouped by clusters (1-6, columns)

	Percent of points in rows in clusters 1-17 grouped by original HMUs (Single-Manhattan)						Percent of points in rows in clusters 1-17 grouped by original HMUs (Centroid-Squared Pearson)					
HMU	1	2	3	4	5	6	1	2	3	4	5	6
B1-1	60				20	20		100				
B2-7		100								100		
C-5	100							100				
D-4	25	50	25				25	25				50
D-6	70	20	10				20	70	10			
G1-8	50	25		25				50		25	25	

Table 2.27 and Figure 2.45 shows clustering results of Nidelva data. Unfortunately there are only a few sample points collected from this reach and therefore the conclusions regarding increased data needs from the case of Tarf are even more expressed here. We have to be careful drawing conclusions from this dataset, but we do note the differences between the clusters and the similarities between the two D-s in case of Single linkage-Manhattan test. The tests show similarities between B1 and C but one must be aware that HMU C-5 is represented with only one sampling point in this study.

It seemed that the original objective of this series of tests and experiments can only partly be reached, but we noticed other interesting features regarding similarities of HMU types that were worth exploring more.

The Cruick dataset was selected to carry out the further tests. Relative data density per HMU is highest in Cruick, so a better representation of physical features was expected here than in the other rivers. Samples from HMU types D and G2 from the original set were extracted and their differences together with their similarities tested. Only the population of clusters in the Single-Manhattan 92% similarity setup was looked at, as this provided the most diverse (colourful) picture. It was hypothesised that (1) the four D type HMUs are from the same population, (2) the three G2 type HMUs are from the same population and (3) that D or G2 type HMUs are from two different populations. These can be tested with one-way ANOVA again. In tests 1 and 2, we compare clustering results (a sample position in the clustering) from four and three individual HMUs, while in test 3 clustering results from HMU types D and G2 were compared.

The results are shown in Table 2.28, Table 2.29 and Table 2.30. The probability plot of residuals is shown on Figure 2.43, where some non-normality in the data can be noticed, but it was assumed to be in the acceptable range. Test 1 showed that there is no significant difference between any of the population means (type D), test 2 shows that at least two of the populations have significantly different means (type G2) and test 3 shows that there is a significant difference between the populations (D-G2).

Table 2.28 One-way ANOVA test for comparing clusters of samples from HMU-type D

Source	DF	SS	MS	F	P
Class	3	54.64	18.21	1.85	0.141
Error	114	1119.7	9.82		
Total	117	1174.3			

Level	N	Mean	St.Dev.
Cru03D	61	5.066	2.676
Cru04D	22	5.455	4.329
Cru07D	29	5.552	3.236
Cru09D	6	2.333	0.816

Table 2.29 One-way ANOVA test for comparing clusters of samples from HMU-type G2

Source	DF	SS	MS	F	P
Class	2	340.1	170	4.5	0.015
Error	63	2378	37.7		
Total	65	2718.1			

Level	N	Mean	StDev
Cru02G2	24	9.958	6.417
Cru06G2	24	13.125	6.388
Cru11G2	18	7.444	5.382

Table 2.30 One-way ANOVA test for comparing clusters of samples from HMU-types D and G2

Source	DF	SS	MS	F	P
Class	1	1191.50	1191.50	55.71	0.00
Error	182	3892.50	21.40		
Total	183	5083.90			

Level	N	Mean	StDev
D	118	5.12	3.168
G2	66	10.4	6.467

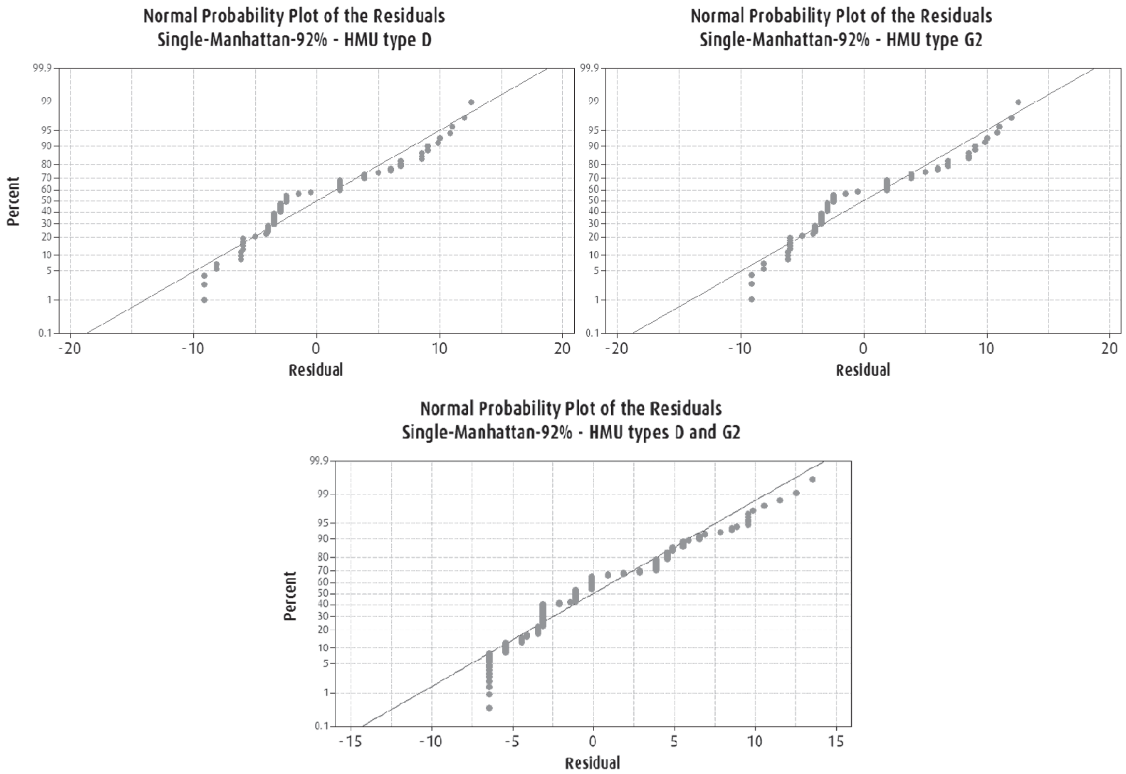


Figure 2.43 Normal probablity plot for the residuals of the ANOVA tests 1, 2 and 3

Tests 1 and 3 resulted as expected, but test 2 gave surprising results. Cluster composition among HMUs of type G2 significantly differed from each other, but among HMUs of type D not. This might indicate two things: either the hypothesis is wrong or there is a difference inherent in the collected data. Naturally this latter one was tried to proove by means of comparing average sample point densities between type D and G2. The values are summarized in Table 2.31. As a reminder, we note that the difference between type D and G2 are in surface flow type and surface flow velocity.

The test would then allow us to assume that the differences in the ANOVA results above are inherent in sample density and not in the absence of HMU type G2. Our first test above already proved the significant differences between samples from G2 and F, which might be considered as a weak proof for this assumption. Another reason is the different distribution of clusters between type D and G2 HMUs shown on Figure 2.44.

Table 2.31: Sample point densities in type D and G2 HMUs in Cruick

HMU type	HMU	N	Area	N/m²
G2	Cru02G2	24	50	0.48
D	Cru03D	61	227	0.27
D	Cru04D	22	114	0.19
G2	Cru06G2	24	91	0.26
D	Cru07D	29	121	0.24
D	Cru09D	6	52	0.12
G2	Cru11G2	18	112	0.16

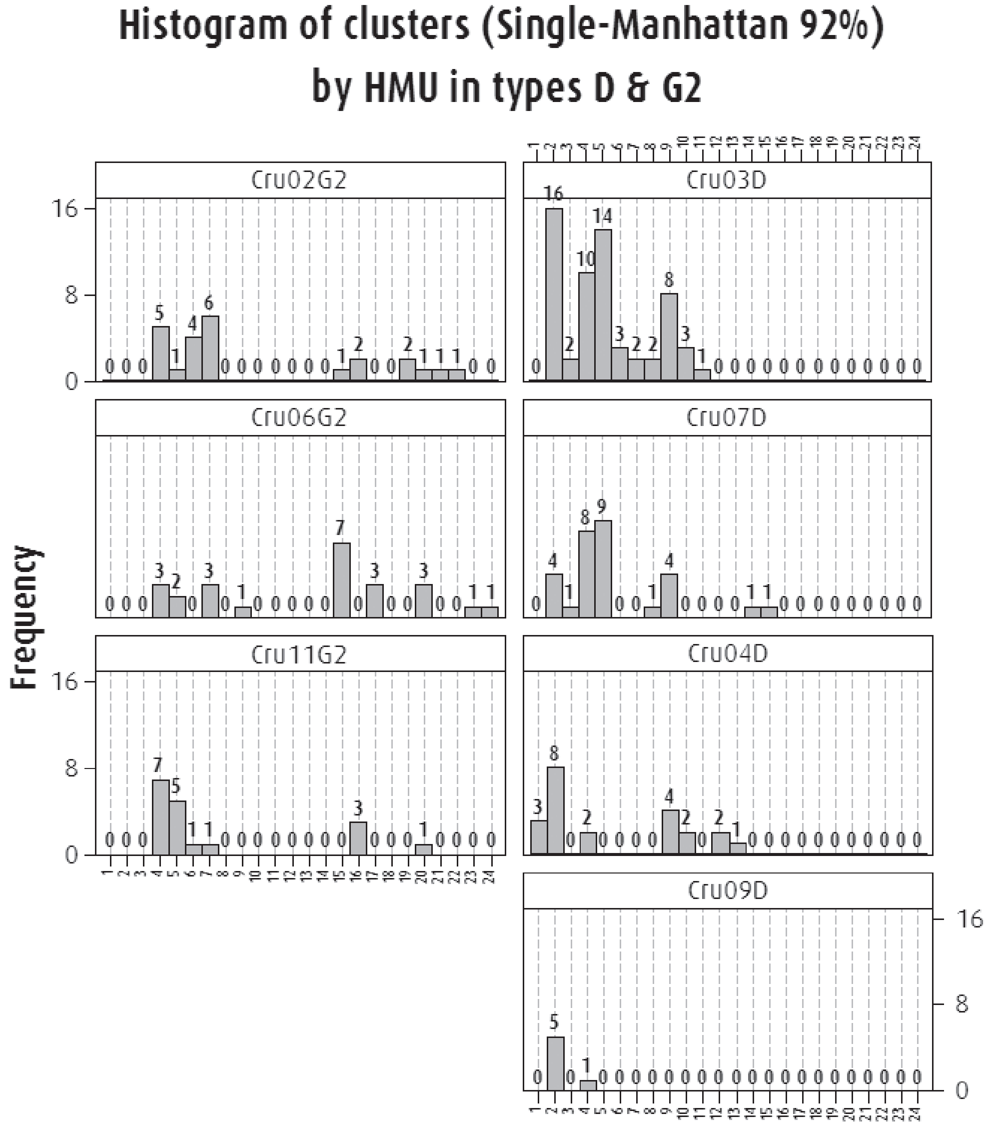


Figure 2.44: Frequencies of the 24 clusters from Single-Manhattan 92% clustering in HMUs of type D and G2 in Cruick

Without providing details, we test for normality (p=0.672 for D and p=0.449 for G2) and equal variances (p=0.171, F-test) between the two groups following the same procedure as above in the previous section. The results allow performing ANOVA.

Table 2.32 shows one-way ANOVA results comparing the two samples of HMUs of type D and G2 in Cruick. The results show that our hypothesis is indeed true, there is probably a significant difference between sample densities. On one hand this does not prove that we found the cause of our unexpected results regarding the previous test showing probably significant differences among cluster composition of G2 types. On the other hand, this might indicate the need for different amount of sampling for different HMU types.

Table 2.32: One-way ANOVA results comparing sample densities inHMUs of type D and G2 in Cruick

Source	DF	SS	MS	F	P
Class	1	0.016	0.016	1.219	0.3198
Error	5	0.067	0.013		
Total	6	0.083			

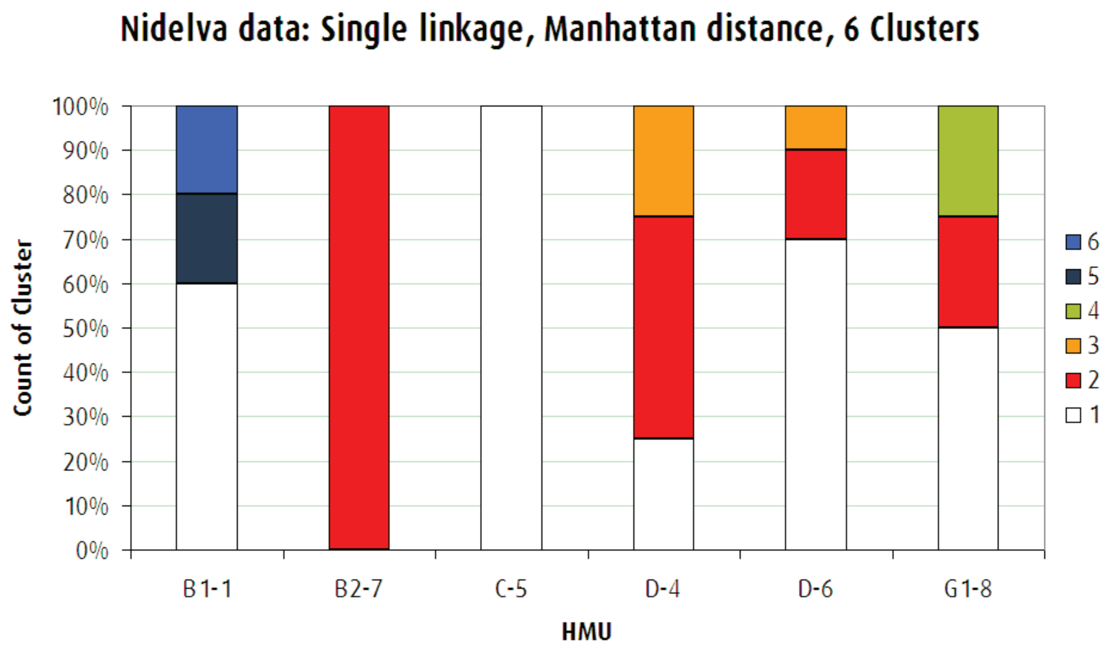
Level	N	Mean	Variance
D	4	0.204	0.004
G2	3	0.301	0.027

Concluding the tests aiming to prove that HMUs as separate entities in the water body do exist, it was found that cluster analysis is a useful tool for identifying multivariate features of HMUs based on measurement and observation data, however a much larger dataset than what was collected and presented here would probably improve the results. It must be noted that cluster analysis itself is of little use without a preliminary concept regarding data structure and formation, because the different clustering techniques often show very different results.

So far it was verified that HMUs are not homogenous units and that they do differ from each other in terms of the five collected parameters (depth, surface and mean velocities, substrate size and surface flow type) included in the analysis. It was found that in some cases (e.g. Cruick data, Centroid-Squared Pearson clustering) HMUs of similar types have more similar composition to each other than to other HMU types.

It is noticed that HMUs of type D (which type dominate our data) are sometimes found close in their features to type C-s depending on the clustering method selected and that HMU type G2-s show close features to type F-s, these however are less similar to each other than D-s to C-s. These similarities are not surprising, when the HMU classification scheme is looked at. Table 2.3 shows that often one single parameter allows to distinguish between HMU types, e.g. in case of types C and D, only parameter “depth”, or in case of types F and G2, only parameter “gradient”.

The last test regarding cluster composition in the Cruick data in HMUs of type D and G2 does not allow drawing statistically sound conclusions, only assumptions. Reformulating our hypothesis, it is suspected that due to differences in HMU structure (represented by clustering differences in the present case) different types of HMUs might need different sample densities in order to be able to cover their physical features in a comparable way.



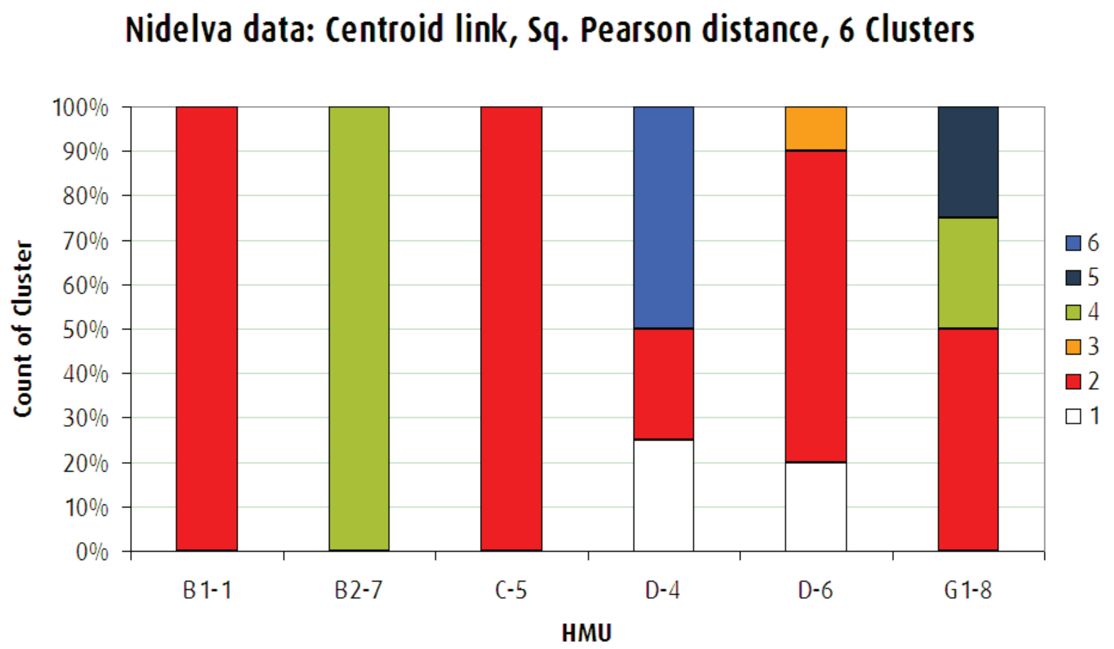


Figure 2.45: Proportional cluster structure for each HMU for Nidelva. The graphical representation of Table 2.27

The problem of small amount of data might be mitigated by improved instrumentation or more intensive measurement campaigns (more dense collection of data from HMUs and more HMUs surveyed). A calibrated 3D hydraulic model with fine cell resolution may be able to provide a part of the hydraulic data (depth, velocities and hydraulic roughness), but other features such as surface flow type or substrate structure are almost impossible to model and thereby would not improve the analysis in every terms. Laboratory experiments with artificial in-door rivers may be of use as well.

Searching for proof that similar HMU types are similar in different rivers

In this series of statistical tests, it is aimed at showing that HMUs of similar types but in different rivers show similar features. For this, an analogous method as in the first test above was followed. ANOVA was used on the Principal components calculated from the five variables collected for each sampling point. For details of the analysis not described here, check the section above.
First, it is checked which HMU types can be included in the tests because the three surveys covered different spans of HMU types. Table 2.33 shows the number of sampling points per river and HMU type.

Table 2.33: Number of sample points in Cruick, Tarf and Nidelva grouped by HMU types

HMU	River	Number of sample points
B1	Nidelva	5
B2	Nidelva	2
C	Cruick	10
	Nidelva	1
D	Cruick	118
	Nidelva	14
	Tarf	52
F	Cruick	19
	Tarf	54
G1	Nidelva	4
G2	Cruick	66
	Tarf	15
H	Cruick	1
	Tarf	44

From Table 2.33 we see that data from HMU types B1, B2, C, G1 and H are not possible to compare in different rivers, either because they were not surveyed in more than one river or because there are too few sampling points in one of the rivers. Thereby, the analysis must be limited to HMU types D (all three rivers), F

and G2 (only Cruick and Tarf). Sampling points are separated from HMU types D, F and G2 from the whole dataset and further analyses were performed only on this subset of the original data.
Results of the Principal component analysis shown in Table 2.34 reveals that it is might be useful to use more than one component in ANOVA if possible. This because we reach about only 51% of total variability with PC1. We must check the normality of the samples and decide which principal components can be used. If possible, we would compare their variances using Multivariate ANOVA (MANOVA) then. But first, we need to test whether principal component populations are normally distributed. Here we assume that multivariate normal distribution is fulfilled if all separate variables (PC1-PC5) are normally distributed. The p-values of the Anderson-Darling tests performed for this reason are shown in Table 2.35.

Table 2.34: Results of eigenalysis of the correlation matrix. PC1-PC5 notes the five possible principle components. "Dep" stands for depth, "Vmean" and "Vsurf" for mean and surface velocity respectively, "SubsCode" for substrate size and "SurfCode" for surface flow type

Variable	PC1	PC2	PC3	PC4	PC5
Eigenvalue	2.5247	1.057	0.8872	0.3972	0.1339
Proportion	0.505	0.211	0.177	0.079	0.027
Cumulative	0.505	0.716	0.894	0.973	1
Dep	0.129	-0.893	-0.294	0.312	-0.054
Vmean	-0.568	-0.218	0.131	-0.384	-0.682
Vsurf	-0.568	-0.261	0.146	-0.25	0.725
SubsCode	-0.26	0.228	-0.931	-0.112	0.028
SurfCode	-0.521	0.188	0.09	0.825	-0.074

In case of HMU type D PC1 and PC4 are probably normally distributed in all three rivers ($p > 0.05$ in all 3 cases), however normality is probably not fulfilled in the Cruick data in PC3 and PC5 ($p < 0.005$ in both cases) and in the Tarf data in PC2 and PC5 ($p < 0.005$). Regarding HMU type F, PC2 and PC5 data from Tarf is probably not normally distributed again ($p < 0.005$) and neither PC3 in Cruick ($P = 0.013$). But PC1 and PC4 are probably normal in both rivers. In case of HMU type G2, PC2 and PC5 are probably not normally distributed in either river, but PC1, PC3 and PC4 are. Therefore, for MANOVA for HMU type D and F, we may use PC1 and PC4, for HMU type G2, PC1, PC3 and PC4. However, the results would be inconsistent if we used different factors and therefore we decided to use only PC1 and PC4 in all cases, knowing that we gain the same reduced variance in all cases than compared to our original data.

Table 2.35: p-values of the Anderson Darling test for all principal components (PC1-PC5) for each tested HMU type (D, F and G2) and river. Populations where assumption of normality is probably not fulfilled are greyed

HMU type	River	PC1	PC2	PC3	PC4	PC5
D	Cruick	0.222	0.345	< 0.005	0.123	< 0.005
	Nidelva	0.101	0.478	0.149	0.696	0.755
	Tarf	0.154	< 0.005	0.195	0.390	< 0.005
F	Cruick	0.846	0.370	0.013	0.715	< 0.005
	Tarf	0.981	< 0.005	0.411	0.844	< 0.005
G2	Cruick	0.902	0.009	0.213	0.930	0.035
	Tarf	0.321	0.048	0.819	0.152	0.028

MANOVA requires not only normal distribution of the populations but also their variances to be equal. A somewhat similar procedure is followed as above and F-tests were performed (Bartlett's test in case of HMU type D: there are three levels of data because of three rivers). The resulting p-values are summarized in Table 2.36. In case of HMU type D, it was found that at least one of the populations of PC1 values in the three rivers have significantly larger variation than the two others. This problem may be resolved by transformation of PC1 values. The transformation formula is PC1-t = $(\text{PC1-1})^{1/5}$. The Bartlett's test result of the new variable, noted as PC1-t is included in the table.

Table 2.36: p-values of F-tests (Bartlett's test in case of HMU type D) to test if populations have equal variances

HMU type	PC1	PC4	PC1-t
D	0.005	0.954	0.573
F	0.376	0.670	-
G2	0.899	0.468	-

Three different MANOVA tests are performed and the resulting p-values are summarized in Table 2.37. In all cases, the null hypotheses are that the compared samples all come from populations with the same (multiple) mean vectors. If $p > 0.05$, then we can be 95% certain that our hypotheses are true.

Table 2.37: p-values of MANOVA using Wilks', Lawley-Hotelling and Pillai's tests

HMU type: Rivers	p (Wilks)	p (Lawley-Hotelling)	p (Pillay)
D: Cruick-Nidelva-Tarf	0.127	0.127	0.128
F: Cruick-Tarf	0.063	0.063	0.063
G2: Cruick-Tarf	0.057	0.057	0.057

Concluding this series of tests regarding whether HMU types are site-independent, it was found that in case of HMU types D, F and G2 comparing three and two rivers respectively the HMUs are similar. However, it is noticed that the comparison was based on two principal components of the original data, which eliminates some of the original variance. In case of HMU type D, the first principal component was transformed in order to fulfil assumptions needed for the MANOVA tests used.
This chapter aimed at unleashing the hydromorphological features of HMUs and HMU types in the NMCM. Direct comparison of surveyed and expected HMUs were presented. The expected HMUs were classified based on directly measured features such as depth, velocity, etc. It was shown that HMUs are not homogenous and that nature and magnitude of variations within them differ from HMU type to HMU type. It was partly proven that statistically significant differences exist between some of the HMU types and HMUs as entities in the continuous river body and that HMU types are site / river independent. However this attempt could not cover all HMU types and therefore did not analyse every aspect of the problems.

2.2 Development summary

As the previous examples show, in order to develop a robust and scalable method, some modifications and extension became necessary compared to our pilot, theory based method. It became clear that:

1. Eight HMU types was not enough to cover naturally occurring HMU types in our study rivers and the base HMU type selection was extended to ten. See Table 2.3 for extended HMU type description.
2. Estimation of slope is practically not feasible and was a weak part of the process. It was also noticed that breaks in gradient never occurred without breaks in any of the other classification factors. Thereby, gradient not being independent from the others, may be treated as a special classification criterion. At any variation in surface flow type, depth or surface velocity we must only confirm variation in gradient too. This way instead of categorizing surface gradients of HMU-s in relation to absolute values (steeper or less steep than 0.4 % as first planned) relative criteria is applied. See section 2.1.3.2 for more details on this issue.
3. The method incorporating substrate information to HMU surveys is another improvement. In section 2.1.3.3, three methods are presented for this purpose. It was concluded that one or two substrate classes such as dominant and subdominant substrate size are sufficient for general purposes and more details may be collected from selected parts of the study reach if necessary.

4. HMU type distribution representing mesohabitat distribution may be analysed by means of GIS. The HMU maps allow both to compare relative HMU proportions as they cover the river in one flow situation and the comparison of proportions of similar HMU types at different flow situations. A range of variables may describe these two alterations in an efficient way. Section 2.1.3.4 details these more.
5. An analysis tool was shown to examine HMU accumulation along the study reaches. The method is an alteration of the work by Takahashi (1994). An example is shown on Figure 2.18 and more details in section 2.1.3.5. By studying breakpoints on these graphs, one can classify river segments by their hydro-morphological composition. This is an easy-to-use, visual tool to describe longer reaches with additional important information to the normally used bed slope or mean water surface charts which are preferred by hydromorphology-based approaches like the one described by Rosgen (1996).
6. Another tool analysing HMU proximity is presented in section 2.1.3.6. Bryce and Clarke (1996) show that not only single habitat types (e.g. spawning or feeding areas) but also their combinations are spatial features that determine quality of a specific habitat occurrence. By means of simple statistics, the most and least occurring class sequences can be identified, which provide qualitatively better methods for habitat evaluation on longer river reaches. Duel et al. (2003) report that physical distributions of such combinations provide us with information on eco-system patchiness, proximity and other important factors that are often considered in large-scale studies of ecosystems.
7. Temporal HMU variations are discussed in section 2.1.4. It is obvious that each HMU survey is only valid in a narrow range of flows close to survey flow. In order to assess HMU linked habitat distribution, the survey has to be repeated in a wide range of flows. The larger the number of HMU surveys, the more reliable the flow-related assessment of habitat variation is. In principle, only two flows are enough to interpolate any HMU (habitat) distribution within their range, however both HMUs and thereby habitats are known to vary in dynamic way. This means that actual HMU distribution is not only determined by the actual flow magnitude, but by other factors as well. HMU distribution between two flow stages are estimated by interpolation, however only a dynamic hydraulic model could provide realistic distribution values, but such a solution is not feasible for the present purpose with today's technical background. A developed and popular method described by Parasiewicz (2001) uses interpolation techniques for this problem.
8. Section 2.1.5 attempts to describe the physical characteristics of HMUs by point sampling. The first part of the analysis is based on two collected parameters in two rivers and then five collected parameters for each sampling point in three rivers. It was attempted to provide an overall picture of in-HMU variation, but this general aim was not fully reached.

It was proven that differences between certain HMU types exist and it is hypothesized that increased amount of data would prove differences between the remaining HMU types. It is partly shown that HMUs following each other in a river differ from each other and similarities between HMUs of the same type were found. Finally, tests were performed to check between-river transferability of the NMCM, which tests partly supported the theory that HMU types are not river specific.

2.3 Resulting methodology

The sections above show that the existing link between meso-scale hydro-morphological units and meso-habitats can provide foundation for development of scaling methods in habitat modelling. The methods need to be based on knowledge from river hydraulics and river habitats from previous micro-habitat studies. The map of hydro-morphological units together with additional physical habitat data allow description and analysis of habitats of the river catchment in a better way than by micro-habitat analysis alone. Habitat formations or situations that are critical for the river biota may be identified, without assuming validity of local (small scale) habitat distribution on larger dimensions in a statistically questionable way. The NMCM has been developed according to these criteria. Further development of the method is still possible and probably necessary, but the examples below already show its potential in its present stage for river management.

2.3.1 Overview

The method developed at the Norwegian University of Science and Technology (NTNU), Sintef Energy Ltd. (SEFAS) and Norwegian Institute of Nature Research (NINA) is based on review of literature for scale issues and meso-scale classification methods for various hydrological and ecological purposes. It builds on the widely applied riffle-run-pool methods, but aims to be more detailed, flexible and objective than the previous approaches. Verification of certain aspects is not complete, but the method is applicable in a wide variety of cases in its present form. For approaches, which served as starting point for the project, see section 1.2 and chapter 2.
The major criteria during development were that:

- the method should be applicable to all Norwegian salmon rivers in general,
- no expert knowledge should be necessary for utilizing it, and
- no special or sophisticated (hi-tech & expensive) instrumentation should be needed to employ the method in any case.

It was also necessary to create a flexible structure (as noted above), so that the method can adapt to previously unforeseen situations. It means in practice, that the specialities of each actual case have to be considered and the typical results of an analysis may vary from river to river. Each analysis attempt will have the same basis, but in their second stages, the method elements are joined or lumped according to the needs of the actual case.
It is assumed that functional habitat distribution is possible to map by using hydromorphological units (HMUs) in a river. HMUs are described by water depth, surface pattern, surface gradient and surface velocity. Classification of HMUs are based on bivariate selection of these variables, for example in case of parameter depth the values may be either “shallow” or “deep”, or in case of surface velocity, slow or fast, etc.
There are ten different base HMU types to select from for the first study stage. Practically impossible – meaning naturally non-appearing or very rare combinations – are neglected. For each HMU dominant and subdominant substrate classes are noted. The survey procedure follows the structure shown on Figure 2.5.
Purposes of the actual application decide how the HMUs are linked with habitat analysis. The HMUs may be analysed separately (each type) by traditional micro- or mesohabitat analysis methods (see section 1.2.7.1 or 1.2.7.2 for such methods respectively) and later HMU types may be analysed jointly by merging them into combined habitat entities that inherit features of all their original parts. These combined features are not separate HMU types anymore because several HMU types build them up.

2.3.2 Practical issues

Water body characterisation follows a regular method in order to maintain compatibility and to allow the analysis of HMU distribution from the HMU maps in an easy way. First, the water body is divided in sections (or short reaches), and in a second step these can be divided further longitudinally into two or three HMUs. Each HMU is surrounded by two borders in the cross-sectional direction (upstream and downstream) and one or two shorelines or another unit in the lateral direction. The divisions in cross-sectional directions reach both banks and each lateral division reach the two neighbouring cross-sections. See Figure 2.5 for visualization of the process.
The classification is carried out by visual observation, estimation and simple measurements if necessary following the decision tree below in Table 2.38 (similar to Table 2.3). Definitions of the bivariate classification criteria for each feature are summarized in Table 2.39.

Table 2.38: Decision tree for HMU classification

surface pattern	surface gradient	surface velocity	water depth	code	NMCM name
smooth / rippled	steep	fast	deep	A	Run
			shallow		Non existing combinations
		slow	deep		
			shallow		
	mild	fast	deep	B1	Deep glide
			shallow	B2	Shallow glide
		slow	deep	C	Pool
			shallow	D	Walk
broken / unbroken standing waves	steep	fast	deep	E	Rapid
			shallow	F	Cascade
		slow	deep		Non existing combinations
			shallow		
	mild	fast	deep	G1	Deep splash
			shallow	G2	Shallow splash
		slow	deep		
			shallow	H	Rill

Table 2.39: Criteria limits for HMU classification

feature	classes	criteria
surface pattern	smooth/rippled	wave height <0.05 m
	broken / unbroken standing waves	wave height >0.05 m
surface gradient	steeper	relative to upstream/ downstream neighbour
	less steep	
surface velocity	fast	>0.5 m/s
	slow	<0.5 m/s
water depth	deep	>0.7 m
	shallow	<0.7 m

It is necessary to work on maps of at least 1:5000 scale, because only this (and higher) resolution is sufficient to provide enough details for identifying HMU extents. Maps of this scale are usually available for all watercourses in Norway. Practically the maps may be in either paper or electronic form, but physical paper copies were often found valuable in case data processing or other computer related problems appeared. Arial photographs, larger scale maps, other products of previous analysis (longitudinal sections, etc.) may be of help for identification of landmarks or macroscale features, but not crucial for sole

HMU surveys, however they may provide better communication platform for discussion with various user groups (hydropower operators, anglers, fish farm managers, municipalities and so forth).

For each HMU sketched on the 1:5000 map during HMU survey, the dominant and subdominant substrate classes are noted. Dominance means relative occupied area within each HMU. Classes may be noted by their actual size as normally used in hydromorphological analysis according to, for example, the Wentworth scale in e.g. Gordon et al. (2004), or by notation standards presented in Raven et al. (1998), etc.

Surveys should be carried out close to steady flow situations and at least close to the lowest and the highest flow of interest for the study. HMU sketches are ought to represent the actual sizes of HMUs both in longitudinal and cross sectional directions, which may require notation of river width at some cases. Handheld instruments using light-reflection are sufficient for this purpose. In case flow varied during the survey, HMU sizes must be altered during digitizing taking into account the alteration in river width. It is not feasible to carry out HMU surveys during relatively large variations in flow, because the produced HMU maps would then reflect a mixed state of the river, limiting the ability of estimating intermediate HMU distribution by interpolation.

2.3.3 Analytical issues

The HMU survey sketches are used to create a GIS database including HMU maps for each surveyed flow. The digitized HMUs represent the layout and size of the original HMUs, so width/length measurements and notes on positioning are already incorporated in the digital maps. See Figure 2.6 as an example.

The GIS is primarily used for calculating statistics of HMU areas for each HMU type. These are their proportion areas, and other optional factors such as median areas, standard deviation of areas, etc., to be decided based on the needs of the actual study. Table 2.7 and Table 2.8 show examples of the set of parameters of possible interest. The calculation is done separately for each flow and study reach. Then the variables for non-surveyed flows are estimated by interpolation from these values, separately for each HMU type. See Figure 2.24 for an example of simple interpolation graphs for proportional and median HMU areas. Naturally, if more than two surveys are available for the same river reach, the interpolation will be more accurate and variations are less dramatic between the steps, so a more accurate prediction of habitat-flow variation will be achieved. However, there is always a trade off between invested work and interpolation quality and one must consider the pros and cons of either side and find a balance between them.

Another use of the GIS is to prepare the longitudinal HMU accumulation charts. These show breakpoints, transition zones and gradients that connect/separate sub-reaches within study reaches based on their hydromorphological properties. Since in fact HMUs are used as describers of mesohabitats, the charts actually show longitudinal mesohabitat distribution graphs and incorporate a large set of information, more than for example slope-graphs that are used in hydrology. The breakpoints may obviously vary with flow, thereby their relative "stability" (that is howm much they vary with flow) provides additional information on macro-characteristics of the study reach. Figure 2.18 and Figure 2.19 show examples of HMU accumulation charts.

The 10 basic HMU types used in the survey are only elements to be merged into fewer numbers of classes that represent complex habitat types. The merging step however depends on the actual needs of the study and varies from case to case: only the basic system elements are the same. Therefore it is required to provide information on the magnitude of the different possible/surveyed HMU proximities. This practically may mean counting the HMU combinations or physical describers of the merged types, such as distance from one element to the other within the new type, etc. Figure 2.20, Figure 2.21 and Figure 2.26 provide examples of such an analysis.

Besides the interpolation of proportional HMU areas (as on Figure 2.24), the GIS allow to identy, how each surveyed point in the river varies with flow. This is achieved by generation of a new map by overlaying the separate HMU surveys onto each other. Such maps provide information on which areas keep their hydromorphological features as flow varies. Such areas may play important role in the overall habitat composition of the river. Similarly, the new maps allow the localization of certain habitat alterations that are important from the habitat point of view, such as possible spawning areas that get dry, or pools that become disconnected from the stream in some flow conditions. Figure 2.27 shows and example of such a map. These maps may then be further analysed to identify trends in flow variations by analysing each HMU type separately and thereby gaining more information than what overall proportional HMU area distribution charts can show. Figure 2.28, Table 2.9, Table 2.10 and Table 2.11 show examples of this analysis.

When classifying water body elements into the 10 predefined HMU categories, the surveyor unintentionally smudge point features of each HMU in order to avoid over-fragmentation of the map. It is important to keep in mind that variation of the describing physical features within HMUs are dependent on HMU type. Some types have higher variation ("point-error") while others have less, which implies different data assessment and analysis requirements when establishing links between HMUs and mesohabitats. The data collected and used for analysing these features did not allow drawing general conclusions, but there is a slight indication of higher variation in HMU types with broken water surface and higher surface flow velocity.

In order to be able to compare habitat distribution and hydromorphological features of different rivers, compatibility of the describing method must be ensured. Statistical tests were performed to prove that the NMCM is river independent, but the data available did not allow performing the complete test. Those HMU types that were statistically possible compare though, supported the hypothesis, so no reason was found assuming site/river dependence in the HMU surveys.

The analytical methods and tools listed above are based on HMU surveys carried out for given stable flow conditions and are used to assess the mesohabitat variation in relation to flow. Here flow can be used as a factor linking habitat quality to the economical aspects of river management because fisheries-related water uses may be translated into monetary value. On the broader perspective however, value assignment to e.g. ecosystems are less straightforward, but still possible (see Straton (in press) more on this issue). For example, in a hydropower system, released discharges are evaluated as produced power by actual power price. In multi-use systems water releases generate other values as well, however it is the discharge that serves as a common currency among all various interests. Water users are able to predict their water uses in order to fulfil their objectives, may that be power production, fish farming or drinking water supply. By combining proposed water uses and the flow related interpolation graphs of HMU types, it is possible to predict temporal variation of HMU distribution. These may then be further analysed in terms of duration, critical lows and highs, frequencies etc. according to the objectives of the actual task. River managers are thereby provided with the opportunity to find balance between the different uses based on their values or the losses they cause.

2.3.4 Comparison of NMCM and MesoHABSIM

Section 1.2 shows the trends followed in procedures for habitat evaluation. Many of these point towards the application of meso-scaled habitat units in this field. The systems and methods that use these usually show their advantages in comparison to classical microhabitat methods. Because of its growing popularity, many research groups describe their own methodology, but little work was done on the comparison of these and conversion of their elements to other methods. Below a common platform is provided for comparing individual mesohabitat based systems in general as well as a comparison of two existing ones.

This section contrasts the distinctly developed MesoHABSIM system described by Parasiewicz (2001) and the NMCM that both operate on meso-sized hydromorphological units and are used in habitat evaluation studies in longer river segments and catchments. The comparison is based only on the physical features of the methods. This condition is necessary because MesoHABSIM incorporates habitat analysis results in modelling habitat dynamics and, thereby, differs from a mostly physical approach that NMCM supports. Opposing to MesoHABSIM, NMCM lets the actual project define its ecological requirements and analysis methods. A conversion table is provided, which enables the translation of data from one method to the other for example for the deeper analysis of an application case.

Despite their independent development, the two methods are similar in number of features and mostly in physical parameters considered as their descriptors. Additional descriptors of HMUs are added to the maps as new layers of information separating e.g. choriotop/substrate and other habitat features

from the classes in both methods. Both provide HMU maps and therefore the application possibilities are also alike, even though their original purposes differ. They handle varying flow in the same way when non-mapped habitat proportions and distribution are estimated by interpolation from mapped situations.
Differences exist in the physical validation procedures, as MesoHABSIM is more accurate and detailed, consequently slower to apply as it incorporates seven measurement points within each class occurrence, where depth, velocity, etc. are measured and observed, while the NMCM focuses on speed of application over accuracy, therefore the parameters are estimated and grouped into class-pairs. Because the included parameters are classified into deep/shallow (for depth), or fast/slow (for velocity) categories, etc., samples are taken in the second level of application, depending on the actual purpose of HMU survey. Thereby, physical description of HMUs is less accurate, but the overall procedure is faster.
In addition, MesoHABSIM is linked with a sophisticated habitat analysis system, which includes standardized methods for fish sampling, registration of specific habitat features and statistical analysis for scaling of the data, while NMCM lacks the predefined link to any habitat verification. NMCM leaves this part to the needs of the actual application. However, previous examples show similarity to some extent. Table 2.40 shows major comparison factors regarding the two methods.

Table 2.40: Basic comparison of MesoHABSIM and NMCM

Factor	MesoHABSIM	NMCM
Purpose	Restoration	Population modelling
Scale	Meso (functional) habitat	Meso (hydromorphological) habitat
Basis of HMU-s	Altered from Bisson and Montgomery (1996)	Combined Bisson and Montgomery (1996) & others
No. of HMU-s	10	10
HMU describers	Velocity, depth, surface flow type	Surface velocity, depth, relative gradient, surface flow type
Additional physical features	gradient, choriotop	(4 factors)
Habitat features included	Predefined list, existence / abundance	Varying according to project needs
Habitat verification	Mass sampling with representative sites	Small sampling with distributed reaches
Physical verification of HMU-s	Designed limited sampling in all HMU occurrences	Random sampling in selected HMU occurrences
Handling of temporal aspects	Mapping at several flows, interpolation	Mapping at several flows, interpolation

The possibility of comparing physical parameters of HMUs was examined. Application of the MesoHABSIM method involved collection of physical data, seven points of each HMU including depth, mean velocity etc, as well as further categorical data, such as presence of boulders or woody debris, etc. The NMCM estimates the physical parameters and consequently, does not produce data during its application that would allow such comparison (section 2.1.5 shows two data collection campaigns to resolve this problem). The data background for verification of the two methods produced different amount and type of data, much less for NMCM than for MesoHABSIM. Data collection for NMCM covered short sections of rivers with limited number of sampling points, while in case of MesoHABSIM the complete study reach was covered and each HMU was sampled with 7 sampling points. These differences might cause problems when carrying out statistical analyses.

Despite of the expected problems, a few tests were carried out to show trends and to identify the problems in a more specific way. Table 2.41 shows a first type of class comparison between the methods. It is noticed that some classes differ in one describer (Riffle versus “H”), while others overlap (e.g. Rapid versus “E” or “G1” or “G2”). However, most classes seem to be comparable in a direct way.

Table 2.41: Class similarities between MesoHABSIM and NTNU method (alterations in brackets)

MesoHABSIM HMU	MesoHABSIM description	Closest HMU type in NMCM
Riffle	Shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient. Convex streambed shape.	H (but moderate gradient)
Rapid	Higher gradient reaches with faster current velocity, coarser substrate and more surface turbulence. Convex streambed shape.	E/G1/G2 (but G: moderate gradient)
Cascade	Stepped rapids with very small pools behind boulders and small waterfalls.	F
Glide	Moderately shallow stream channels with laminar flow, lacking pronounced turbulence. Flat streambed shape.	B2
Run	Monotone stream channels with well determined thalweg. Streambed is longitudinally flat and laterally concave shaped.	A
Fast run	Uniform fast flowing stream channels.	A
Pool	Deep water impounded by a channel blockage or partial channel obstruction. Slow. Concave streambed shape.	C
Plunge pool	Where main flow passes over a complete channel obstruction and drops vertically to scour the streambed.	C/B1 (but B1: fast flow)
Backwater	A slack area along channel margins, caused by eddies behind obstructions.	D
Side arm	Channels around the islands, smaller than half river width, frequently at different elevation than main channel.	D/G2/H

3 Example applications

This chapter provides two examples for problems related to hydropeaking issues. The first example shows the beginning phase of a project investigating effects of proposed river regulations on habitat mitigation, where mesohabitats are linked with salmon production modelling. This is a test of the environmental modelling capabilities of the methodology presented in section 2.3. The second example is presented in two versions. Version 1 demonstrates how physical habitat modelling may be applied for water release scheduling in a hydropower system and how value of power production may be linked to habitat availability. It demonstrates the possibility of linking existing models for pricing environmental requirements in a river system regulated for hydropower, but NMCM is not applied int this version yet. Then Version 2 of the same project is presented, which is a trial for incorporating the NMCM by automatic generation of HMU maps to the updated (but fundamentally same) system as in Version 1.

3.1 Scaling for assessment of production potential on River Nausta – first iteration

The section describes a recent application of the Norwegian Mesohabitat Classification Method (NMCM) and shows its use when an over 12 km long river reach is the subject of a study for mitigation and improvement of habitat.

3.1.1 Introduction

This example forms part of a larger joint project with the purposes of developing a production prognosis model for salmon and establishing a framework that allows the sustainable management of Norwegian salmon rivers based on results from this model. The project is financed by the foundation “Nausta – a future for wild salmon”, founded by “Naustdal Elveigarlag” (Nausta River Owners Association).

The larger project has the following ultimate goals:

1. Survey the actual potential of salmon production and suggest means/ actions to utilize that
2. Improve utilization of local salmon resources
3. Develop a prognosis model for returning adult salmon to ensure sustainable stock size and to provide maximal production in the watercourse
4. Improve possibilities and basis for economical and sustainable utilization of salmon resources together with other interests (e.g. public access to the river)

From these points, partly no. 1 and 3 are looked at here. Expressing the project goals differently, we can say that the practical purpose of the study is to identify crucial factors and to suggest necessary measures, which can serve as basis for sustainable river management regarding the maintenance of the salmon population of River Nausta in Western-Norway. Appendix A.1.6 provides general information about the catchment of River Nausta.

3.1.2 Methods

The project utilizes distributed sampled data over the study reach in this particular river, by means of the previously described Norwegian Mesohabitat Classification Method (NMCM). The method is linked to calculated fish densities, thus a link between hydro-morphology and assumed habitat quality is provided. The study reach covered the main stem of Nausta River between Kallandsfossen and Naustdalfossen. It was mapped at a discharge close to mean annual flow (10-11 m^3/s). The mapping procedure took about two days to complete on 8-10 September 2003.

According to the NMCM, the study reach was surveyed and the river was classified into 10 predefined types of hydromorphological units (HMUs). Definitions of these are derived from respectively two classes of surface flow velocity, surface flow pattern, depth and relative surface gradient. Dominant and subdominant substrate sizes for each HMU were also noted. These values were not measured during the surveying process and therefore should be understood as estimations, such as the HMU classification itself (since the classifying features

are estimated there too). Values of dominant and subdominant substrate mean the diameter of the particles, covering respectively the largest and second largest areas of each HMU. The collected data was used to prepare a geographical information system database (GIS), which served as starting point for the further analyses.
Besides the components of NMCM, additional physical habitat data were measured and analysed from within and bordering eight selected fish sampling stations. This included depth, mean column velocity, dominant and subdominant substrate, embeddedness and roughness height. Embeddedness gives an indication of how compact the substrate structure is at a particular spot, or at a station if looking at average values. A value of 100 % stands for fully compact substrate, assumably no room for hiding for young fish. Roughness height shows an approximation of the hydraulic roughness height at a particular spot. Generally, ten irregularly spaced points were selected from within the selected fish sampling stations and about 30 additional points outside of the actual sampling area, but still in the same HMU where the station lays.
23 fish sampling stations were utilized and fished by electro-fishing equipment during early autumn 2003. Atlantic salmon (*Salmo salar*), Brown trout (*Salmo trutta*) youngs-of-the-year and older parrs were collected. The criteria for selecting the locations of these stations were that these had to be accessible under various flow conditions and had to be shallow enough to use the handheld electro-fishing equipment (See Figure 3.9, right picture). These stations were established before surveying spawning areas of salmon along the river and the present project simply utilized them.
The stations are distributed more or less evenly all over the study reach, but less evenly in HMUs defined in the NMCM (see section 3.1.3.2 more on this issue). Most stations cover about 100 m^2, therefore calculated fish densities are expressed in number of fish over 100 m^2. Nine of the stations were fished in three successive runs approaching from downstream towards the upstream direction, while the others were fished in one run. Density of fish and catch efficiency were estimated according to Bohlin et al. (1989) for the stations with three fishing runs. These catch efficiencies were also used to estimate fish density on the stations with only one fishing run. The calculations were carried out separately for the salmon, trout, for youngs-of-the-year and for older parrs. Youngs-of-the-year salmon (hereafter YoY) are 0+ fish, which were hatched during spring 2003, while older salmon parr that we registered were mainly 1+, 2+ and a few examples of 3-year-old fish. Lengths of all sampled fishes were measured on the field and a subsample of fish was taken to laboratory for determination of age. Atlantic salmon is the dominating species in Nausta and our study in the following was focusing only to this. Trout related data is not utilized in the present study.

3.1.3 Results

A gauging station situated at the lower third (Hovefoss, see Figure 3.8) of the reach, provided a reference discharge of about 10 m^3/s for the surveying days. The surveyed river area reached over 6.5 km^2, excluding the brackish zone of lower estuary which covers some 0.2 km^2 in addition. The survey divided the reach into 270 HMUs, using the ten classes of the NMCM. Figure 3.7, Figure 3.8 and Figure 3.9 shows HMU maps of the whole reach.

3.1.3.1 Physical habitat description

Table 3.1 summarizes HMU area, dominant and subdominant substrate sizes by descriptive statistical means. In the table, “Count” stands for the number of HMUs in each type of group (e.g. type A, B1 etc.). Minitab (2003) gives the following definitions of some selected variables in the table: “Coefficient of variation” expresses the standard deviation of the data as a percentage of the mean. “Skewness” is a measure of lack of symmetry. A value close to zero indicates symmetric data. Negative values indicate negative/left skew, while positive values indicate positive/right skew. “Kurtosis” is a measure of how sharply peaked a distribution is. Values close to zero indicate normally peaked data. Negative values indicate a distribution that is flatter than normal. Positive values indicate a distribution with a sharper than normal peak.

Table 3.1: Descriptive statistics of HMU types by area, dominant and subdominant substrate sizes on River Nausta. Data is derived from the survey of 8-10 September 2003

Variable	HMU type	Count	Mean	Standard deviation	Coefficient of variation	Minimum	Median	Maximum	Skewness	Kurtosis
HMU Area (m^2)	A	3	1897	1146	60.42	929	1600	3163	1.09	-
	B1	27	2620	1799	68.66	462	1939	6463	0.67	-0.7
	B2	85	2875	2288	79.56	484	2211	15647	2.57	10.8
	C	26	2545	3195	125.52	339	1338	15801	3.17	11.96
	D	51	1981	1645	83	212	1690	8315	1.68	3.48
	E	4	2589	1752	67.68	1184	2108	4957	1.06	-0.16
	F	12	2147	1326	61.76	376	1555	4662	0.88	-0.2
	G1	7	2712	1159	42.74	1304	2728	4838	0.77	1.42
	G2	40	2332	1733	74.29	329	1721	7345	1.57	2.07
	H	16	997	634	63.58	247	885	2273	0.76	-0.29
Dominant substrate size (cm)	A	3	16.7	28.9	173.21	0	0	50	1.73	-
	B1	27	14.64	14.54	99.35	0.2	10	40	0.87	-0.9
	B2	85	11.038	9.191	83.27	0	10	50	1.75	3.76
	C	26	11.08	11.21	101.21	1	9	40	1.6	1.56
	D	51	9.47	7.58	80.03	0.2	8	35	1.56	2.21
	E	4	8.75	17.5	200	0	0	35	2	4
	F	12	24	15.87	66.14	10	15	50	0.75	-1.14
	G1	7	10	11.55	115.47	0	5	25	0.57	-1.92
	G2	40	11.98	12.19	101.81	0	10	50	1.95	3.62
	H	16	9.69	6.7	69.17	0	10	25	1.46	2.28
Subdominant substrate size (cm)	A	3	1.67	2.89	173.21	0	0	5	1.73	-
	B1	27	10.88	8.64	79.43	0.1	15	30	0.32	-0.91
	B2	85	9.54	9.72	101.81	0	5	50	1.27	2.18
	C	26	8.13	6.53	80.3	0.1	5	20	0.41	-1.25
	D	51	7.63	8.08	105.93	0.1	2	30	0.73	-0.47
	E	4	0.5	1	200	0	0	2	2	4
	F	12	14.38	12.87	89.47	0.1	12.5	40	0.66	-0.45
	G1	7	14.29	14.27	99.87	0	15	30	0.02	-2.47
	G2	40	15.05	10.66	70.84	0	15	50	0.85	1.65
	H	16	6.65	6.61	99.33	0	3.5	15	0.33	-1.86

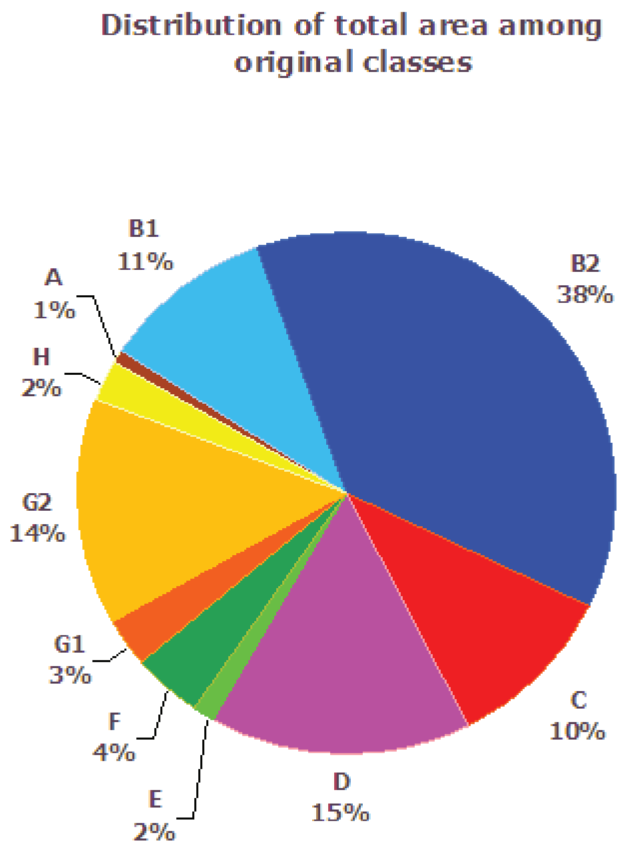


Figure 3.1: Class distributions in River Nausta

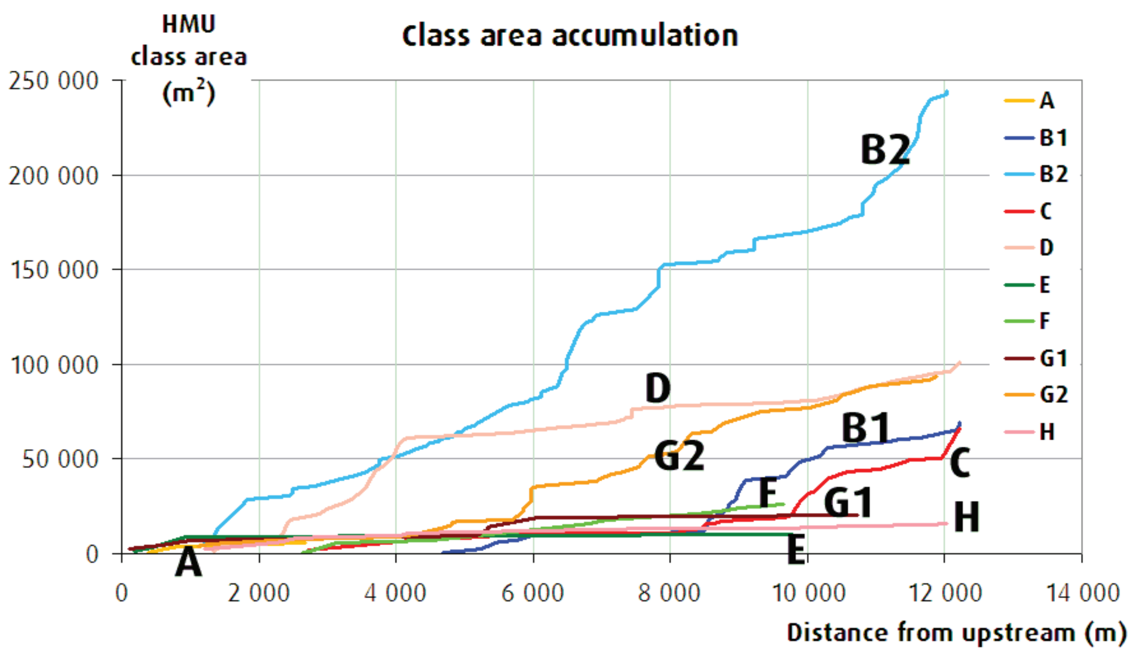


Figure 3.2: HMU class area accumulation chart along River Nausta measured from upstream

A total of 652414 m^2 of river was surveyed, Dividing this among the ten given HMU types, their relative proportions of the total area can be compared. Figure 3.1 shows proportions of the total surveyed area divided among HMU classes.
By means of usual GIS features, a table was constructed with upstream and downstream distances to all neighbours of each HMU on the map. Linking these distances with HMU chainage along the river, it is possible to create HMU accumulation charts for each type of HMU. One may accumulate features such as HMU area or estimated volume. Figure 3.2 shows accumulation of horizontally projected areas of HMUs grouped by HMU type along the river. The distances are measured from the upstream end of the study reach. The graph lines are horizontal, in case no occurrences of a particular HMU class is found on the actual river part. On the other hand, if graph lines increase rapidly, a large number of HMU features (in this particular case extent of HMU areas) are found on the actual part of the river. These graphs are helpful when the reach has to be looked at based on habitat related features. Breakpoints of graphs indicate lateral changes in physical habitat and thereby appointing borders to consider during analyses.
The GIS also allows checking for proximity among the HMU types. Frequency charts of the neighbouring combinations give an idea how the different types can be lumped in order to provide a more generalized description of the river. Fish habitat was described in the river by mesohabitat features. A rule for combination of HMUs into fewer classes is to group those into separate groups that provide the highest number of neighbouring combinations (that in a way contribute most to diversity). Figure 3.3 shows the most often occurring neighbouring combinations among HMU types. Counts of neighbours of similar HMU types are filtered and excluded (e.g. B2 <-> B2), as they only appear due to technical rules followed in the surveying procedure. Such combinations of HMU neighbours do not provide additional information to the analysis and therefore are not considered here.

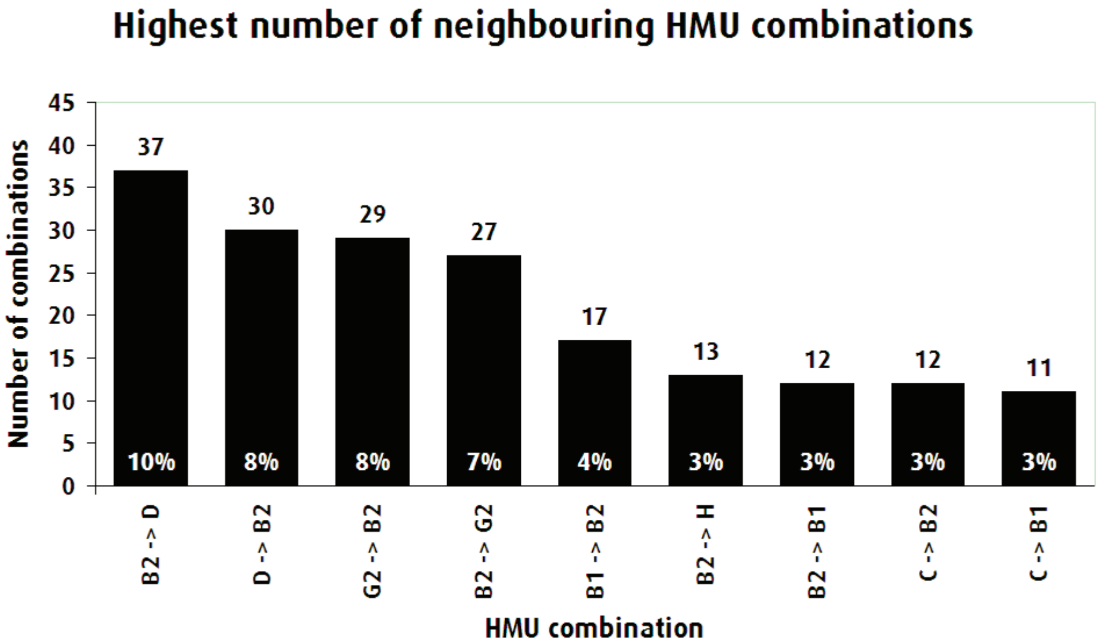


Figure 3.3: Absolute and relative number of neighbouring HMU combinations on River Nausta

During surveying, together with HMU types, average sizes of dominant and subdominant substrate were also registered for each HMU. Thereby an approximate substrate size and distribution map is gained as also shown on Figure 3.6, Figure 3.7 and Figure 3.8. On these maps, varying dot sizes give an impression of the actual substrate sizes. The dominant substrate is shown in blue, subdominant in orange colour. Two dots are present for each HMU entity, showing observed dominant and subdominant sizes for that particular entity.

Since each of the 270 observed HMUs has registered substrate values, it is possible to calculate average of sizes per HMU class by grouping them (such as averages for type A, B1, B2, etc.). Figure 3.4 shows average dominant (on the graph “AvgDom.”) and subdominant (on the graph “AvgSubD.”) substrate sizes calculated from all surveyed HMUs. The values are given in centimetres. The figure does not reflect the different numbers of HMU types, these are indicated in column “count” in Table 3.1.

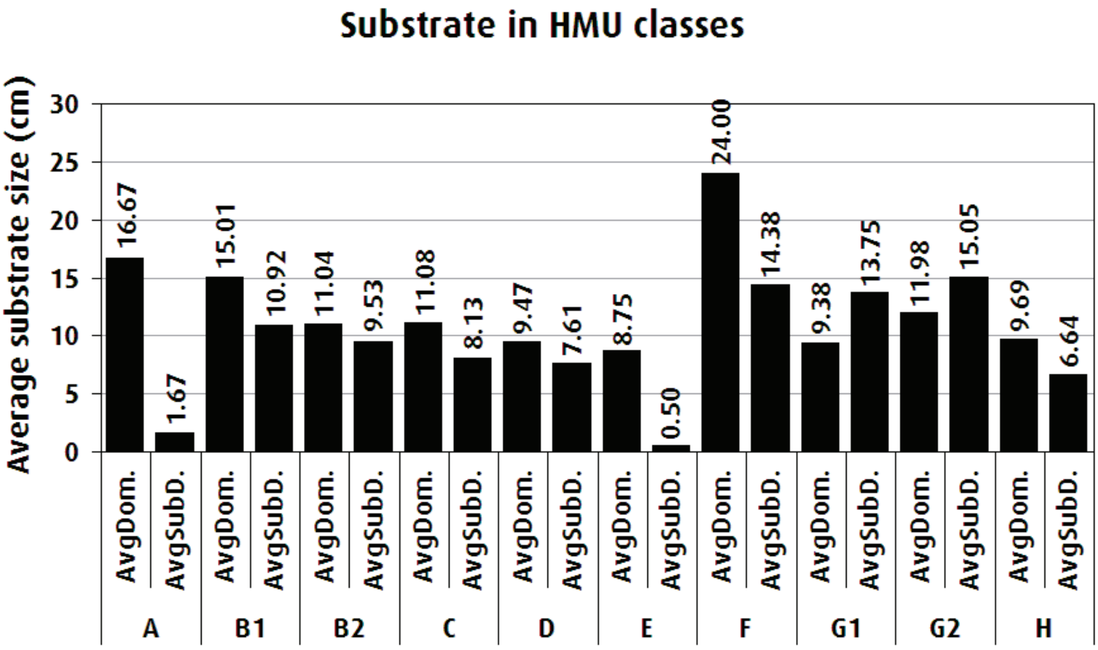


Figure 3.4: Average substrate sizes per each HMU class

Similarly to the separate HMU area accumulation charts (Figure 3.3), we can draw substrate distribution graphs along the study reach. Figure 3.6 shows how substrate sizes vary with river distance, measured from upstream of the study reach. Separate graphs are shown for dominant, subdominant and combined substrate sizes. The combined value is arbitrarily calculated as the weighted average of dominant (double weight) and subdominant (single weight) sizes.

Since there is a large variation among the values (black line), two interpolating functions are added for each graph. One is a second order polynomial interpolation (red line), the other is a moving average interpolation based on 20 neighbours (blue line). The interpolating functions may give an idea about the trends in substrate size variation along the study reach, helping identifying longitudinal breakpoints in addition to the HMU area accumulation charts.

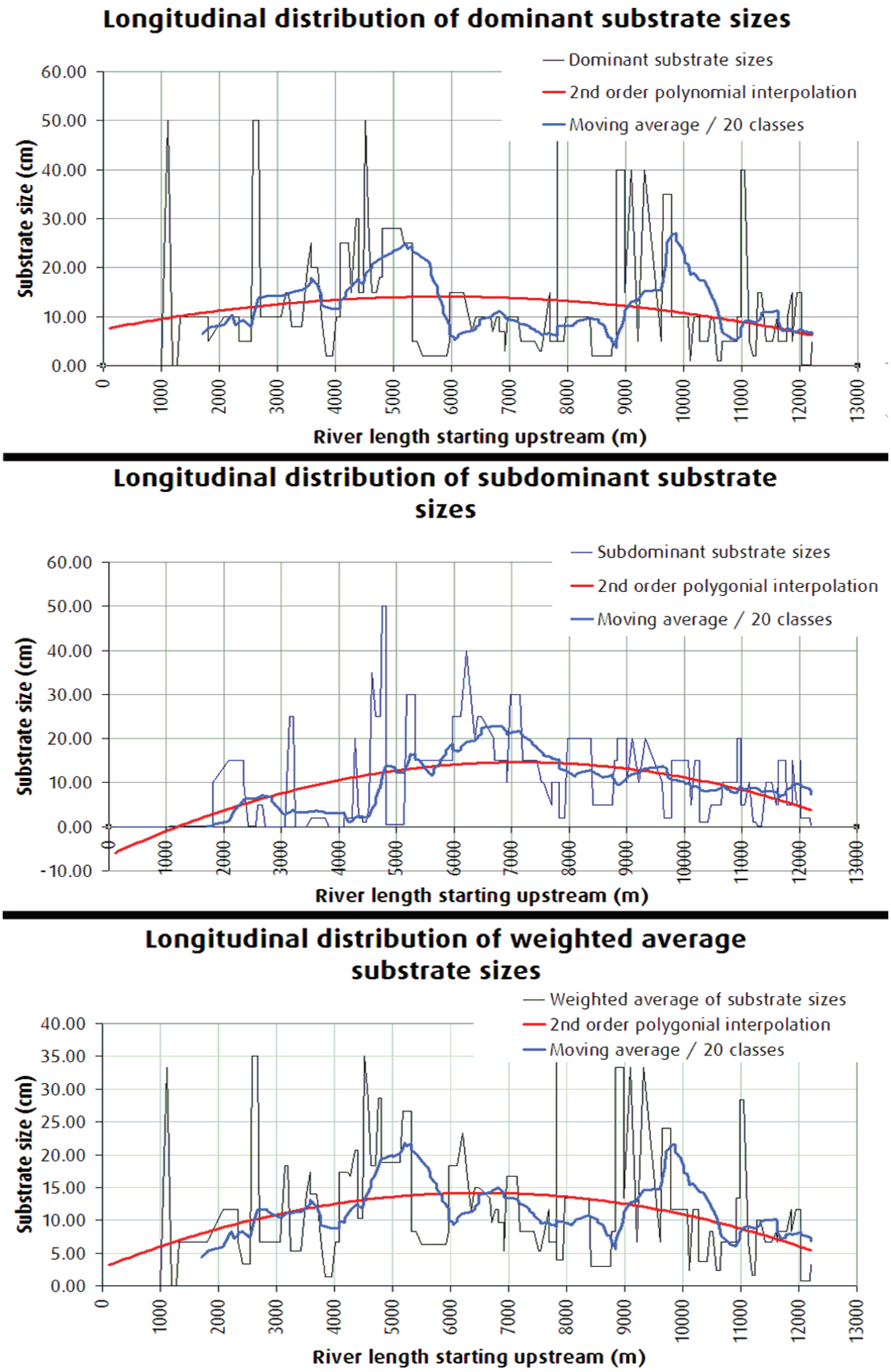


Figure 3.5: Distribution of dominant and subdominant substrate sizes along the study reach, starting from upstream. A 2nd order polynomial interpolation (red line) and moving average of 20 neighbouring points (blue line) are included.

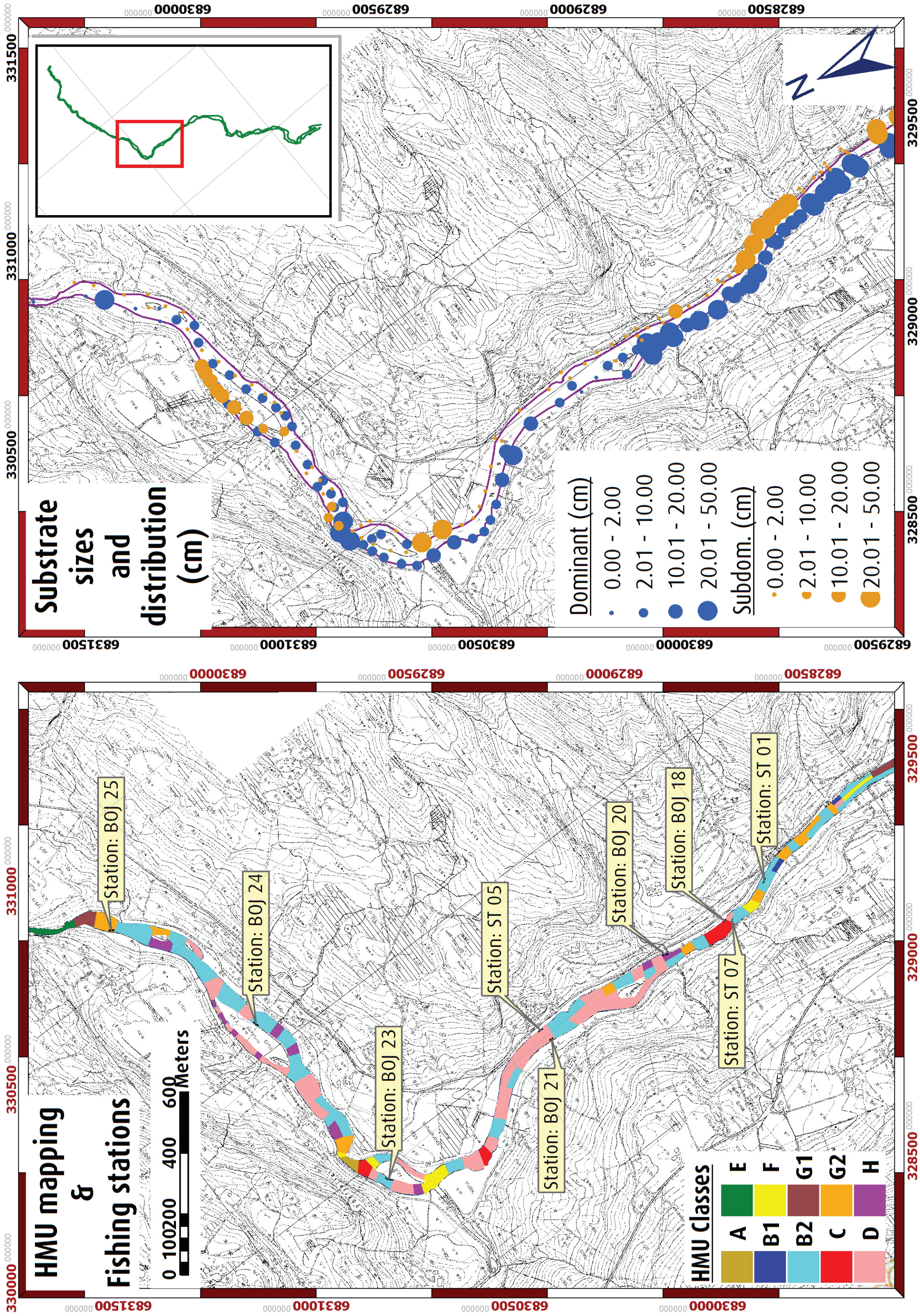


Figure 3.6: Upstream reach of River Nausta. HMU types and substrate sizes

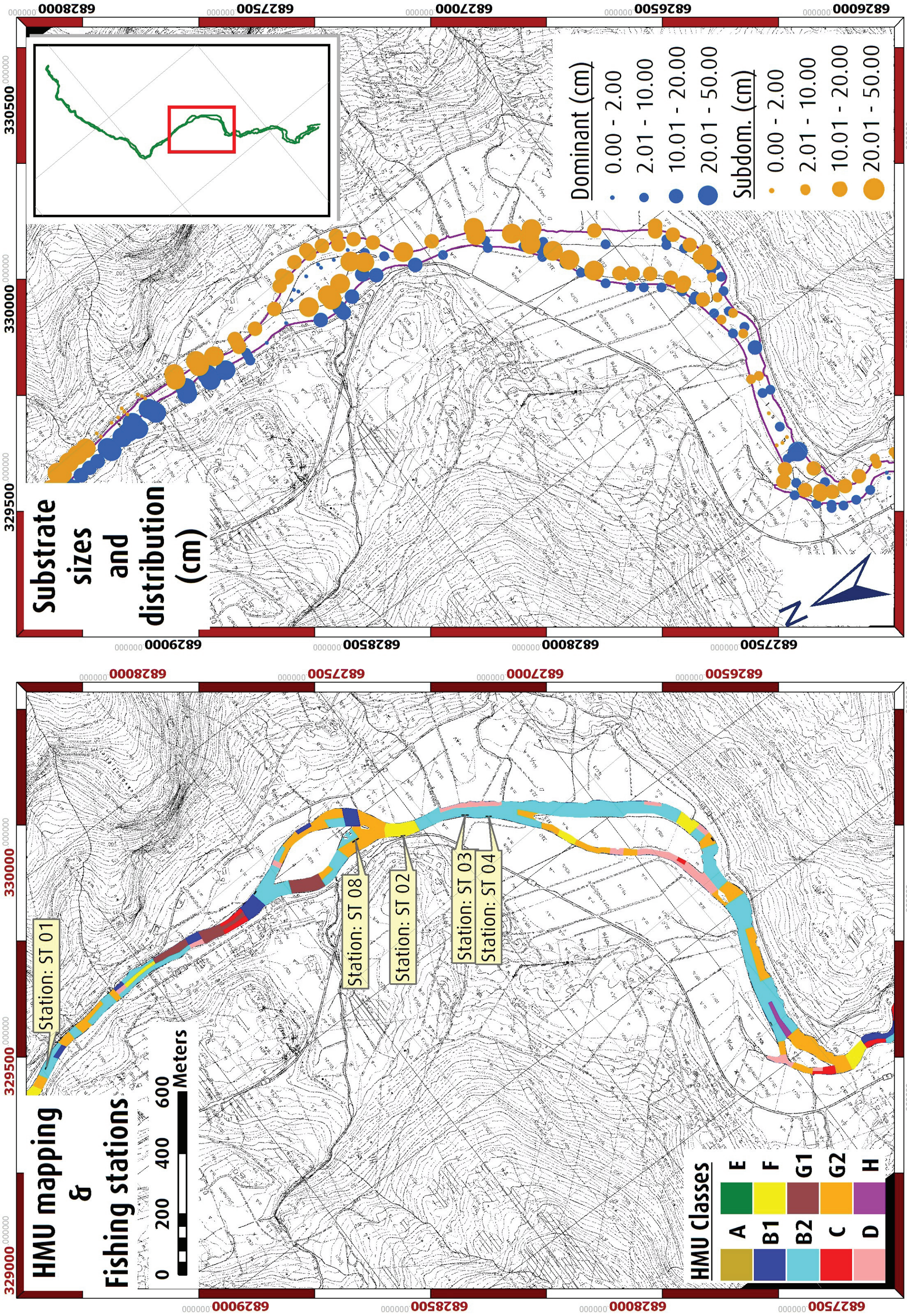


Figure 3.7: Middle reach of River Nausta. HMU types and substrate sizes

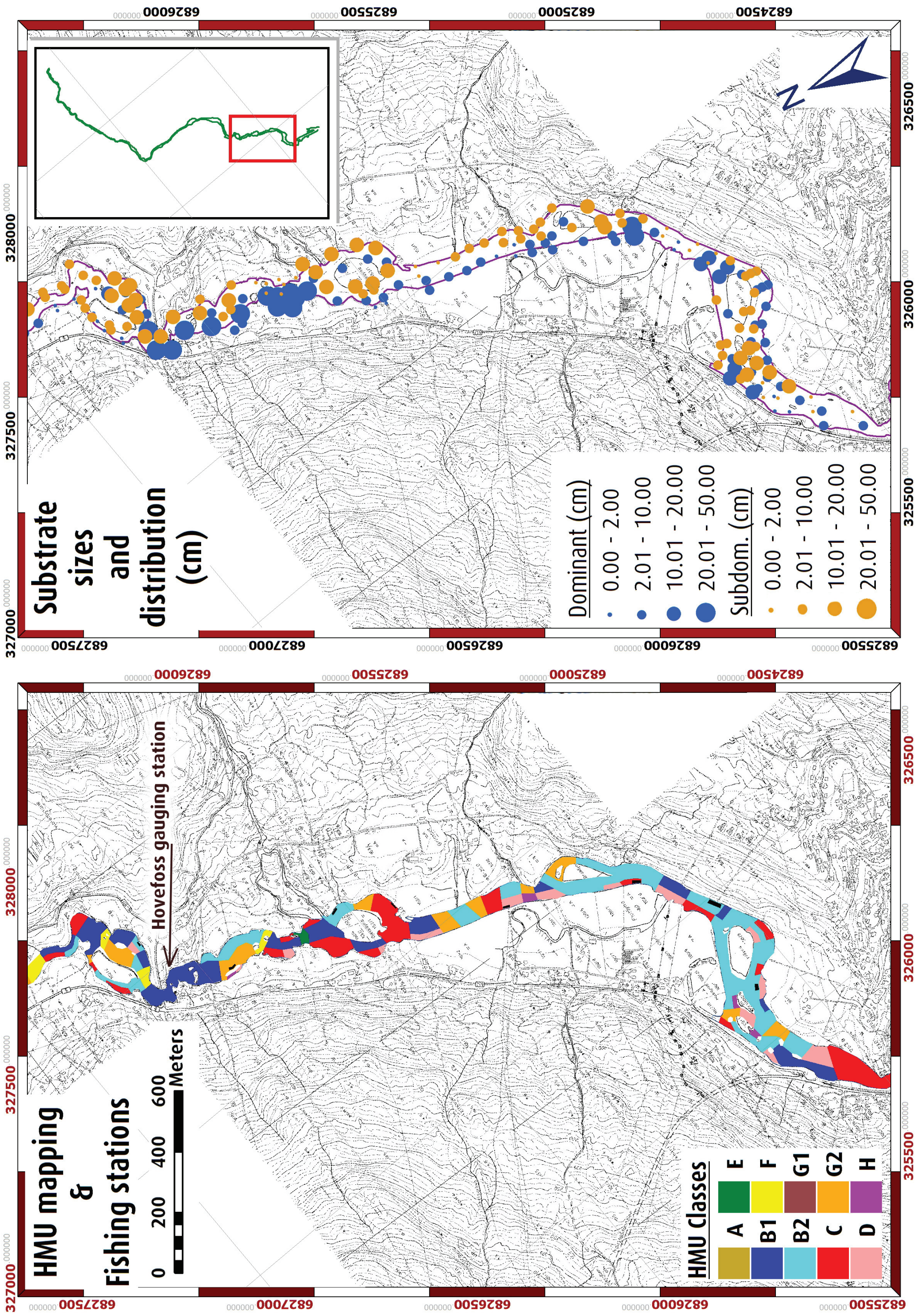


Figure 3.8: Downstream reach of River Nausta. HMU types and substrate sizes

3.1.3.2 Fish sampling

Parallel to the HMU survey, fish sampling was carried out on selected fishing stations. Table 3.2 shows data collected from these stations in 2003. "HMU type" values are derived from the HMU survey described in Section 3.1.3.1. The "Shape" column tells the approximate square sizes of the sampling stations, where their shapes are rectangular. The last two columns are averages of the corresponding salmon and trout densities. The abbreviation "YoY" stands for "Young-of-the-year". Density values are projected to 100 m^2. Figure 3.6, Figure 3.7 and Figure 3.8 show the location of the stations.

Table 3.2: Description of fish sampling stations and fish sample values on River Nausta during autumn 2003

Fish sampling station	HMU type	Shape (m × m)	Distance from upstream (m)	Density of salmon YoY (#/100 m^2)	Density of older salmon parr (#/100 m^2)
BOJ 25	G2	25*4	1107	185.9	57.2
BOJ 24	B2	20*5	1672	69.4	57.6
BOJ 23	B2	20*5	2943	119.3	22.7
BOJ 21	D	12*8	3699	30.6	16.7
ST 05	D	irregular	3699	16.2	177.4
BOJ 20	H	12.5*4	4173	29.9	0.0
BOJ 18	C	10*4.5	4406	14.3	3.0
ST 07	B2	irregular	4435	31.9	161.7
ST 01	B2	25*4	4633	47.7	131.9
BOJ 19	B2	15*8	5611	71.1	13.5
ST 08	G2	13*6.5	5976	14.4	84.4
ST 02	F	25*4	6214	16.9	104.5
ST 03	B2	25*4	6415	36.3	110.2
ST 04	B2	25*4	6415	42.6	55.4
BOJ 09	G2	20*5	6914	102.0	113.6
BOJ 08	B2	20*5	7929	74.5	162.3
BOJ 07	B2	20*5	8803	18.4	156.1
BOJ 06	G2	20*5	9329	71.2	0.0
BOJ 05	B2	20*5	9966	114.8	36.3
BOJ 04	D	20*5	10642	237.5	50.0
BOJ 03	C	20*5	11048	28.9	32.8
BOJ 02	B2	20*5	11278	51.7	8.1

Table 3.2 shows data from each fish sampling station. Note that if looking at the sampled HMU types, most deep class types (B1, E, G1) are missing from the table, because these could not be sampled. This is due to the technique applied

for electro-fishing. The equipment used does not allow sampling from spots where depth is larger than 70-90 cm especially if this is coupled with fast flow. Other methods (e.g. exposed grid sampling) exist, but are either expensive or unusual in Norway (see Figure 3.9 for limitations due to little extent of shocking current in the water on both photographs). In addition, lack of experience and proper equipment prevents them being spread in practice and consequently being applied here. However, there are no widely spread or accepted methods for sampling from fast flowing and deep spots in general either. Such areas therefore must be excluded from sampling. On the other hand, it is unlikely that small fish with limited abilities of movement preferred fast flowing parts of the river, simply because these are incapable holding position in such an environment.

Figure 3.9: Electro fishing in practice in Canada (left) and in Norway (right)

3.1.3.3 Relation between habitat on fish sampling stations and HMUs

In addition to registering fish densities, physical habitat data was collected at some of these stations. Table 3.3 shows the average of the collected values for each station. Data was collected at a reasonably similar discharge to that of the HMU survey. The number of sample points per station varied between 12 and 42, with an average of 36. Difficulties occurred at station “ST 02”, where only 12 samples were taken.

Table 3.3: Summary of physical habitat data collected from fish sampling stations

Fish sampling Station	Number of sample points (inside + outside)	Average depth (m)	Average mean column velocity (m/s)	Average dominant substrate size (cm)	Average of subdominant substrate size (cm)	Average embeddedness (%)	Average roughness height (cm)
BOJ 20	10+30	0.42	0.51	4.33	6.43	58	2.5
ST 01	10+30	0.58	0.58	27.08	8.82	37	18.0
ST 02	12+0	0.59	0.65	34.55	10.21	31	16.5
ST 03	10+29	0.64	0.28	14.17	7.10	55	6.3
ST 04	10+30	0.54	0.39	8.34	10.29	59	3.2
ST 05	10+32	0.49	0.47	10.75	8.63	56	7.3
ST 07	10+21	0.71	0.49	27.36	6.22	53	19.4
ST 08	10+31	0.34	0.75	7.44	11.73	45	5.7

To provide a better overview of the data collected, Figure 3.10 and Figure 3.11 show separate statistics inside and next to (referred to as "in" and "out" respectively) the fish sampling stations.

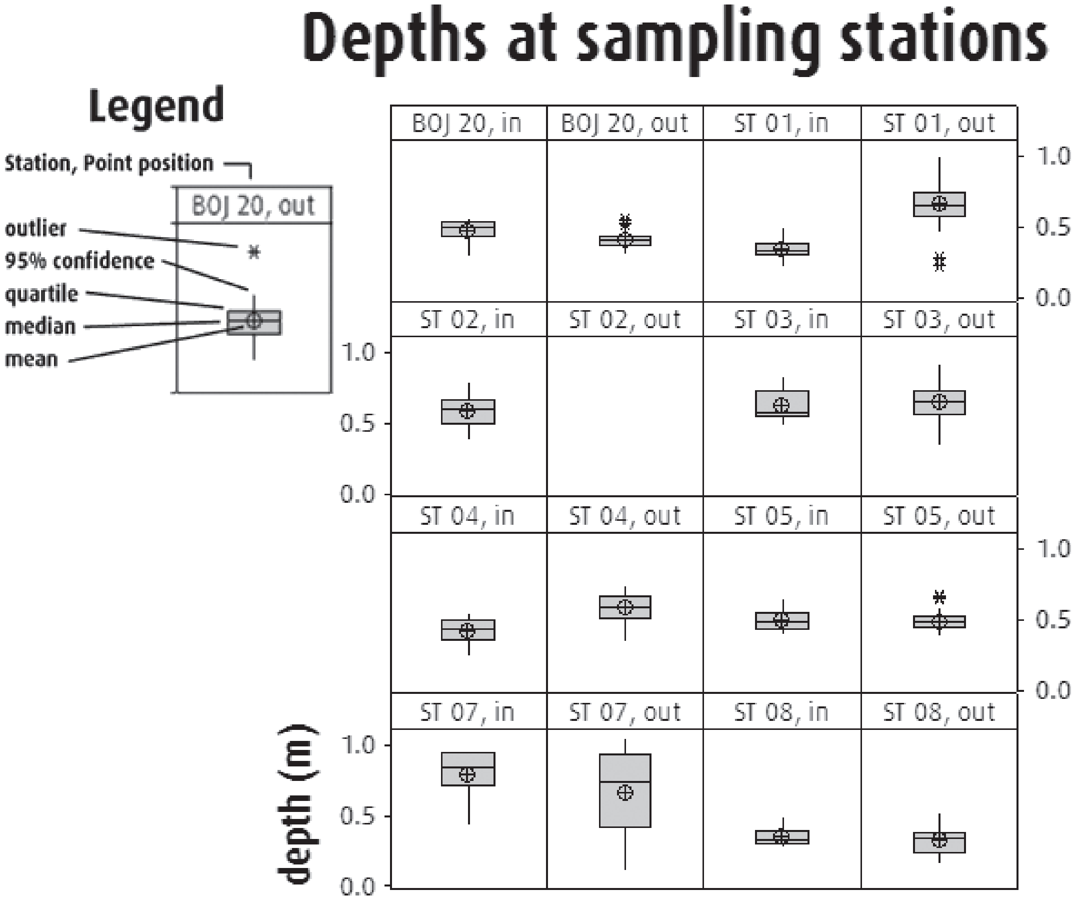


Figure 3.10: Distribution of depth samples from within ("in") and next to ("out") selected fish sampling stations

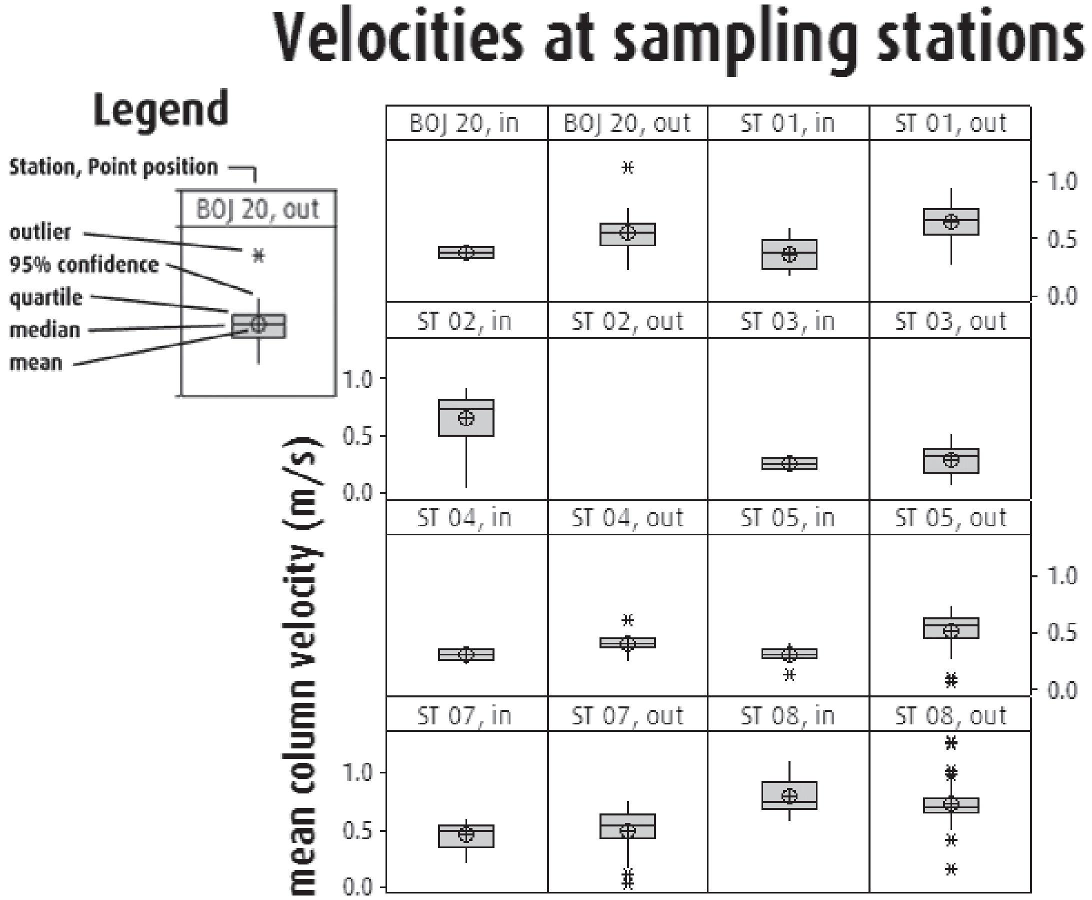


Figure 3.11: Distribution of mean column velocity samples from within ("in") and next to ("out") selected fish sampling stations

Furthermore, there is also a difference between the HMU types of fish sampling stations derived from the GIS (based on their geographical positions) and the expected HMU type derived from measurement averages. Depth and velocity values alone, without combining them with surface flow type and surface gradient do not allow explicit classification of the sites into HMU types of the NMCM. These expected HMU categories therefore include several of the original HMUs. Table 3.4 shows a summary of expected and surveyed HMUs at selected fish sampling stations. Please note that mean column velocities were measured and used for finding expected HMUs, while in the NMCM definition surface velocities are used. Also note that generally 10 measuring points laid inside and 30 outside of fish sampling stations and so "in" values are averages of about 10 values, "out" values are of about 30 and "average" values of about 40 in Table 3.4.

Table 3.4: Expected (measured) and observed HMUs at selected fish sampling stations

Fish sampling station	Sample position	Mean depth (m)	Mean velocity (m/s)	Expected HMU from measurements	Actual HMU from survey
BOJ 20	in	0.47	0.38	D/H	H
	out	0.41	0.56	B2/F/G2	
	average	0.42	0.51	B2/F/G2	
ST 01	in	0.34	0.37	D/H	B2
	out	0.66	0.65	B2/F/G2	
	average	0.58	0.58	B2/F/G2	
ST 02	in	0.59	0.65	B2/F/G2	F
	average	0.59	0.65	B2/F/G2	
ST 03	in	0.62	0.25	D/H	B2
	out	0.65	0.28	D/H	
	average	0.64	0.28	D/H	
ST 04	in	0.42	0.31	D/H	B2
	out	0.59	0.42	D/H	
	average	0.54	0.39	D/H	
ST 05	in	0.49	0.31	D/H	D
	out	0.49	0.52	B2/F/G2	
	average	0.49	0.47	D/H	
ST 07	in	0.80	0.46	C	B2
	out	0.67	0.50	D/H	
	average	0.71	0.49	C	
ST 08	in	0.36	0.80	B2/F/G2	G2
	out	0.33	0.74	B2/F/G2	
	average	0.34	0.75	B2/F/G2	

3.1.4 Discussion

In this section a procedure is shown for scaling up the fish density values from the sampling stations. The scaling is not straightforward, as certain constrains appear regarding data validity over the study reach. First, the method to select representative HMU types of fish sampling stations is discussed and a simplification of the HMU classification structure for this particular case is proposed. Then internal borders are identified within the reach, which distinguish between validity of different scaling functions. Finally, the actual scaling procedure is presented.

3.1.4.1 Relation of HMU types and fish sampling stations

In Table 3.4, differences are shown between expected HMU types and surveyed HMU types at selected fish sampling stations. Expected values are derived from averages of mean column velocities and averages of depth values sampled from within and around the actual stations. Surveyed values are derived from estimation of average surface flow velocity, average depth and other factors. In most cases (BOJ 20, ST 03 and ST 04) the reason of deviation is related to flow velocity. Station BOJ 20 has an average mean velocity of 0.51 m/s, 0.01 m/s higher than the border defined in NMCM, therefore can easily be categorized as acceptable error. Stations ST 03 and ST 04 lay on the edge of a large B2 type HMU (see Figure 3.8) and the stations cover only a small portion of this. Therefore we can say that the samples collected are not representative for the whole HMU, however the HMU is assumed to represent the fish sampling stations in the scaling procedure. This assumption may be correct given the limited extent of fish sampling stations compared to the actual extent of area the fish might be using of this particular HMU type. Finally, ST 07 is expected to lie in HMU type C, while it is surveyed as B2. Looking at both average depth (0.71 m) and velocity (0.49 m/s) values, we note that they are very close to predefined NMCM borders (0.7 m for depth and 0.5 m/s for surface velocity) and therefore can also be categorized as acceptable error. After this analysis, it is concluded that the HMU survey is representative for the fish sampling stations with some minor errors.

3.1.4.2 Simplification of the HMU class structure

Firstly, to comply with the ultimate goal of population modelling, and secondly, in order to provide a better basis for communication with local investors, it was decided to reduce the ten original HMU types to five lumped types. The method for lumping HMUs is customized for this particular project and is based on the hydromorphological and substrate features subset of this particular study reach. Local interest focuses strongly on sport fishing, therefore expressions familiar to anglers had to be used instead of notation more similar to the NMCM coding.
Figure 3.2 shows proportions of the total surveyed area divided among HMU classes. It can be noticed that B1, B2, D and G2 cover the largest amount of area (respectively 11%, 38%, 15% and 14%, altogether 78% of total surveyed area), of the study reach and therefore these should be kept as separate starting points for the new HMU groups.

Figure 3.4 shows the most often occurring neighbouring class combinations. If the HMU classification scheme is simplified, but the diversity of classes are kept at a similar level, the selected combinations must be separated in the new scheme as well. HMU type B2 neighbouring D provides 18% (= 10% + 8%) of all combinations, while HMU type G2 neighbouring B2 gives 15% (= 8% + 7%). The third largest combination is B1 next to B2 giving 7% (= 4% + 3%). Since the first three groups give a large 40% of all appearing combinations, B1, B2, D and G2 types should be kept separate, which corresponds well with the findings derived from class area proportions above.

The lumped class types are then built around these four core types and grouped together with others with partly similar features. The definitions are shown below. Fishing experience was also utilized in the lumping process, however the core procedure is well founded as shown above. For a more detailed reference on angling terms and adventurous fishing stories see Schwiebert (1978).

- “Pools”, as salmon anglers usually mean them. These are typically deep, smooth slow flowing sections of water together with their faster flowing, smooth and deep inlets and outlets. With original notation these are types “B1” and “C”.
- “Deep runs” are deep and fast flowing parts usually on steep and narrow parts of the river with mostly broken surface. With original notation these are types “A”, “E” and “G1”.
- “Rapids” are what most anglers would interpret as rapids. These are rather shallow, fast flowing sections with broken surface. With original notation these are types “F” and “G2”.
- “Glides” are rather shallow sections with smaller waves on the surface than in rapids, but still fast flow. With original notation this is type “B2”.
- “Shallows” are shallow areas with slow flow. With original notation, these are types “D” and “H”.

Figure 3.12 shows the distribution of the new lumped classes on the study reach. Note, that they have a more balanced distribution than the original HMU types. Using the new classification scheme, one may regenerate the class area accumulation chart. Figure 3.13 shows the regenerated graphs.

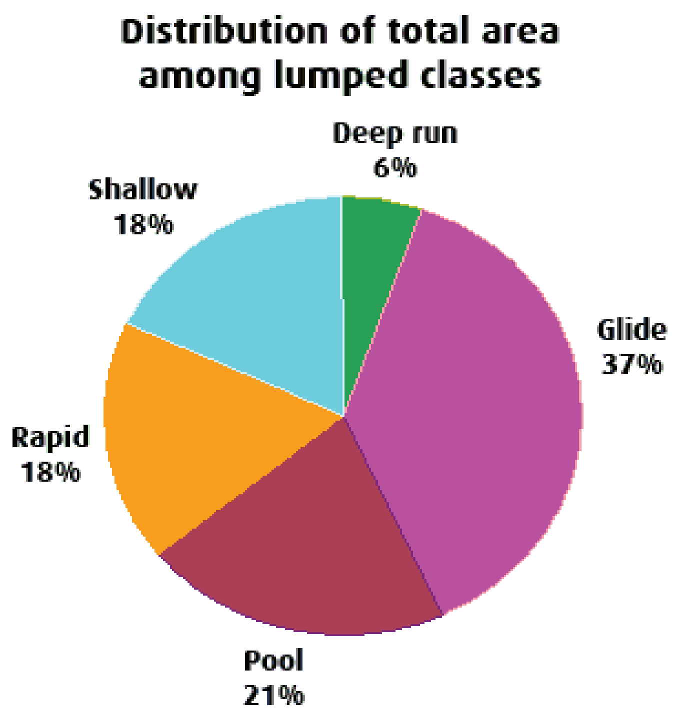


Figure 3.12: Distribution of the lumped HMU types on River Nausta

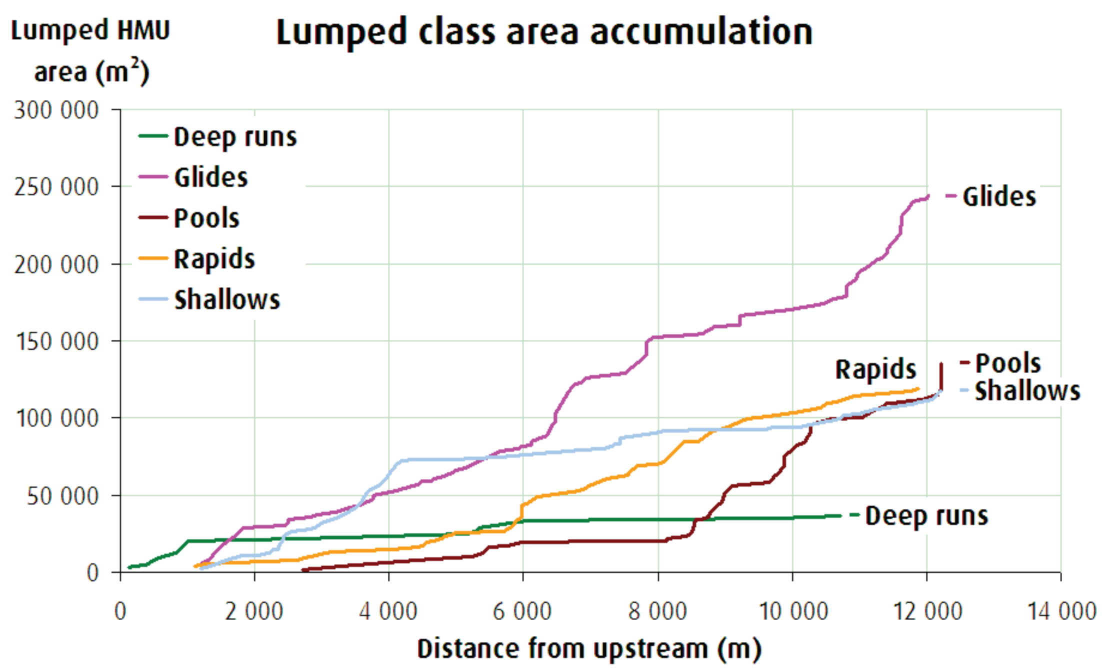


Figure 3.13: Accumulation of lumped class areas on River Nausta

3.1.4.3 Identification of possible breakpoints

It is possible to use catch averages for each class to estimate production of the reach, but the high deviation between samples probably require a finer resolution of the reach. Therefore, we should identify one or more breakpoints based on results presented above and carry out upscaling of the catch values for two or more sub-reaches.

Table 3.2 summarizes fish densities calculated from catches at each fish sampling station. Note that there is a large variation among density values, which are further analysed on Figure 3.14. All values were calculated from Table 3.2. The figure shows deviations from mean values of young-of-the-year ("YoY" on the figure) and parr catches for each sampling station. The sequence of stations on the figure follows their real sequence along the river, being "BOJ 25" the most upstream station. Even though deviation values do not show clear trends, it is clear that densities of older parr deviate negatively from average downstream from station "ST 04" and over 50% (negative value) downstream from station "BOJ 08" in all cases. We also notice that upstream from station "BOJ 09" most young of the year catches are below average values, except at stations "BOJ 18" and "BOJ 20", where opposing values appear (deviation over +150%) and at stations "BOJ 21", "BOJ 24"and BOJ 25 (deviation below +100%). A slightly less articulated, but notable change occurs around station "ST 01", upstream from which relatively high densities of both youngs of the year and parrs are observed in most cases.

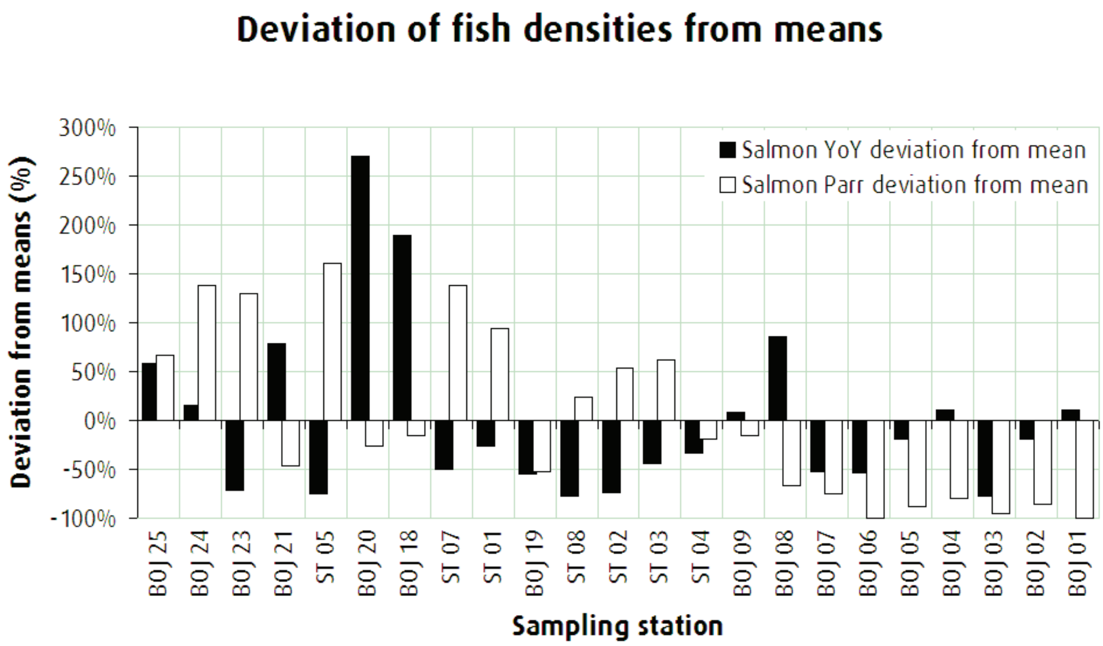


Figure 3.14: Deviation of fish densities from means of all stations at each sampling station.

Looking at both versions of class accumulation charts (original NMCM and lumped classes), we note several possible breakpoints in physical habitat accumulation. On Figure 3.3 accumulation of HMU type D shows a clear breakpoint at around 4000 m, which is obviously repeated in the lumped class accumulation chart on Figure 3.13 on the graph of “Shallows”. The other graphs do not repeat this at this breakpoint. Looking at class B2 (Figure 3.3) or “Glides” (Figure 3.13) types providing the largest portion of the reach, other breakpoints at approximately 6500, 7500 and 11000 meters are found. Class G2 (Figure 3.3) or “Rapids” (Figure 3.13) show a break at around 6000 m and B1 and C (Figure 3.3) at around 9000-10000 m, but when looking at their combination, “Pools” (Figure 3.13) the breakpoint appears at around 8000 meters.
Substrate variation as shown on Figure 3.6 shows less clear borders within the reach then the class area accumulation charts. Still, looking at the “Moving average trend lines” especially on the graph of subdominant substrate, we note a breakpoint at about 4500 m and another at around 7000 metres. The same interpolation for the dominant substrate graph shows two-three breakpoints, at 5300 m, (7500 m) and 9600 meters. The combination graph breaks at 5500 m 8800 and 9500 meters. If only the polynomial interpolation of the combined substrate graph are looked at, a maximum value at about 6500 metres is seen.
Summarizing all methods, breakpoints at around fish sampling station “ST 01” (4633 m) and “BOJ 09” (6914 m) are looked for. “ST 01” corresponds with a breakpoint in subdominant substrate distribution (4500 m), while “BOJ 09” roughly corresponds with a breakpoint in dominant substrate distribution graph (7500 m) and one in the combined substrate distribution graph (6500 m). This latter two also appear on the “Glide” graph (6500 m and 7500 m). After considering all these aspects and incorporating our local knowledge, it was decided to divide the study reach into two parts at distance about 7500 m measured from the upstream end. This place is just downstream from station “BOJ 09” at the confluence of the two arms (see Figure 3.8).

3.1.4.4 Recalculation of fish sample data

Verification of the position of fish sampling stations on the maps showed that some were incorrectly placed. The reason for this error is that these stations lay in the close neighbourhood of HMU borders and thereby little uncertainty in their actual position results in wrong classification. Thereby data presented in Table 3.2 is altered in the final calculation. If the river was divided between sampling stations upstream and downstream from border point 7500 m measured from the upstream end of the study reach, two different sets of fish density samples arise. These are then distributed and averaged among the lumped HMU types. Thereby separate production estimates for both age groups appear, for both reaches and all five lumped HMUs, giving altogether 20 (2 × 2 × 5) fish density values. Though “Deep Run” class types were not sampled, values for these are estimated from results of other previous studies. The calculated values are shown in Table 3.5.

Table 3.5: Calculated fish densities for the upper and lower reaches

Reach	Lumped class	Average of density of older parr (#/100m^2)	Average of density of YoY (#/100m^2)
upper	Glides	116	48
	Pools	n/a	n/a
	Rapids	82	34
	Shallows	80	139
	Deep runs	n/a	n/a
lower	Glides	12	65
	Pools	3	14
	Rapids	0	30
	Shallows	14	71
	Deep runs	n/a	n/a

It was shown before, that the distribution of the fish sampling stations on the study reach is not ideal for scaling purposes. The stations are unevenly distributed among both HMU types and the lumped classes, and thereby, do not represent the study reach correctly. The errors in station positioning also worsen the quality of our results. Therefore, the calculated density data was corrected by experts in fresh water fish biology using their professional judgement. Table 3.6 shows the altered values, considered in the final calculation.

Table 3.6: Corrected fish densities for the upper and lower reaches

Reach	Lumped class	Average of density of older parr (#/100m^2)	Average of density of YoY (#/100m^2)
upper	Glides	116	54
	Pools	25	15
	Rapids	82	33
	Shallows	48	125
	Deep runs	25	10
lower	Glides	9	54
	Pools	9	15
	Rapids	9	33
	Shallows	9	125
	Deep runs	9	10

3.1.4.5 Upscaling

The similarity of fish production from each station and their neighbouring HMUs, where the station is actually situated were assumed as well as for similar lumped class types within one reach (that is for example each type “Glide” has the same production of fish on the upper reach). Fish densities were multiplied with corresponding areas, so an annual production value is calculated for each lumped HMU type and reach. Table 3.7 shows the summary of this calculation.

Table 3.7: Estimated production of young fish in 2003 on River Nausta. “YoY” stands for young of the year

Upper reach			Lower reach		
Lumped HMU types	Data	Total	Lumped HMU type	Data	Total
Deep runs	Sum of older parr	8423	Deep runs	Sum of older parr	242
	Sum of YoY	3369		Sum of YoY	269
Glides	Sum of older parr	149784	Glides	Sum of older parr	28821
	Sum of YoY	69727		Sum of YoY	11528
Pools	Sum of older parr	5043	Pools	Sum of older parr	10386
	Sum of YoY	3026		Sum of YoY	62317
Rapids	Sum of older parr	49512	Rapids	Sum of older parr	5281
	Sum of YoY	19926		Sum of YoY	8802
Shallows	Sum of older parr	41835	Shallows	Sum of older parr	2685
	Sum of YoY	108946		Sum of YoY	9846
Total older parr upstream		254597	Total older parr downstream		47415
Total YoY upstream		204994	Total YoY downstream		92762

Given the areas of the lumped classes, these are multiplied with one hundredth of the separate fish density estimates (as they are expressed in number of fish per 100 m^2), which values are then summed for all lumped HMUs and reaches. So in total the production of older parr is estimated to 254597+47415=302013 and young-of-the-year to 204994+92762=370736 on the study reach.

3.1.5 Follow up studies

During 1-3 October 2004 new fish samples were collected from the reach. However these samples were not taken exactly from the 2003 stations, but partly from different ones and from seven additional ones. Altogether 31 fish sampling stations were defined and their positions were selected so that they provide a better coverage of all lumped HMU types. Unfortunately, flow did not remain steady during sampling and thereby there is a larger deviation from the original HMU map than in 2003. Results of this second phase still show large variation between densities of fish from the same type of lumped HMUs on the same reach. The reasons may be incorrect grouping of HMUs to lumped HMU groups, incorrect division of the study reach to upper and lower parts or incorrect choice of variable describing fish production (fish density). The reasons are being analysed presently and therefore are not discussed here any further.

3.2 Decision support systems to evaluate environmental impacts of hydropower peaking operation

This section describes two versions of a decision support system to be applied in river management. The final objective is to provide decision makers with a tool for optimizing management issues where hydro-economy and hydro-ecology require opposite management strategies. The evaluation of habitat quality under varying flow conditions is especially emphasized. The first version follows a classical preference based microhabitat modelling approach, whereas the second version aims at the automatic generation of HMU maps, which are then used for further analysis.

The system is based on the combined use of models constructed for various purposes. Both in version one and two the nMag model is used to simulate the operation of a hydropower system. It generates fluctuating flow values in hourly time resolution from a predefined hydropower system and runoff data as input. Killingtveit and Sælthun (1995); Killingtveit (2004) provide further information on the nMag model.

The simulated flow time series were fed in a 1D hydraulic model, DAMBRK in version one and HEC-RAS in version two. See BOSS-International (2001) for details on the DAMBRK model and HEC-USACE (1998) for HEC-RAS. The hydraulic models simulate temporally varied flow propagation in a given channel. The channel is defined by a series of cross sections and related hydraulic roughness values in both versions. The results of the hydraulic simulations provide flow, stage, velocity etc., time series for each cross section.

Version one utilizes the HABITAT model for habitat analysis. See Alfredsen (1998a) for details on the model. HABITAT generates time-dependent microhabitat distribution maps and other physical habitat describing data based on given habitat preferences from the results of the hydraulic simulations. Version two utilizes HEC-GeoRas extension of ArcView, the desktop GIS software package. See Ackerman (2002) for details on HEC-GeoRas extension and ESRI (1996) for ArcView. HEC-GeoRas requires a digital terrain model of the river channel (TIN) as input and is used both before and after performing the hydraulic simulations. The extension is first used to generate channel geometry for the hydraulic model and results of the hydraulic simulations are fed back to the original terrain model, which then serves as a platform for further analysis of habitat quality, by means of the NMCM then.

Both versions are partly automated and, in case individual system components did not provide sufficient platform for data export or import, Visual Basic scripts were used to organize internal data flow.

The two-step development was necessary, for the following reasons:

- by the time development started, NMCM was in its beginning phase, not yet ready to be applied in such a framework for habitat analysis. On the other hand, preference based microhabitat models were already tested and applied in many different situations, thereby were more suitable as an element for the first phase;
- difficulties were expected when testing the combined use of a series of models and thereby the system ought to have been well tested in its details. This way, the difficulties would then mostly be related to the actual coupling, but not the actual elements.

3.2.1 Version one – habitat analysis with classical microhabitat modelling

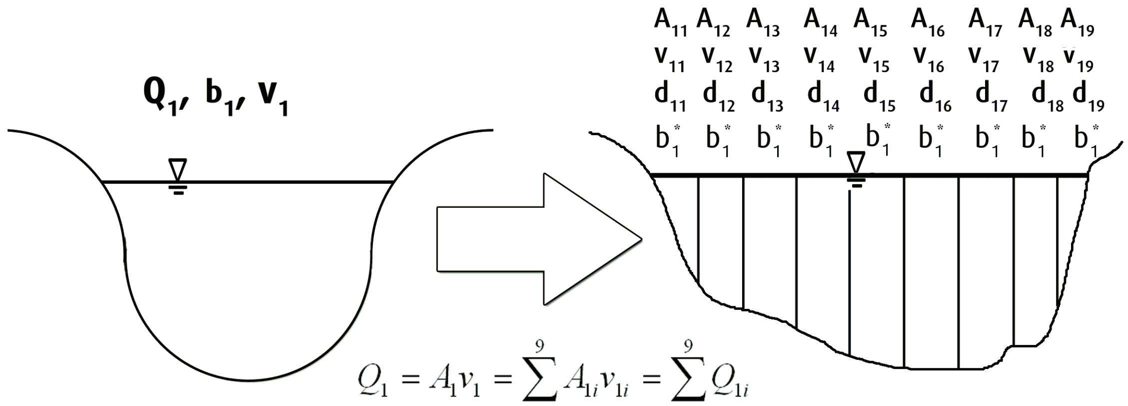
Hydropower peaking is a common economical way of producing power during hours when consumption is high (see section 1.1.2 for details on hydropeaking). But the environmental consequences of this strategy may be negative if the power plant discharges directly into a river reach. In this case, the swift water level and discharge variations may degrade habitat quality for species in the river ecosystem. Different research groups reported by Bradford (1997), Saltveit et al. (2001) and Halleraker et al. (2003) showed that the risk of stranding fish on the shore is a function of time, duration and rate of peaking, especially during daytime in the winter season. It would therefore be useful to adjust the pattern of peaking based on knowledge about physical and biological responses in the river and by this to strike a better balance between hydropower economy and environmental impacts.

The study presented here established a modelling system in order to study different peaking schemes and it consists of three major modules and their linking framework.
The Norwegian nMag model, described by Killingtveit (1999), (2004), was used for the hydropower simulations. From catchment runoff data, the model can calculate power production, discharge, spillage and other hydropower related values in a predefined system.
BOSS-International (2001) gives details on the special BOSS version of the DAMBRK hydraulic model applied here, which is able to model fluctuating river discharge regimes (such as floodwaves for example). It is a 1D hydrodynamic flood routing model, which can consider the effects of spillway and turbine flow, downstream tail-water elevations, frictional resistance and lateral inflows and outflows amongst other features.
The habitat modelling part links hydraulic modelling of the river reach with the habitat selection of different species and is described by Alfredsen (1997). Only one fish species is taken into account here under the assumption that it represents a wide range of affected animals. Preference functions describe the fish response to different hydro-physical parameters (e.g. water velocity or depth) by assigning preference values to hydro-physical parameters. All of these parameters relate to water flow, in this case, to the results of the hydrodynamic simulation. The effects of other important aspects such as cover or substrate are neglected here.
The combination of these models results in a decision support tool that gives the functional relationship between power production and the habitat availability. The connecting framework allows data to move seamlessly from one model to the other and demonstrates some of the results.

3.2.1.1 Models

The system consists of a hydropower simulation model (nMag), a one-dimensional dynamic hydraulic model (BOSS DAMBRK), a habitat model (Habitat) and the links between them. Appendix A.2 provides general description of the models utilized in this project. However the framework providing the connection between these models is not formulized in a predefined environment, therefore it is detailed here.
The selected models needed to be connected in such a way that results from hydropower simulations could be fed in the hydraulic model that in turn should provide inputs to the habitat module. The emphasis was on defining and testing useful analysis and presentation methods and less weight was put on automating the computational process.
Because the models operate on different temporal and spatial scales, it was necessary to develop scripts to transform for example nMag output discharges into inflow hydrographs for DAMBRK. Furthermore, the mean cross section velocities calculated by DAMBRK from discharge, water level and channel geometry do not comply with the basic requirements of microhabitat analysis.

When calculating habitat indices, Habitat needs a finer velocity distribution as input for each cross section of the modelled reach. Velocity distributions are calculated from the average cross sectional velocities by distributing them according to vertically dissected cross section areas. Figure 3.15 illustrates the method of dissection. At present, transformation and conversion calculations are performed manually by means of Excel spreadsheets and scripts.



$$Q_1 = A_1 v_1 = \sum_{i=1}^{9} A_{1i} v_{1i} = \sum_{i=1}^{9} Q_{1i}$$

$$9b_1^* = b_1 \qquad \frac{Q_{1i}}{Q_{1(i+1)}} = \frac{d_{1i}}{d_{1(i+1)}}$$

Figure 3.15: Distribution of average velocities within a cross section

3.2.1.2 Study site

The lower section of Nidelva, which flows through Trondheim, was used as a test case. This river is famous for its sport fishing. Like many other rivers in Norway, the river is also utilized for hydropower production, thus actual flow conditions are strongly influenced by the operation of the upstream power plants most of the time.

The study reach extends from the outlet of two hydropower stations, Nedre Leirfoss and Bratsberg, down to the river mouth that flows into the Trondheim Fjord (Trondheimsfjorden). Figure A.1.4 shows the schematic of the hydropower system releasing water to the study reach and appendix A.1.1 provides further details on the location. Nedre Leirfoss is an over 100 years old power plant and is run with almost continuous flow of 30-40 m^3/s, its capacity is 60 m^3/s presently. Nidelva has a fixed minimum flow regime of 30 m^3/s which is usually provided by this plant. Bratsberg is a modern power plant with peaking capability. Its intake is at the large regulating reservoir Sebusjøen and the outlet of the tailwater channel discharges at the same place as Nedre Leirfoss. The capacity of this plant is 103 m^3/s.

According to measurements, an immediate complete shutdown from full to zero production results in drop in discharge from ~130 m^3/s to ~40 m^3/s within 5-6 minutes at the tailwater outlets. The drop in discharge attenuates as getting further from the outlets downstream, for example about 5 km from the discharge drops within 40 minutes, while another 5 km further downstream it takes more than one hour for the river to reach minimum flow. Figure 3.16 shows modelled hydrographs at three different cross sections, each about 5 km-s from each other with the same upstream flow release as boundary condition in the model.

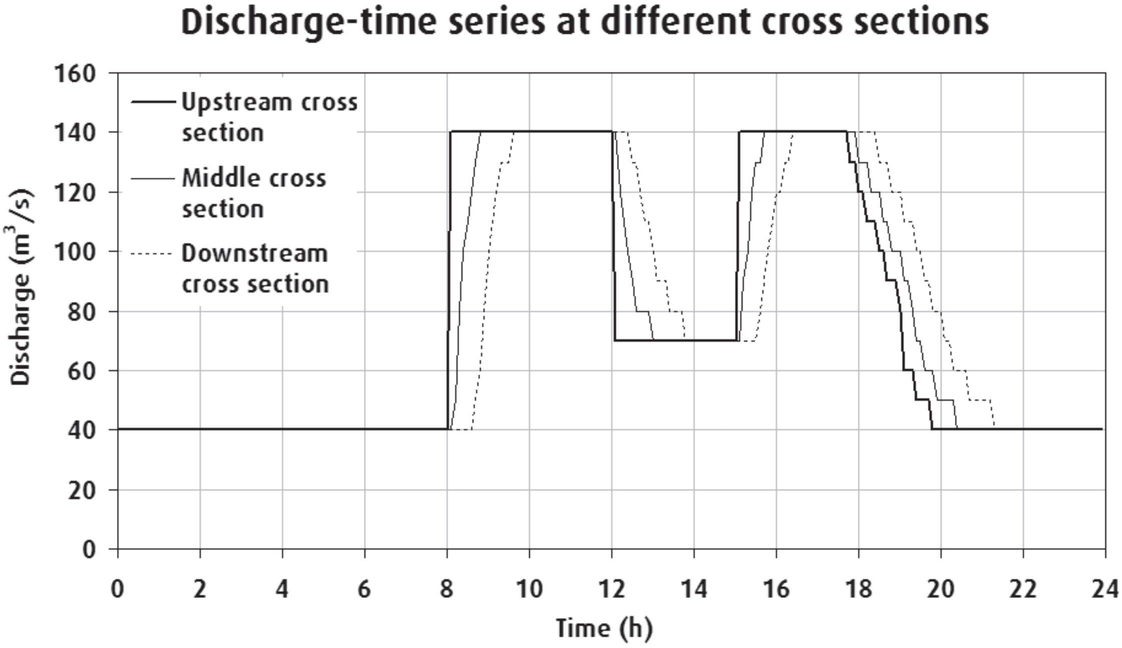


Figure 3.16: Flood propagation approaching downstream on Nidelva during peaking power production

Two different peaking strategies were specified in the study. They are referred to as "normal peaking" and "habitat friendly peaking". Both strategies aim at producing the same value each day. During normal peaking, the simulated discharge drop occurs abruptly as it usually does in reality in most cases. During habitat friendly peaking the power plant is not shutdown immediately. After starting the shutting down process, there is still some production initially. The production then drops at low level, but still high enough to prevent damaging machinery due to e.g. cavitation on the turbines, or to be uneconomical due to inefficient production. The lowest possible production level is set to 30% of the maximum capacity of the turbines. Shutdown is completed over two hours in two steps. The two peaking strategies are shown on Figure 3.17.

It is important to know that Bratsberg power station has two turbines of equal capacity, about 103 m^3/s maximum discharge total. Our strategy builds on the following configurations:

- both turbines at maximum capacity (103 m^3/s);
- one turbine shuts down (52 m^3/s);

- both turbines at 30% (31 m^3/s);
- one turbine shuts down, the other at 30% (21 m^3/s).

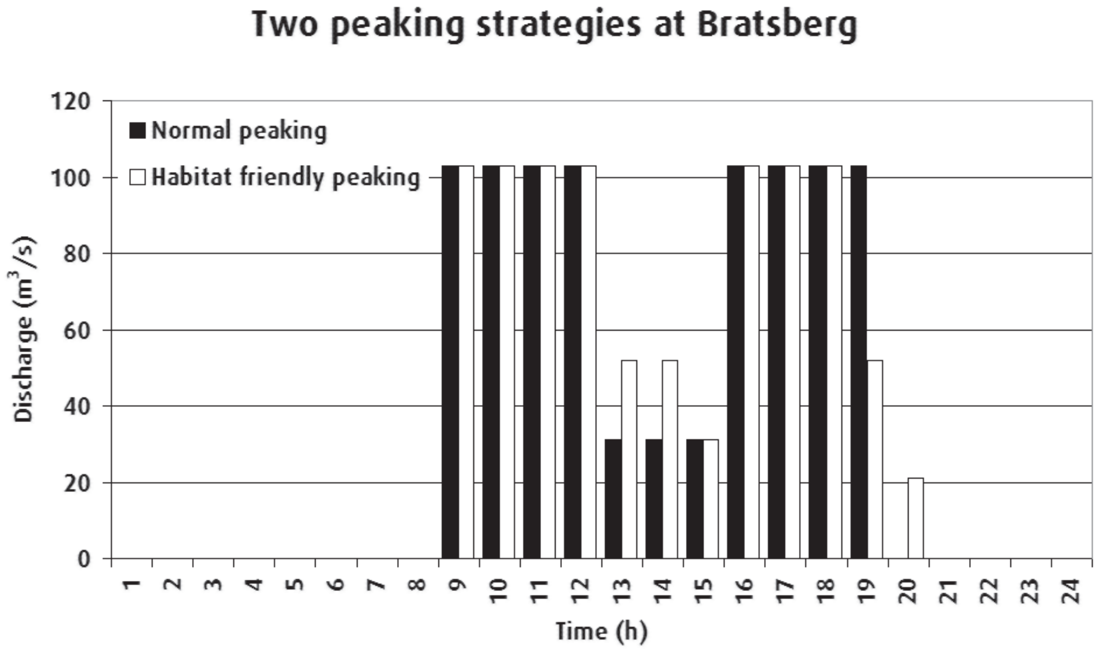


Figure 3.17: Two strategies tested for the peaking power plant in the model

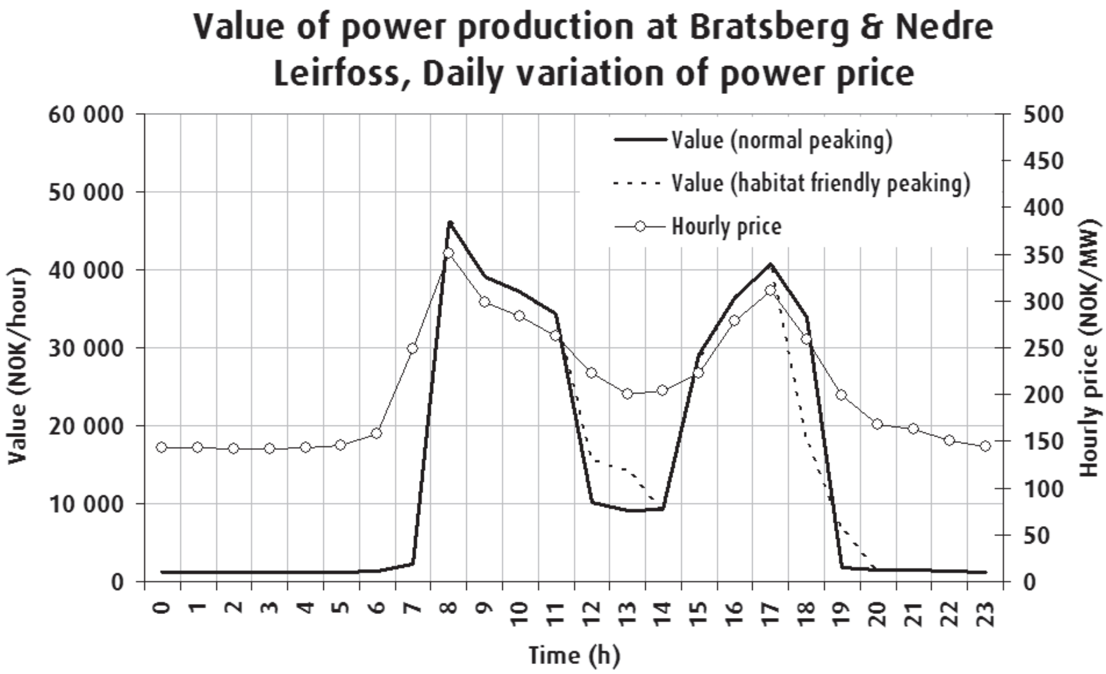


Figure 3.18: Sum value of power production in Bratsberg and Nedre Leirfoss and hourly power price

Table 3.8: Calculation table to compare values of production in the two peaking strategies

Time (h)	Bratsberg		Nedre Leirfoss		EEKV× 3600 kW/m³		Production (MW)		Power price	Produced value (NOK)	
	Normal peaking	Habitat friendly peaking	Normal peaking	Habitat friendly peaking	Bratsberg	Nedre Leirfoss	Normal peaking	Habitat friendly peaking		Normal peaking	Habitat friendly peaking
0	0	0	40.3	40.3	1188	216	8.7	8.7	143.56	1250	1250
1	0	0	40.3	40.3	1188	216	8.7	8.7	142.65	1242	1242
2	0	0	40.3	40.3	1188	216	8.7	8.7	141.49	1232	1232
3	0	0	40.3	40.3	1188	216	8.7	8.7	141.63	1233	1233
4	0	0	40.3	40.3	1188	216	8.7	8.7	142.43	1240	1240
5	0	0	40.3	40.3	1188	216	8.7	8.7	145.69	1268	1268
6	0	0	40.3	40.3	1188	216	8.7	8.7	157.87	1374	1374
7	0	0	40.3	40.3	1188	216	8.7	8.7	248.63	2164	2164
8	103	103	40.3	40.3	1188	216	131.1	131.1	351.31	46045	46045
9	103	103	40.3	40.3	1188	216	131.1	131.1	298.51	39125	39125
10	103	103	40.3	40.3	1188	216	131.1	131.1	283.70	37185	37185
11	103	103	40.3	40.3	1188	216	131.1	131.1	262.18	34363	34363
12	31	52	40.3	40.3	1188	216	45.5	70.5	222.63	10137	15691
13	31	52	40.3	40.3	1188	216	45.5	70.5	200.23	9117	14112
14	31	31	40.3	40.3	1188	216	45.5	45.5	203.39	9261	9261
15	103	103	40.3	40.3	1188	216	131.1	131.1	222.57	29172	29172
16	103	103	40.3	40.3	1188	216	131.1	131.1	278.38	36486	36486
17	103	103	40.3	40.3	1188	216	131.1	131.1	311.08	40773	40773
18	103	52	40.3	40.3	1188	216	131.1	70.5	258.12	33831	18192
19	0	21	40.3	40.3	1188	216	8.7	33.7	199.20	1734	6704
20	0	0	40.3	40.3	1188	216	8.7	8.7	168.52	1467	1467
21	0	0	40.3	40.3	1188	216	8.7	8.7	163.29	1421	1421
22	0	0	40.3	40.3	1188	216	8.7	8.7	150.24	1308	1308
23	0	0	40.3	40.3	1188	216	8.7	8.7	144.04	1254	1254
								Sum:		343682	343562
							Loss related to normal::			120	NOK/day

Besides the physical limitations of the installation itself, the idea behind the actual design of the two strategies is to produce approximately similar amounts of capital value. To calculate produced value energy equivalents of the power stations and an estimation of the daily power price must be included. Table 3.8 shows the calculation procedure and Figure 3.18 shows the results. Only the two downstream power plants considered in this calculation: Nedre Leirfoss operating continuously on 40.3 m^3/s in both strategies and Bratsberg following the peaking strategy described above.

It is important to note, that the proposed strategies serve as guidelines in the hydropower model and are not necessarily fulfilled every day through the modelled period. In case an upstream reservoir reaches its lowest regulated water level, the required discharge cannot be provided downstream any longer. Similarly, if a reservoir reaches its highest regulated water level, the required discharges will be exceeded; since there is no more storage capacity upstream, spillage occurs. These phenomena result in further differences in the production values of the two strategies.

Experimental preferences for Brown Trout (*Salmo trutta*) were used for habitat simulation, assuming that these preferences are valid all over the study reach. This assumption is not verified, but is accepted for the present purposes. Figure 3.19 shows graphs of the calculated Habitat Suitability Indices for depth and mean column velocity (HSI curves) in the ranges of 0-1 m and 0-1 m/s respectively. HSI curves are normalized with actual availability of ranges of variables and take values between -1 and +1, where -1 mark avoided ranges and +1 mark preferred ranges. See section 1.2.5.2 for more about preferences of species.

We carry out simulations for two years data, 1937 and 1938. The runoff series for these are shown on Figure 3.20. The years were selected from the period 1931-1960 as a consecutive wet and dry sequence. 1937 in the series is the dry, while 1938 is the wet year. Figure 3.21 shows an overview of the reach and a simplified scheme of the hydraulic model.

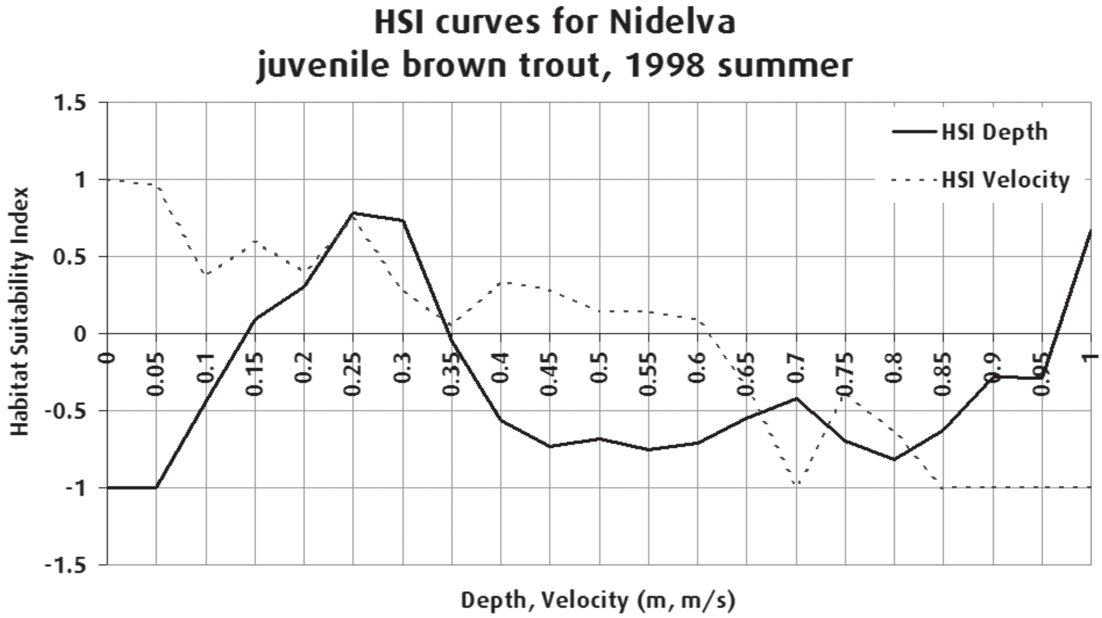


Figure 3.19: Habitat Suitability Indices for depth and mean column velocity in Nidelva.

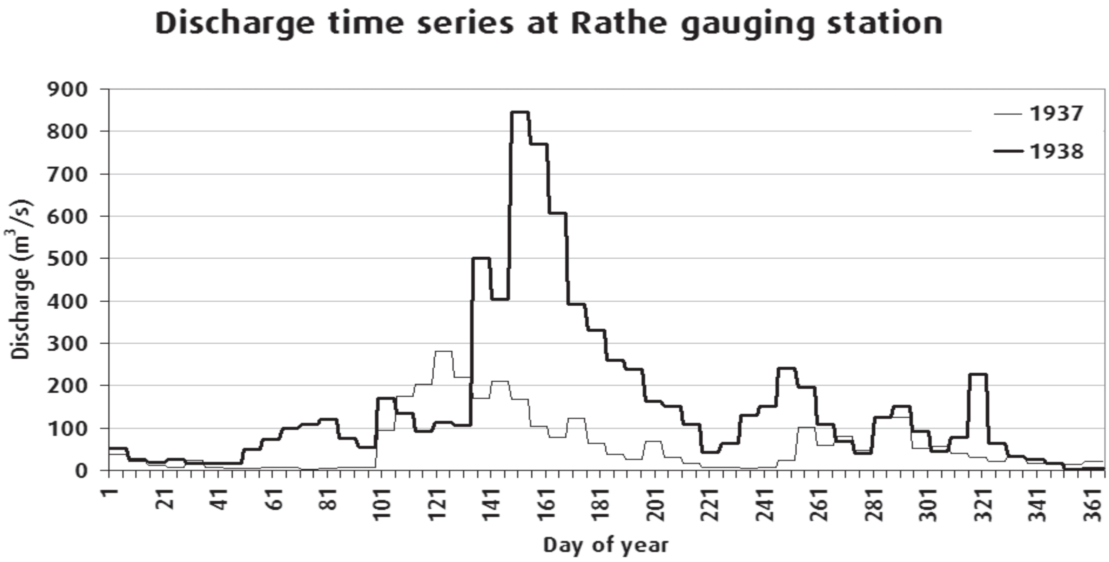


Figure 3.20: Discharge time series measured at Rathe gauging station for simulation years 1937 and 1938

3.2.1.3 Results of version one

Habitat variations were examined first, by means of microhabitat-based methods on a selected simulation day both when Normal or Habitat friendly strategies are followed. Habitat index values were calculated along the reach at each hour of the day. Table 3.9 and Figure 3.22 show habitat suitability graphs on the study reach. A separate panel shows variations of total usable, indifferent and avoided areas. The three different panels allow the cases of Normal and Habitat friendly peaking to compare easily. It was assumed that the larger the total area of usable habitats is and the longer their extent is maintained in time, the better the habitat quality is. Habitat quality is related here only to distribution of depth and velocity. Conversely it was also assumed, that if avoided conditions stabilize for long periods, or if usable areas change abruptly to avoided, fish are likely to be negatively affected. Saltveit et al. (2001) for example report that if usable areas appear more often during peaking, or if the habitat is changed in a gentle manner, the physical habitat is probably less degraded.

Habitat plots help visualizing the habitat distribution on the model reach. The plots show the four evening hours when most of the differences are found between the two strategies. Figure 3.23 shows five pairs of plots following both Habitat friendly and Normal peaking strategies. For ease of representation only situations for hours 18, 19, 20, 21 and 22 are shown. The different colours on the plot mark the habitat quality between the model cross sections. Green circles note the most important differences due to the two strategies. By comparing the two series of habitat plots, critical sites, i.e. where usable areas turn into avoided areas with flow decrease can be located. Only plots based on velocity preference are shown.

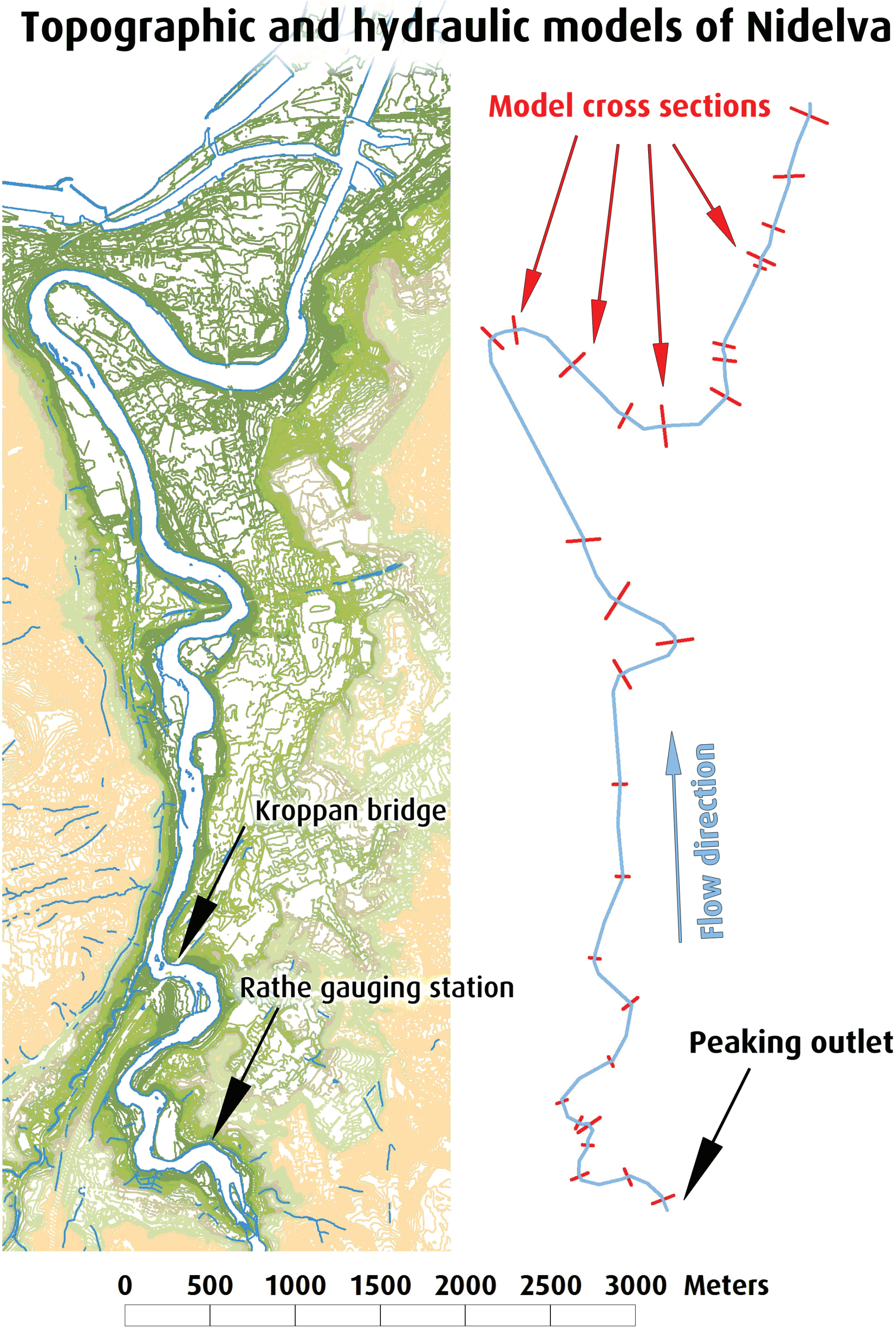


Figure 3.21: Topographic and hydraulic model maps of Nidelva

3.2.1.4 Discussion of version one

Figure 3.22 shows that by applying Normal peaking strategy, avoided conditions ensue around one hour longer in the evening (18:00-19:00). Moreover, the Habitat friendly strategy results in usable areas first becoming indifferent and then avoidable rather than changing abruptly. These suggest that in our case Habitat friendly peaking gives indeed better conditions in terms of habitat quality maintenance than Normal peaking.

Comparing the plots on Figure 3.23, we note that habitat distribution at 18:00 and at 22:00 on the modelled day are equal, the different strategies give similar results. However, in the meantime, the variation occurs in different ways. At 19:00 we note a difference on the downstream part of the study reach, which seems better on the Habitat friendly peaking plot. We noted before (Figure 3.16) that flood wave propagation takes longer than one hour through the whole study reach, thereby it is impossible that the differences appear due to the different strategies. The hydraulic model incorporates tidal variations as downstream boundary condition, these must the reason for flow velocity variations at 19:00. At 20:00 on the modelled day, we see some slight changes on the middle of the reach and downstream. These show better situations in case of Habitat friendly peaking mid-upstream but surprisingly for Normal peaking as well as mid-downstream. Close to the fjord (the estuary) the Habitat friendly strategy results in better habitat situation. At 21:00, the situation is slightly better on the middle of the reach at Normal peaking, but remains the same at the downstream end of the reach at Habitat friendly peaking.

The production differences for the two strategies are calculated for the whole two-year long period. Following Habitat friendly peaking strategy 434.18 M NOK is produced with 2200 GWh firm power level during the two years. Following Normal peaking strategy, 434.66 M NOK is produced with the same firm power level as before. The difference between produced capital in the selected two years is 0.48 M NOK, where Normal peaking produced more money according to the model.

Concluding the achievements of version one, we note that the idea of linking the hydropower simulation model through dynamic hydraulic simulations to a physical habitat model is possible and useful because it enables the evaluation of different hydropower production strategies by incorporating both economical and environmental means. We proposed two different standardized strategies of peaking. Normal peaking represents a usual peaking method when opening and closing turbines occur abruptly, while Habitat friendly peaking represents a peaking method that smoothens the shutdown procedure, reducing ramping rates. We showed that Normal peaking has more adverse effects on physical habitat than Habitat friendly peaking, however the proposed Habitat friendly strategy comes with a price, a loss in produced capital. The differences were more pronounced in distribution of total habitat areas than when comparing actual locations of the study reach. Further studies could focus more on details of effects of seasons, dry or wet years, or other strategies as well.

Table 3.9: Distribution of combined habitat on the model day

	habitat friendly peaking			normal peaking		
hour of modelled day	usable	indifferent	avoidable	usable	indifferent	avoidable
8:00	523 173	161 032	28 770	523 173	161 032	28 770
9:00	501 299	118 409	141 795	501 299	118 409	141 795
10:00	501 981	132 817	176 314	501 981	132 817	176 314
11:00	502 156	157 344	151 612	502 156	157 344	151 612
12:00	466 943	192 556	151 612	466 943	192 556	151 612
13:00	446 274	184 871	146 975	446 274	184 871	146 975
15:00	429 379	205 032	98 336	429 379	205 032	98 336
16:00	350 593	167 792	227 675	350 593	167 792	227 675
17:00	279 495	157 341	339 153	279 495	157 341	339 153
18:00	278 461	167 819	344 978	279 495	175 415	336 348
19:00	291 722	268 600	228 111	289 134	157 310	344 989
20:00	480 460	140 531	126 300	449 444	114 941	212 782
21:00	485 641	158 974	68 360	485 641	158 974	68 360
22:00	578 528	105 677	28 770	578 528	105 677	28 770
average	436 865	165 628	161 340	434 538	156 394	175 249
difference	+2 326	+9 235	-13 909			

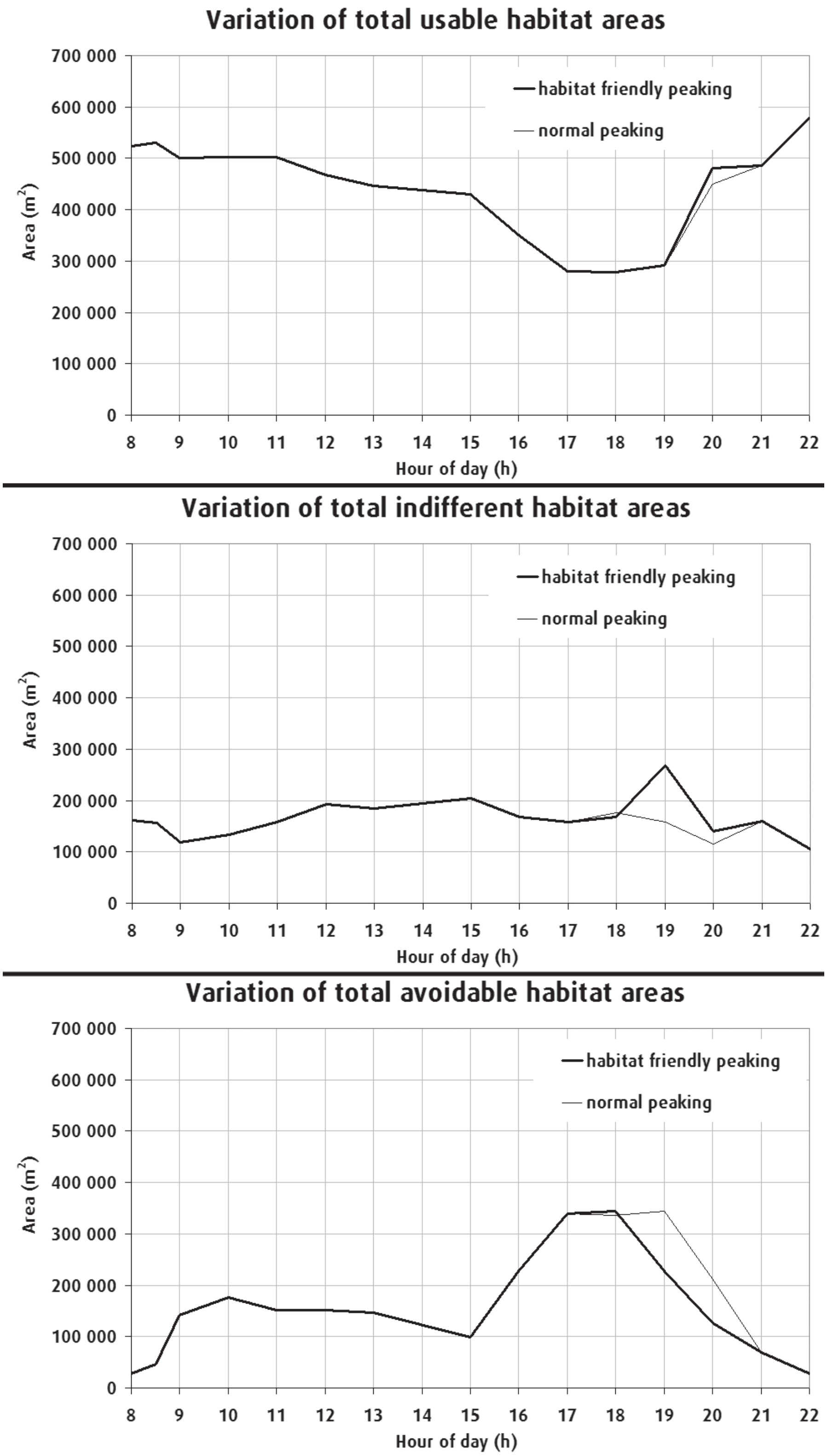


Figure 3.22: Variations in areas of combined depth & velocity habitat on one day

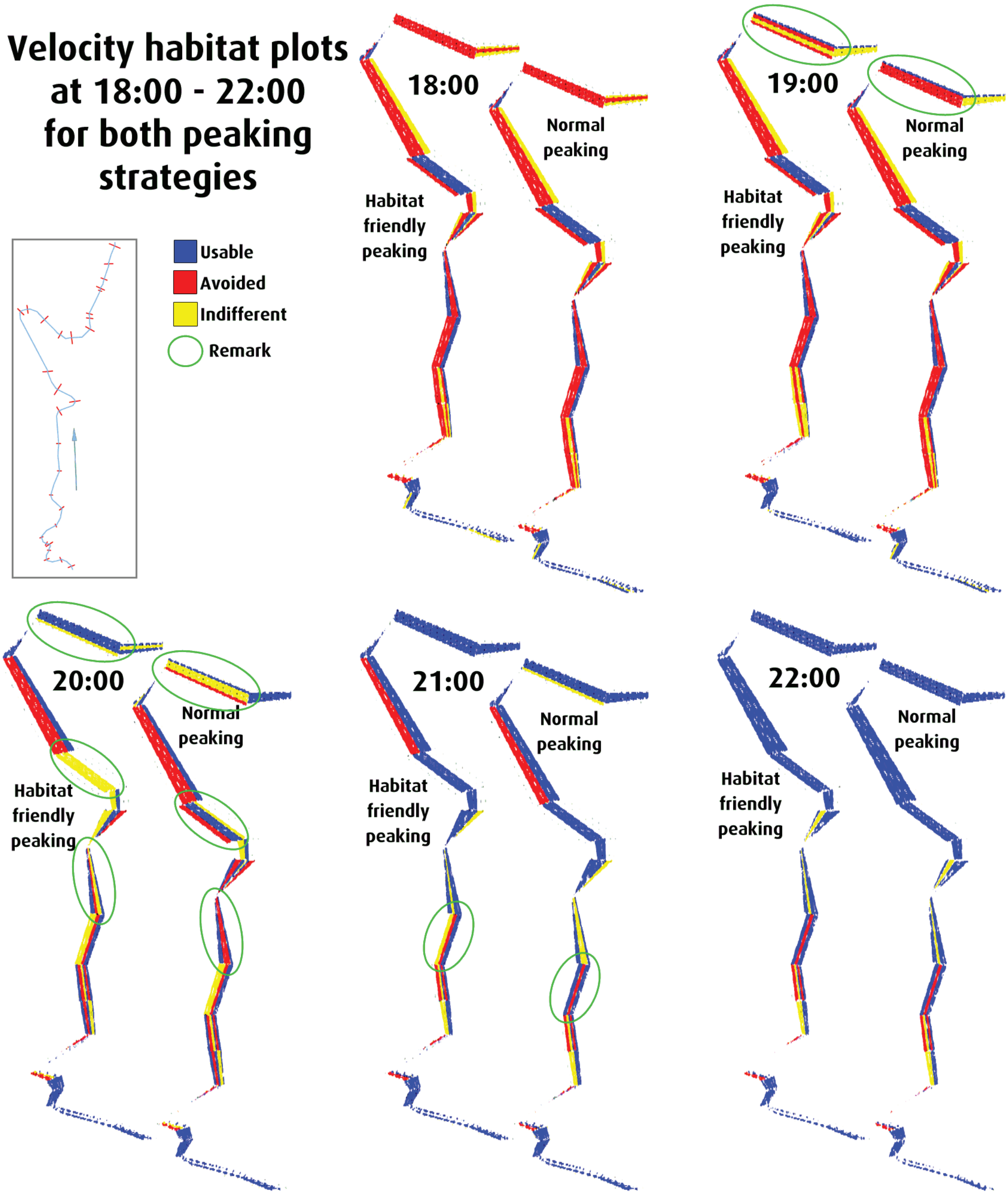


Figure 3.23: Habitat plots at 18:00, 19:00, 20:00, 21:00 and 22:00 on the simulated day following both peaking strategies. The plots are shown in pairs for each time. The left plots show situation when Habitat friendly peaking is applied and right plots when Normal peaking is applied.

3.2.2 Version two – habitat quality assessment based on mesohabitats

Recent development in technology allows to utilize more suitable models for the purposes described in the previous section. These developments include the following:

- possibility of running dynamic hydraulic simulations in HEC-RAS,
- the improved connection between Microsoft Excel and the HEC-DSS database storage system,
- the use of large capacity field-data collection devices and finally
- the automatic channel-generation and result analysis tool HEC-GeoRAS, which provides a link between a DEM in a GIS and the hydraulic model.

The new possibilities arising from these are that:

- the cross-section transformation and velocity distribution steps (necessary for DAMBRK) can be eliminated,
- data flow from the hydropower production model to the hydraulic model is more simple, because the result files generated by nMag can be read to Microsoft Excel with the help of the previously developed scripts. This data can be written directly to a HEC-DSS database, which is then read by HEC-RAS at run-time, as upstream (flow) boundary condition. The same database may be used to store downstream (stage) boundary condition as well,
- large amount of topographical data can be collected and utilized, enabling generation of channel form in a statistically proper and hydraulically more flexible manner, not limiting us to previously measured and placed (thereby fixed) cross sections, and finally,
- the use of a digital elevation model (DEM) through GIS together with the hydraulic model makes possible the repeated and more thorough, comprehensive analysis of any scale of physical habitat between micro and reach scales,
- the elements of the NMCM are partly possible to incorporate to the same GIS, thereby providing a different habitat analysis tool than in version one

3.2.2.1 Purpose

Summarizing the possibilities and plans, the present proposed system had two purposes:

1. Compare economic consequences of the two peaking strategies preferably for a period of several years.
2. Automatically generate HMU maps based on results of the hydraulic simulation in the GIS and provide means to analyse them.

3.2.2.2 The models included

Appendix A.3 describes the models and software packages utilized in this study. As in the first version, nMag was used for hydropower simulation. Peaking flow data from the Nea-Nidelva system provided flow input for HEC-RAS, a dynamic one-dimensional hydraulic model, through the HEC-DSS database system. Channel topography was generated by the HEC-GeoRAS extension in ArcView 3.3 from a triangular irregular network (TIN) topographical model representing the channel and its surrounding areas. The results from the hydraulic simulation were fed back to the original GIS, where depth, velocity, slope and their combinations show physical habitat information. Cross section-wise velocity distribution is approximated by HEC-RAS based on the conveyance parameter. See HEC-USACE (1998), (2002) for scientific background of the hydraulic calculations.

3.2.2.3 Model setup

Similar peaking strategies were followed as in section 3.2.1. A completely new part is introduced to the system by utilizing GIS and linking it to the hydraulic model. Communication between these modules was readily made by the providers of the software packages. Physical habitat analysis then naturally took also place in the GIS module.
The same hydropower system as in the first version, the Nea-Nidelva catchment in Central-Norway was modelled using historical runoff data. The same peaking strategies were tested as in version one. Normal peaking strategy incorporates the highest possible magnitude of fluctuations and Habitat friendly strategy incorporates the technically smoothest possible flow decrease (Figure 3.17). The resulting simulated flow-time series at the outlets of Bratsberg and Nedre Leirfoss power plants (see Figure 3.21) were fed into the hydraulic model via a HEC-DSS database as upstream boundary condition. The downstream boundary condition imitates the tide variation in Trondheimsfjorden: a stage-time series was applied for this purpose.

HEC-RAS & HEC-GeoRAS

The US Army Corps of Engineers develops the RAS modelling system for simulation of one-dimensional steady and unsteady flows. It replaced DAMBRK in the present version to carry out the dynamic hydraulic computations. Please note that previous versions of HEC-RAS and the HEC2 software were designed to simulate steady-state flows only. This limitation is not valid for versions HEC-RAS 3.x and above. See HEC-USACE (2002) for details on the computation limitations and the numerical solution applied in the software package. Channel geometry and the flow data components have to be specified as input to the model. HEC-RAS has the advantage over DAMBRK that it is able to utilize the original cross-section data, no transformation of the field measurements are necessary. In addition, the model can estimate velocity distribution at each cross section based on conveyance parameters. HEC-USACE (2002) provides details of the velocity distribution method used in HEC-RAS. It is important to note that this method is only an estimation of velocity distribution, because a 1D hydraulic model is theoretically incapable to simulate and address 2D flow features. Nevertheless it was assumed that higher order hydraulic simulations were not feasible to carry out (by for example developing a 2D or 3D model of the study reach), therefore this source of error was accepted as best present solution for the purposes of the study.

The channel geometry was obtained from a digital elevation model (DEM) by means of ArcView's HEC-GeoRAS extension. The model channel included data on flow paths, stream lines, left and right overbanks, cross section cutlines and other optional channel features. These were used to generate the 3D channel geometry. Thus, an almost complete HEC-RAS geometry file (channel model) could be generated automatically from field data. In the present case, only hydraulic roughness values had to be added. Hydraulic roughness values were estimated by calibration for one flow.

Clearly, the quality of the DEM is crucial for the hydraulic model, which was the most challenging to prepare in this case. Even though high quality data were readily available of banks and surrounding dry areas, riverbed topography (bathymetry) had to be modelled.

Bathymetry (DEM)

Although not playing a crucial role in the analysis, and as such, not being the primary problem in this project, channel generation turned out to be a difficult part. Historical cross section data was only utilized first for generation of the full 3D elevation model. The lowland-type channel-profile, meandering, islands and uneven distribution of the measured sections altogether resulted in difficulties when interpolating the channel and caused generation of unsatisfactory results. If cross section cutlines for automatic generation of the hydraulic model in the following step were selected in between the historical ones (which were used for generating the DEM itself), the generated cross sections were unrealistic in shape and thereby unusable.

Therefore additional topography points were collected by means of two sets of differential global positioning systems (DGPS) and a device for mapping bathymetry (Echo Sounder). One DGPS and the Echo Sounder were operated jointly and this combined instrument collected horizontal coordinates and depth values. In paralell, the other DGPS was used to collect coordinates of points on the water edge. The vertical coordinate values collected by the joint DGPS-Echo Sounder instrument had a known error that exceeded our expectations and therefore were not considered for further calculations. This is the reason for using the DGPS for collecting high accuracy points on the water edge. These points were used to generate a water surface model for the entire modeled reach. Coupling the depth data and a water surface model was used to improve our original DEM, which then could be used in the further development of the modelling process.

Errors in the DEM generation

Due to limitations of the Echo Sounder, depth values in shallow water were not recorded. In cases water depth was below measurement limit of the device (about 30 cm), only the X and Y coordinates were logged. These points were assumed to lay in a depth at most 45 cm below water surface (30 cm measurement limit + depth of immersion, about 15 cm) when generating the channel bathymetry. To distinguish between error logs due to limitations of the device and actual false values, only erroneous points within 10 m from the water edge were included in the calculations later.

Another type of error occurred when the GPS part of the Echo Sounder lost the communication with the base station and did not reconnect automatically. The chosen method for employment of the Echo Sounder (kayaking in the river) did not allow the continuous surveillance of the instrument and thereby in such cases no data was logged until kayaking was stopped and communication re-established between the GPS parts. This error caused discontinuity in the mapping, which later was visible in the interpolated channel as well.

3.2.2.4 Economical results

The economical analysis is performed by comparing production and monetary production values for the two peaking strategies in different periods calculated by the nMag model. Three years are selected in the reference period 1931-1960, which represent a dry, a median and a wet year. Two averages were compared for each of these years. One takes average production over the whole modelled period, which for example in case of the median year 1933 would cover years 1931, 1932 and 1933. The other only considered the actual year, but incorporating the historical simulations preceding that. In case of the median year this would involve simulation of the period 1931-33, but taking production averages only from 1933. The selected years were 1933 as median, 1937 as dry and 1938 as wet years. Table 3.10 shows the simulated values. Figure 3.24 shows charts of average production only for Bratsberg for the selected years and Figure 3.25 shows values over the entire period preceding each selected year and the entire hydropower system.

Table 3.10: Comparison of average production values for different periods and peaking strategies

Average production (GWh)	Normal peaking	Habitat friendly peaking	Difference (Norm-HabFr)
1931-60 (reference)	2373.89	2377.34	-3.45
1931-33 (median)	2523.57	2528.41	-4.84
1931-37 (dry)	2466.89	2472.50	-5.61
1931-38 (wet)	2473.54	2479.23	-5.69
Average value (M NOK)			
1931-60 (reference)	463.89	464.77	-0.88
1931-33 (median)	485.59	486.09	-0.50
1931-37 (dry)	477.84	478.40	-0.56
1931-38 (wet)	471.27	471.80	-0.53
Average production Bratsberg (GWh)			
1933 (median)	62.37	62.33	0.04
1937 (dry)	43.86	43.22	0.64
1938 (wet)	60.47	61.33	-0.86

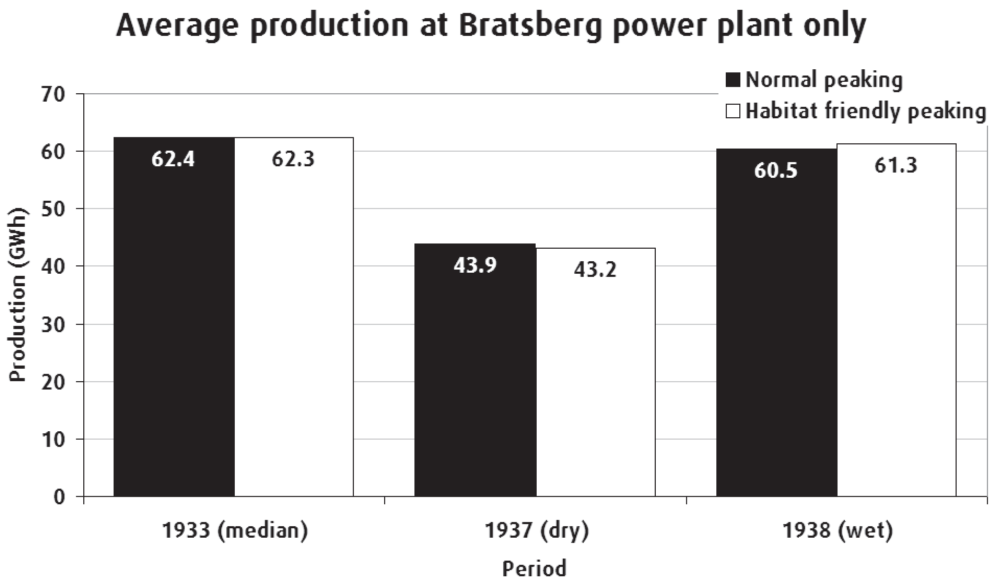
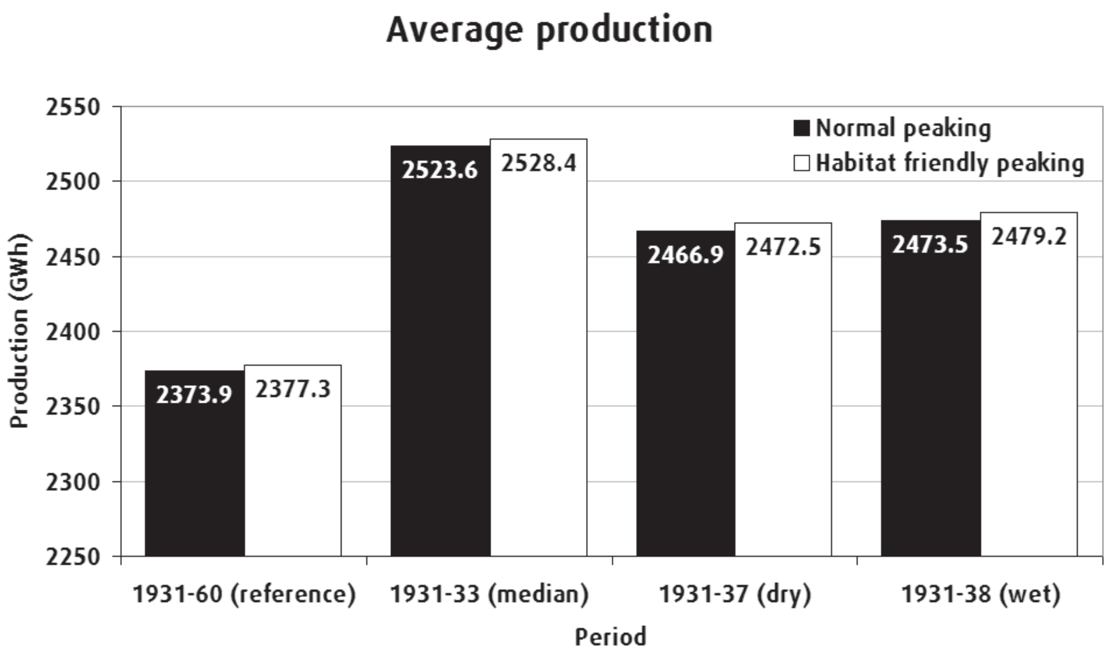


Figure 3.24: Average annual production in Bratsberg power plant in selected years. Extracted from simulation period 1931-1960



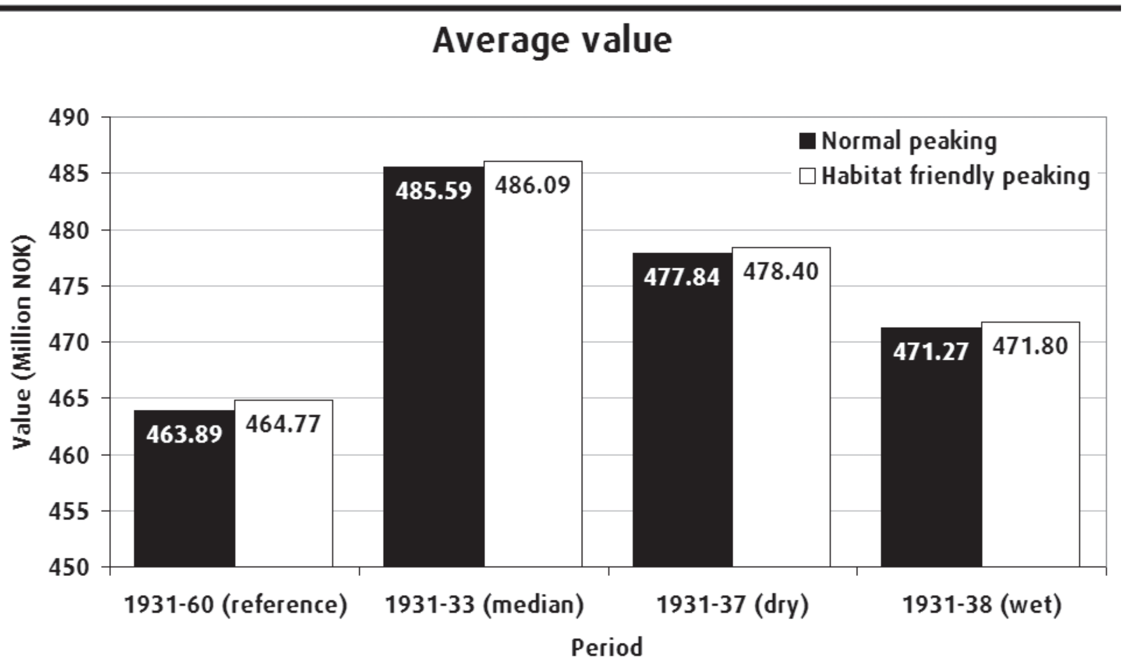


Figure 3.25: Average annual production values considering the entire period preceding the selected median, wet and dry years for both peaking strategies. Values for period 1931-1960 provided for reference

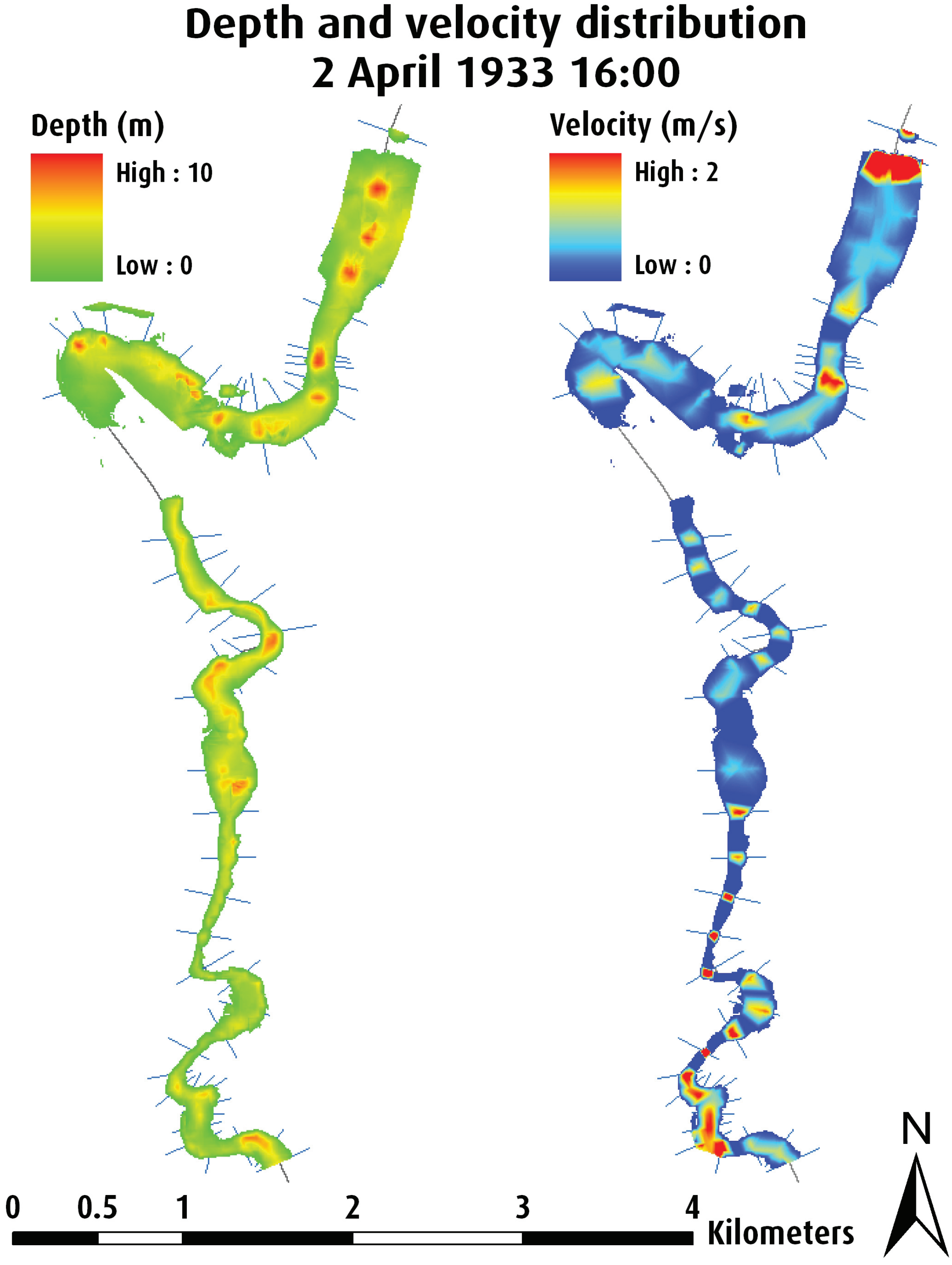


Figure 3.26: Simulated depth and velocity distribution maps used for trouble shooting. Snapshot taken at 16:00 on the modelled day.

3.2.2.5 Habitat simulation results

The problems mentioned in relation with the DEM generation made it difficult to ensure the overall quality of the habitat analysis. Figure 3.26 shows distribution of depth and velocity values on the study reach. The upstream part of the reach was considered to be more realistic than the downstream part. The "better-modelled" part lies between the tailwater channels of the Bratsberg and Nedre Leirfoss power plants and Kroppan bridge (see Figure 3.21 for location of the bridge).

Habitat analysis is limited to a shorter period than economical analysis, because the software packages employed did not allow generation of infinite amount of depth and velocity distribution maps. Therefore one day in the simulation period was selected, where the different peaking strategies resulted in two different flow generation patterns from the hydropower system. The hydrographs for this day are shown on Figure 3.27. Please note that the mid-day drops were overridden by the model due to other prioritized rules in operation startegy and only the evening drops in flow appear.

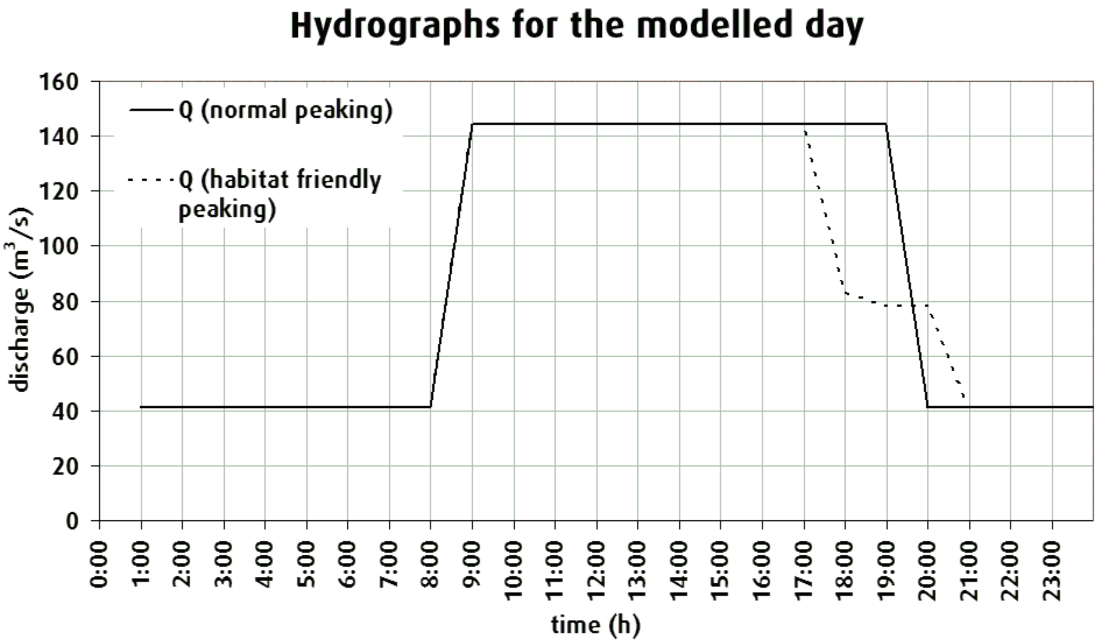


Figure 3.27: Hydrographs for the model day for normal and habitat friendly peaking strategies at the most upstream section of the hydraulic model

Due to limitations in 1D hydraulics simulation, results can only provide cross-section-wise depth distribution and one mean velocity value for reach cross section (see section 1.2.5.5 for differences between 1D, 2D and 3D hydraulic models). The cross-section-wise distribution of mean velocities is estimated utilizing the conveyance parameter between the cross sections. Depth and velocity points from cross sections are used to generate a full 3D map of the distributions and so maps were produced as shown on Figure 3.26. Such maps could be generated for each simulation time step (1h in this case) and analysed by GIS tools. Slope and surface flow type are not possible to simulate within reasonable error tolerances by means of a 1D hydraulic model and thereby were neglected here. This way the distribution of four HMU types, deep-fast, deep-slow, shallow-fast and shallow-slow were calculated.

The maps generated for hours 16, 17, 18, 19 and 20 on the simulated day were classified in two different ways. The NMCM classification criteria (0.7 m for depth and 0.5 m/s for mean velocity) were first considered (referred to as “NMCM rules” below) and for second a statistical classification, the ranges and distribution of the simulated data, referred to as “relaxed rules”. These were divided into groups with equal amount of samples. Table 3.11 shows the total areas for both classification methods, peaking strategies and the four HMU types. Figure 3.28 shows the results in chart form following NMCM classification and Figure 3.29 following statistical classification. Figure 3.30 and Figure 3.31 show the actual HMU plots following normal and habitat friendly peaking respectively, both classified according to NMCM criteria. Figure 3.32 and Figure 3.33 show plots based on the same data sets, but classified according to statistical criteria.

Discrepancies in depth and velocity simulation data were suspected due to known problems of the DEM and the fact that 1D hydraulics cannot produce multidimensional results. For this reason maps of water surface variations between each simulated hour on the modelled day were generated, as shown on Figure 3.34. The maps are based on water surface values only, which feature was used for calibrating the model. The calibration was considered to be reasonably accurate. Water level variations were classified following the results of Halleraker et al. (2003), considering risk of stranding of young fish.

Table 3.11: Variation of simulated HMU areas in time on modelled day 16:00 – 20:00 following both peaking strategies, classified according to NMCM standards and relaxed, statistical standards. Values given in m²

	16:00	17:00	18:00	19:00	20:00
Normal peaking, NMCM classification					
slow-shallow	137988	138164	140712	143000	150648
slow-deep	1543476	1521872	1495072	1478928	1447920
fast-shallow	4404	4648	5052	4724	4632
fast-deep	35368	38380	40756	35492	30356
Habitat friendly peaking, NMCM classification					
slow-shallow	137588	138164	142100	145920	149864
slow-deep	1543476	1521872	1483224	1444328	1412236
fast-shallow	4404	4648	5044	4728	4504
fast-deep	35368	38380	37528	29088	22504
Normal peaking, relaxed, statistical classification					
slow-shallow	520492	514440	497800	501972	473120
slow-deep	272076	271500	279836	275672	283852
fast-shallow	317464	329080	323288	318496	318824
fast-deep	611564	597528	583844	59644	553972
Habitat friendly peaking, relaxed, statistical classification					
slow-shallow	517584	539208	484732	488380	459040
slow-deep	268076	306488	273560	292040	279832
fast-shallow	319528	294964	336316	308872	311884
fast-deep	615648	562404	573288	534772	538352

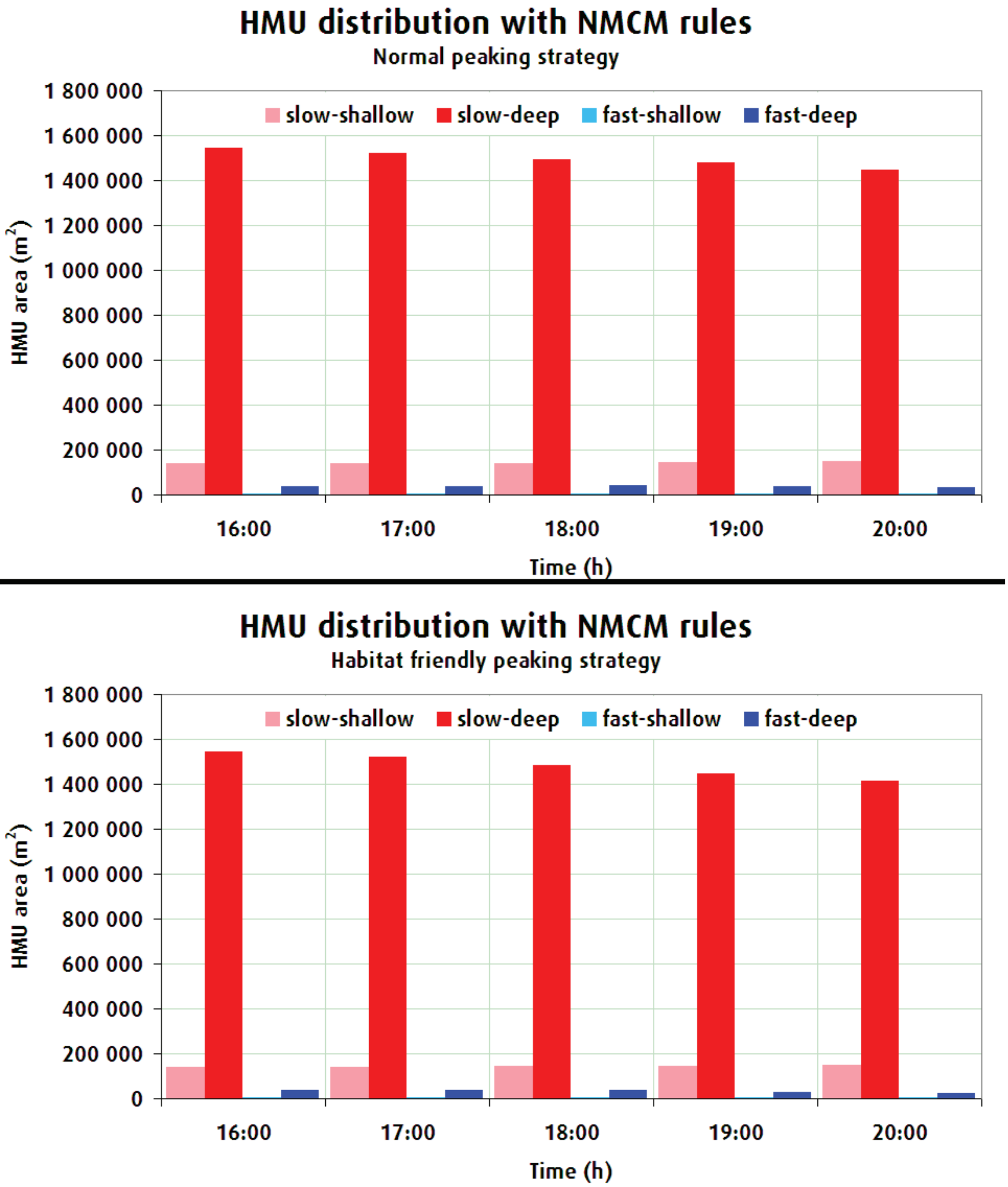


Figure 3.28: Variation of simulated HMU areas in time on modelled day 16:00 – 20:00 following both peaking strategies, classified according to NMCM rules

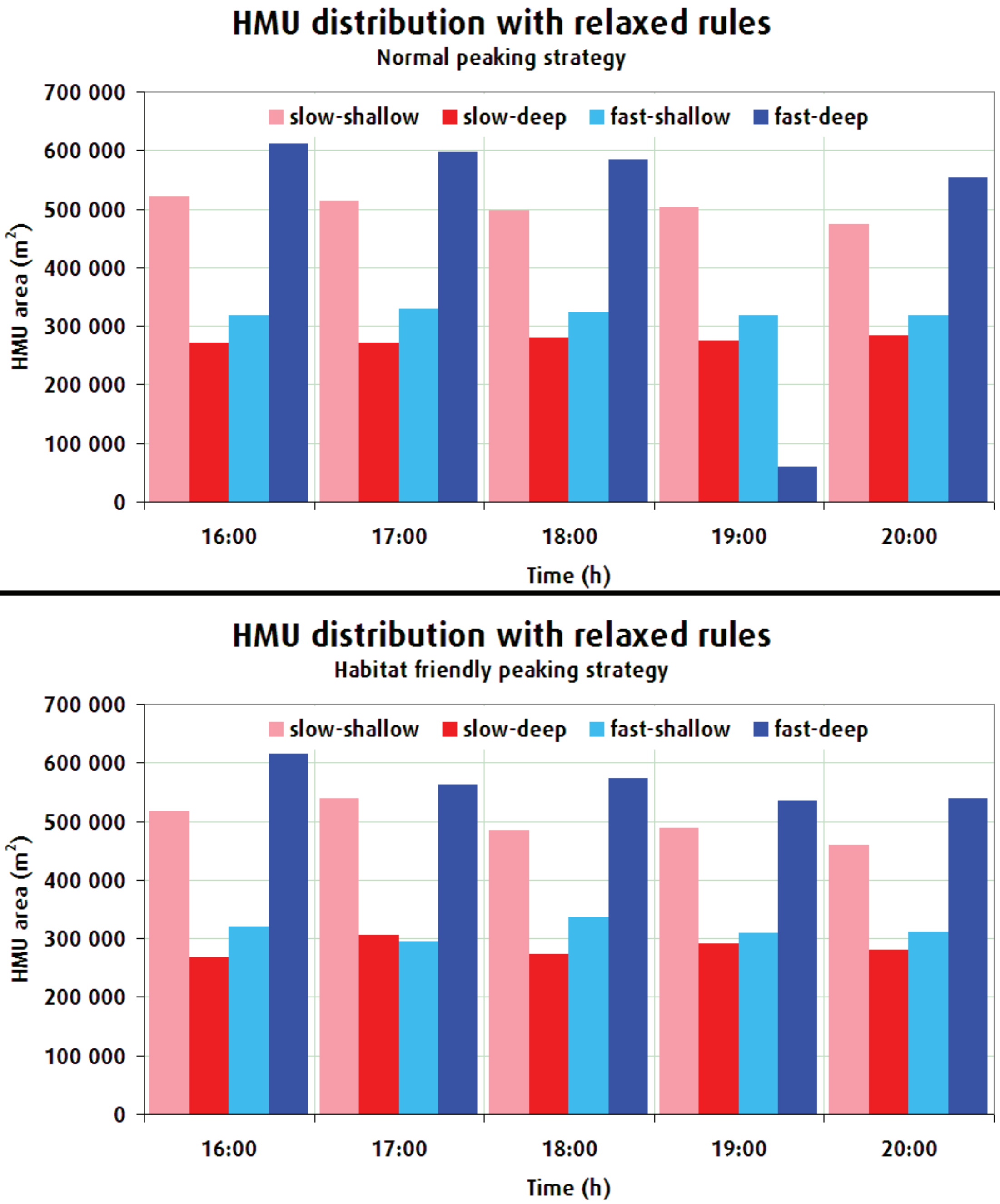


Figure 3.29: Variation of simulated HMU areas in time on modelled day 16:00 – 20:00 following both peaking strategies, classified according to relaxed rules

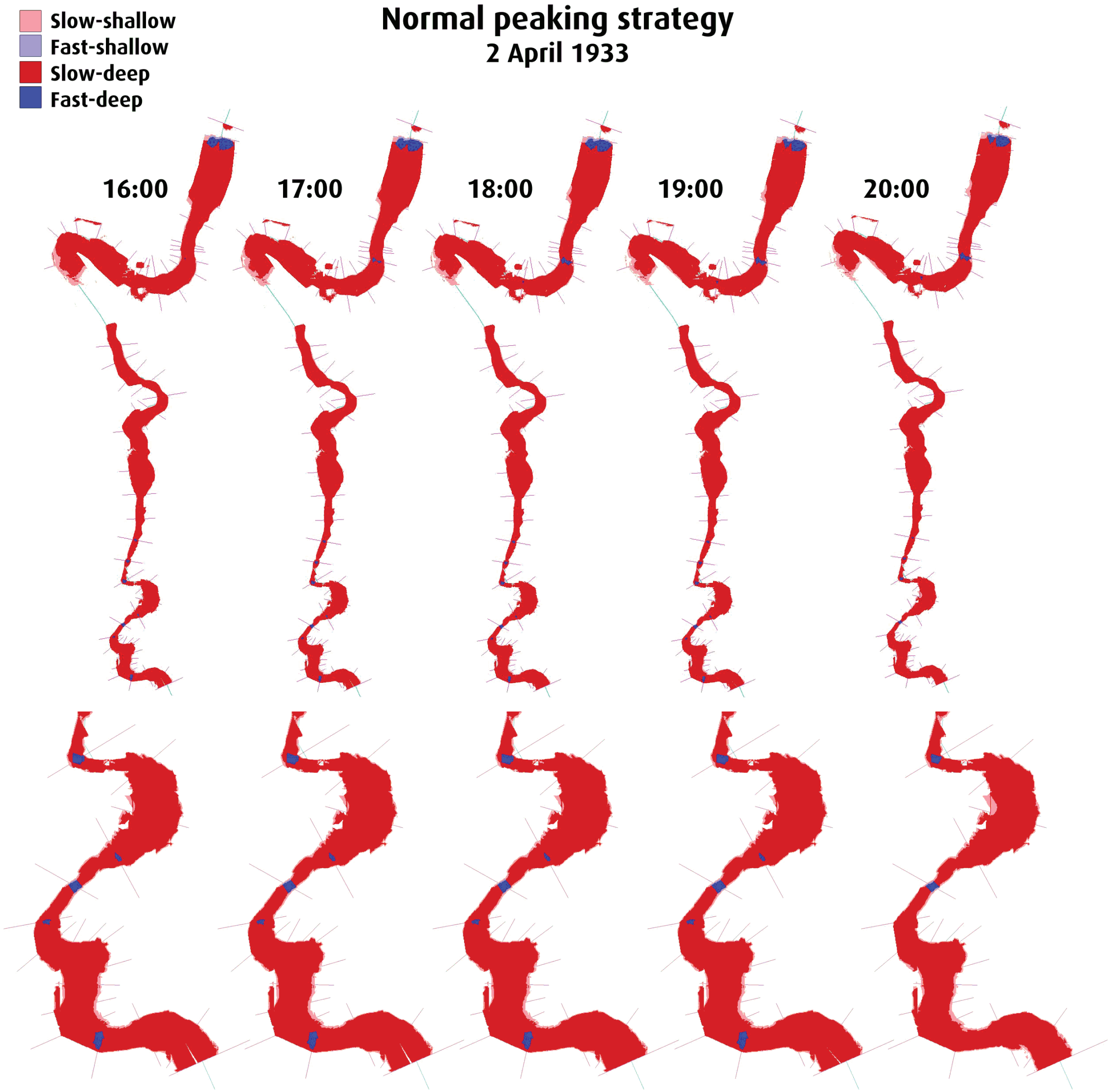


Figure 3.30: HMU plots following normal peaking with NMCM rules

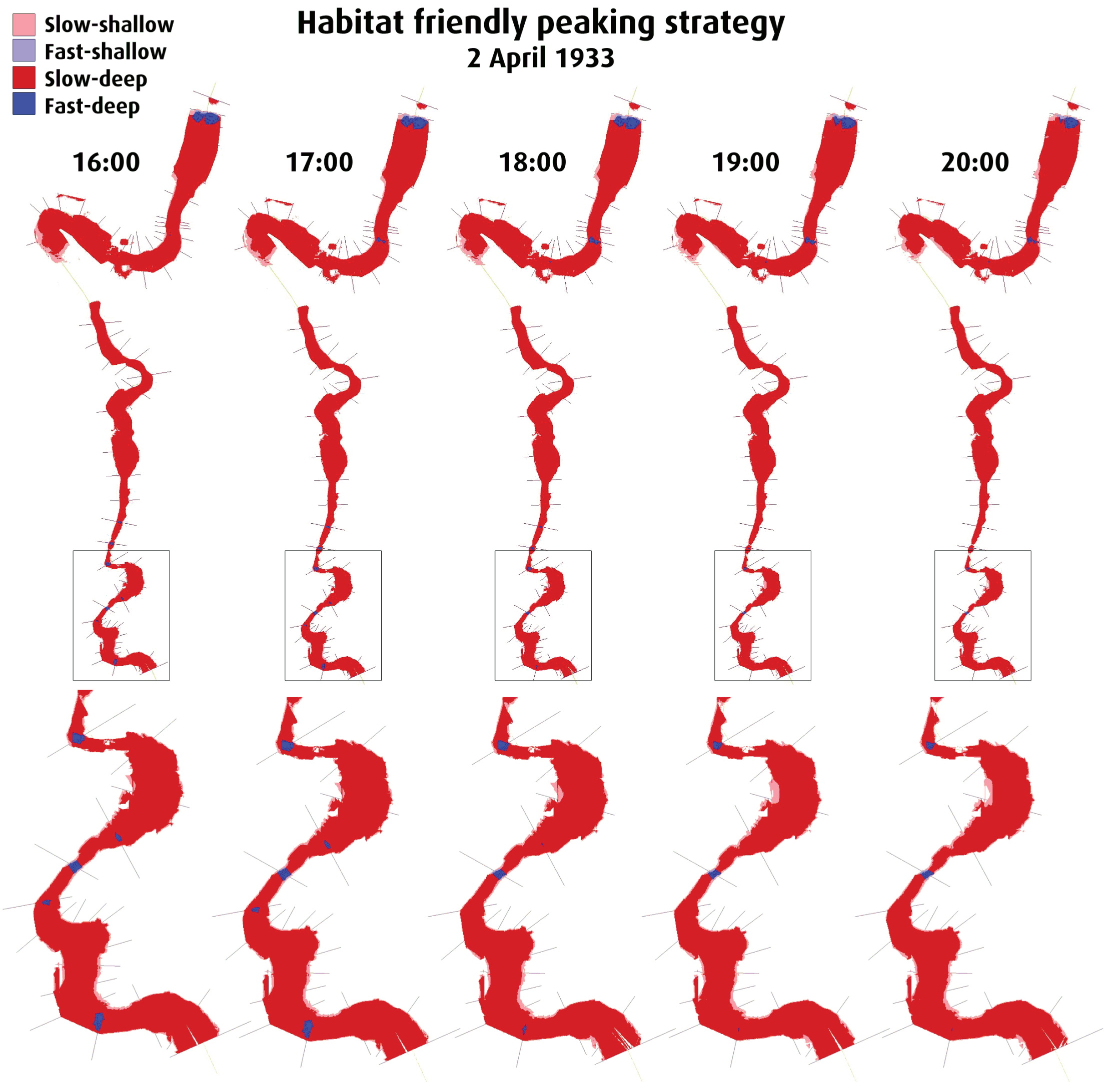


Figure 3.31: HMU plots following habitat friendly peaking, NMCM rules

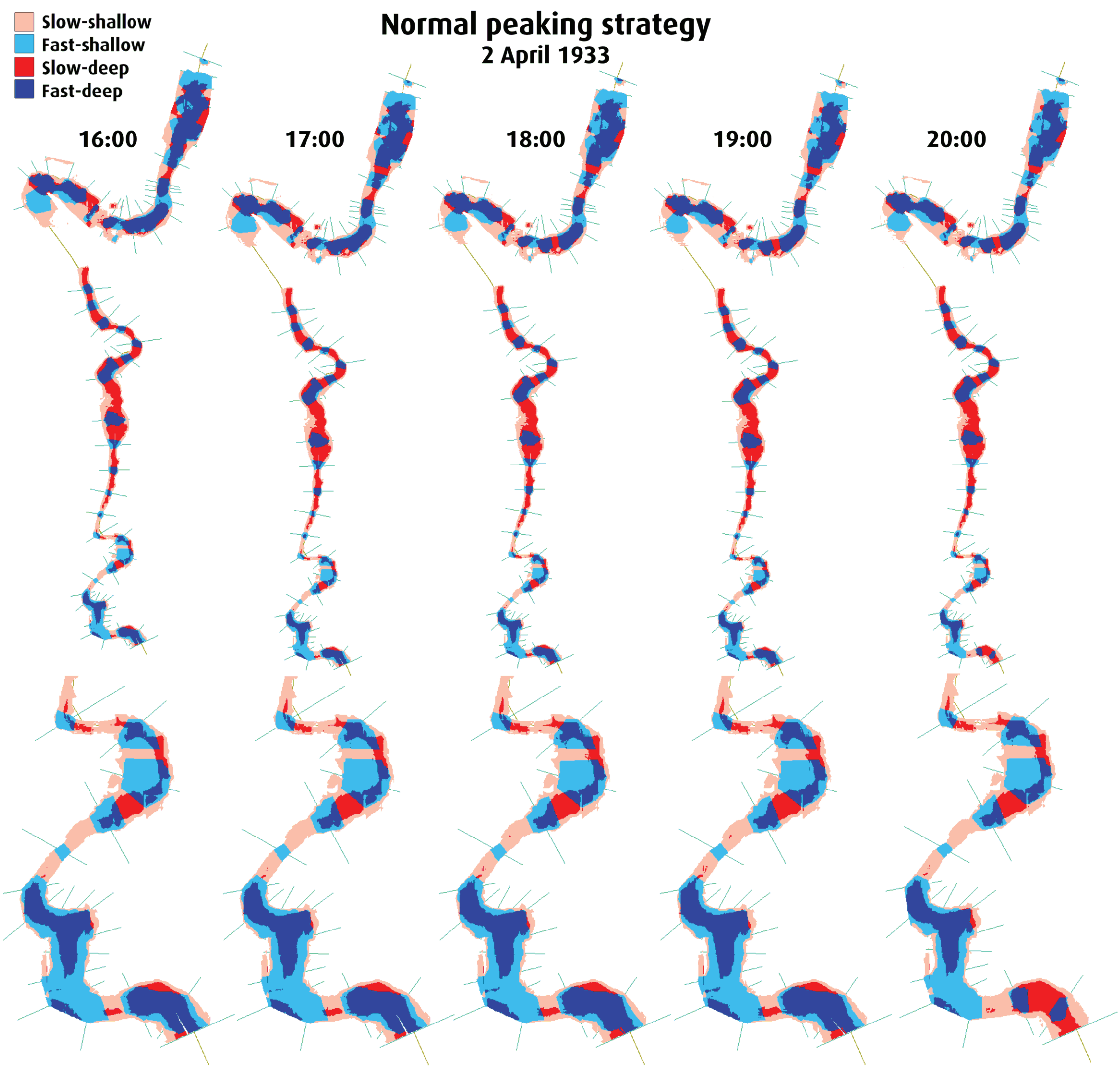


Figure 3.32: HMU plots following normal peaking, statistical rules

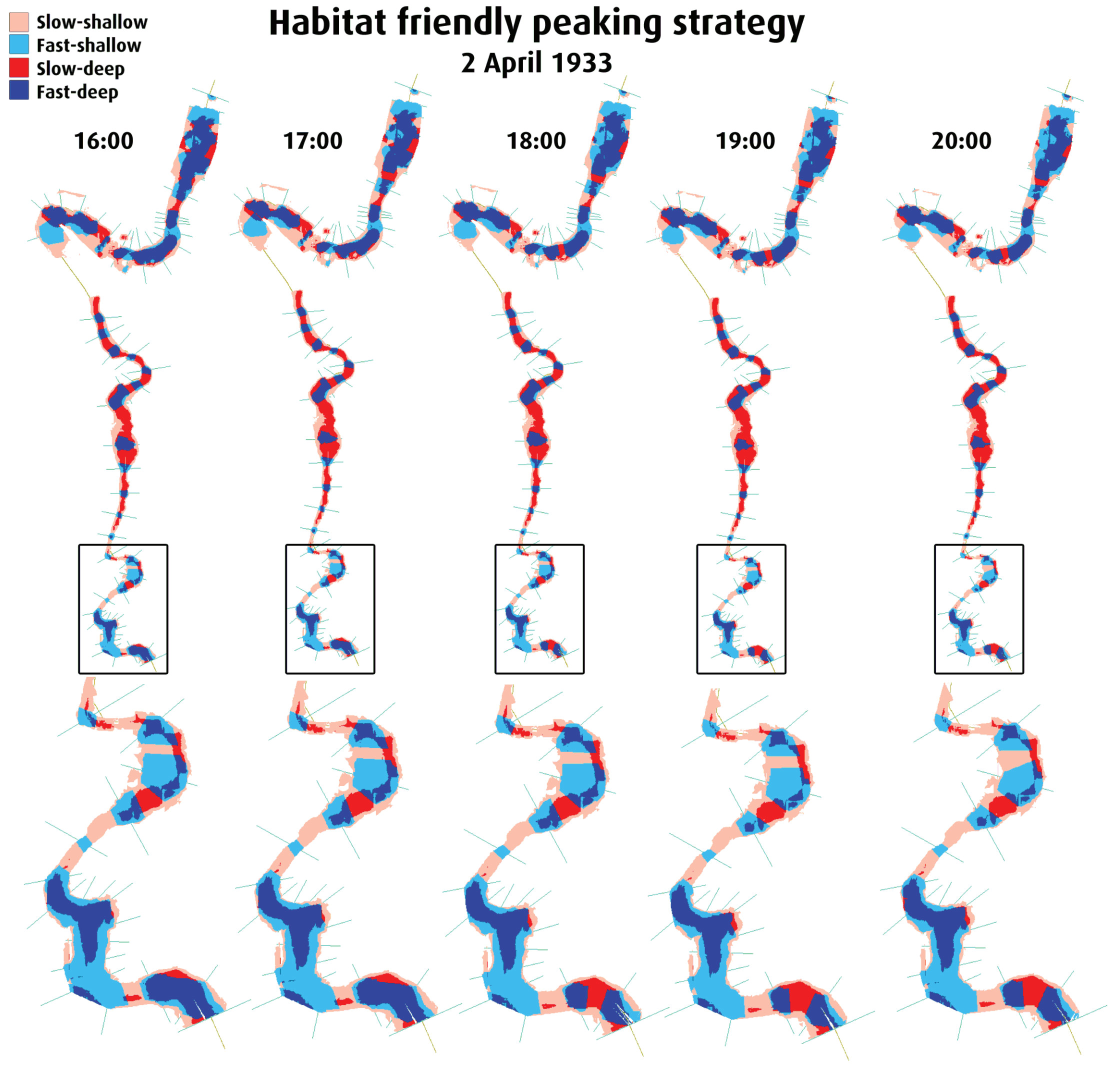


Figure 3.33: HMU plots following habitat friendly peaking, statistical rules

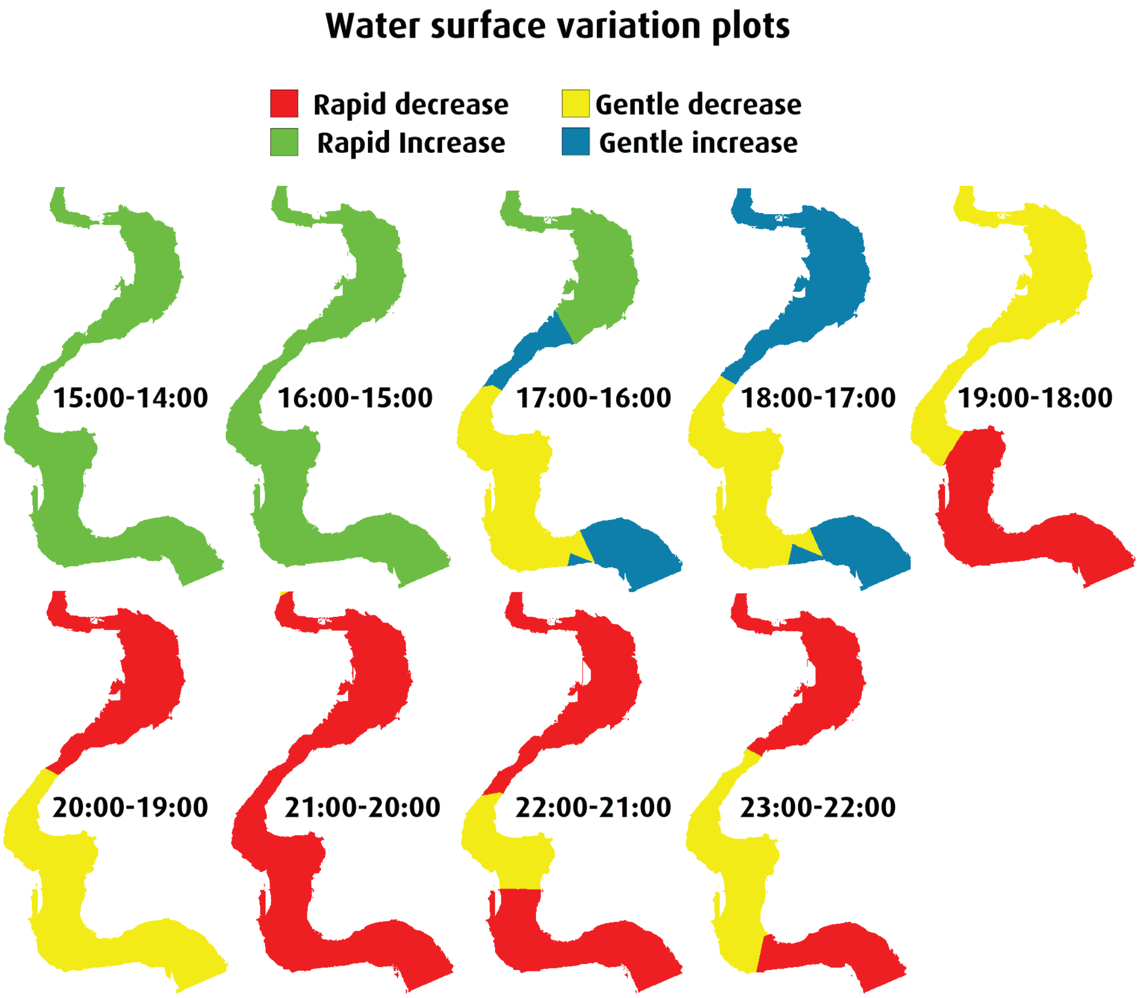


Figure 3.34: Water surface variation plots during one modelled day, Habitat friendly peaking

3.2.2.6 Discussion

Economical results of production and production values suggest that the different peaking strategies have minor effects on long-term production results. It seems that actual runoff and its distribution has a stronger effect here. Figure 3.24 shows that there is almost no difference between the two strategies in average annual production if a separate year with average runoff is simulated (0.1 GWh). There are slight differences in separate dry and wet years, higher production following normal peaking in the dry and higher production following habitat friendly peaking in the wet year. The differences are 0.7 and 0.8 GWh respectively. The values refer to production only at Bratsberg power plant.

When comparing average annual production in periods ending at normal, dry or wet years, but including their production history from the previous years as well, different sum values result and somewhat different trends (not strongly pronounced). Values of average annual production as shown on Figure 3.25 were always higher following habitat friendly peaking strategy than in case of normal peaking according to our simulation. It must be noted, that in a real life situation the peaking strategies are frequently revised according to actual situation in reservoir volume, runoff and consumption forecasts among other parameters. So the presented results should not in any circumstances be considered as real-life examples, because the operation strategies were left intact throughout the entire simulation period. This may result in unrealistic simulation results, especially regarding the two theoretically designed peaking strategies, but for such purpose, a theoretical comparison are still feasible.

The set of velocity habitat plots allowed the comparison of distribution of velocity habitats resulting from habitat friendly peaking in the two versions. Comparison of parts of Figure 3.23 and Figure 3.26 are difficult since in version one only a schematic represents the study reach not imitating the real wetted areas. Version two provides a better overview of the extents of the reach, but the different classification criteria don't allow overlaying the maps directly on each other.

The two different classification criteria (NMCM and relaxed) for presenting the simulated HMU maps show the imperfection of simulation results. For verification, the original HMU surveys of Nidelva may be used as shown on Figure 2.6. Compare these maps with those presented on Figure 3.30, Figure 3.31, Figure 3.32 and Figure 3.33. It is clear that the results on the simulated maps are strongly influenced by the position of cross sections used in the DEM generation. In the neighbourhood of almost every cross sections, velocity values are higher and depth values are lower than at locations elsewhere. This phenomenon indicates the discontinuity of gradients of the DEM at these cross sections. In order to overcome this problem, probably equvalent density of terrain points need to be achieved for DEM generation. However, neglecting some of the available cross section points, gradually degrades the overall quality of the DEM. During generation of the present DEM, these ideas were considered, and thus the results are the best available with the given dataset.

Not being able to produce depth and velocity results that better match our verification, analysis of water surface variations were considered instead, shown on Figure 3.34. Please note that water surface variation served as a crucial feature when designing the two peaking strategies. The hydraulic model used here was calibrated using water surface elevation measurements, and so, this particular model result could not have been seriously influenced by DEM quality, consequently it is assumed to reflect realistic variations in a reasonably proper way.

Looking at the maps on Figure 3.34, one can identify sub-reaches that are more and others that are less exposed to water surface variations and classify them into high and low stranding risk categories. Note that certain areas are not at all, or only occasionally exposed to rapid ramping (green and turquoise areas on the map), while others are almost continuously (red and yellow areas on the map). These maps can be utilized to focus efforts on mitigation measures or local studies.

Concluding the development of version two of the decision support system, it was shown that simulation based generation of complete HMU maps cannot be completely realized by means used in the project. The major reason for the partial results is assumed to be the inaccurate DEM together with 1D hydraulic modelling. Advances in the quality of the results are expected if both topography and hydraulic simulation means are improved. Presently analyses are limited to the use of simulated water surface elevation maps, which are linked with stranding potential of the parts of the study reach. However, analyses means are also limited and only short time periods may be looked at. This problem may be overcome by application of image processing and GIS scripting, which are not tested here.

4 Conclusion

This chapter presents the core of the thesis as well as possible directions of development. The purpose is to provide an ultimate punctuated list of the most important issues and findings detailed in the previous chapters. The points are meant to give guidelines for those using this work to realize and act in case present limitations could be overcome, and thereby, meaningful improvement of the existing methodology became possible.

4.1 Development summary

Hydropower is not fully considered among the environmentally friendly means of power production because of the non-natural character of the water regime downstream of installations during their operation. This thesis provides a tool for analysing some of the direct and indirect effects of river regulation on the river environment for economical purposes. The method contributes to, for example, the establishment of environmentally aware hydropower generation by incorporating environmental values into hydropower operation planning. In general terms, the present work endorses the international recognition of the need to establish a standardized system for scaling and characterisation of the water bodies based on both physical and biological features. Principally, concepts of hydro-ecology and hydropower economy are used.

4.1.1 Environmental flows and approaches of catchment management

Recent research has demonstrated a large potential for using meso-scale classification in eco-hydraulics. The problems inherent in applying habitat models developed for small scales to larger scales may be overcome by application of meso-scale classes for upscaling. Analyses of existing methods of water body characterisation for environmentally aware river management are presented.

4.1.2 River basin management in Norway

The NMCM should primarily be applicable in Norway, and therefore, the actual status, routines and techniques in Norway are reviewed and presented. The following issues were of high importance during the development of the NMCM: applicability to all Norwegian salmon rivers, avoiding the need of specialist background for the application and avoiding the need of sophisticated instrumentation. This in principle provides rapid applicability, cost-efficiency, effectiveness, robustness and flexibility.

4.1.3 Development of a scaling and classification system

The pilot version of the method employed eight hydromorphological units (HMUs). The HMUs were described by four bivalued physical parameters directly, which were estimated during surveying. Substrate information was not incorporated into the system yet. Temporal HMU variations were observed at different flows and HMU-flow relations were found assuming stable bed. HMU-habitat link was established by describing HMUs with classical preference-based methods. General features of mesohabitat-based classification systems were identified and used to compare the NMCM at that stage with another individually developed system.

4.1.4 Evaluation, feedback and the resulting methodology

The use of habitat models incorporating mesohabitat features enables the large-scale application of traditional habitat modelling systems. Existing solutions however differ in structure and objectives. Nevertheless, approaches developed completely independently sometimes lead to similar conclusion and results. A common platform for such comparisons helped us finding the most suitable method for our actual purposes.

The method developed was tested in different countries on rivers mostly of small to large sizes (as commonly understood in the Norwegian environment). Based on test results and comparison, an improved methodology for scaling and classification based on river biotopes is designed. Survey of hydromorphological units (HMUs) described by their approximate average surface velocity, depth, surface gradient, surface flow type and substrate composition serves as foundation of the method. There are ten HMU types defined in the core system, which are possible to combine depending on each actual application. HMU maps covering several flows incorporate the surveyed information in a GIS. By means of statistical analyses, features such as standard deviation and mean areas of the HMU types, their relative distribution, proximity, longitudinal accumulation and alteration with flow are extracted. Observation of habitat use within the units ensures the link with functional habitats. In such a way, functional habitat variation with flow can be modelled and numerous methods allow to evaluate habitat quality alteration. Predictive capacity is achieved through intra- or extrapolation of HMU distribution-flow functions.

The economical evaluation is possible through simulation of various regulation schemes, using discharge as “currency of water” to balance between the different uses. For example in the case of hydropower use, flow variations would be simulated by models of hydropower systems.

4.1.5 Scaling for assessment of production potential on River Nausta – first iteration

The NMCM is applied in an assessment study of production potential and mitigation of environmental effects of proposed river regulation.

A Norwegian salmon river was surveyed and analysed regarding salmon production potential. The NMCM provided a fast, robust framework for analysis of an arbitrary environmental factor, fish density in this particular case. The success indicates the potential inherent in the methodology to be used for environmental studies. On the other hand, imperfections exist in the solution of this problem due to limitations in time and other resources, which factors should not be neglected in actual future studies of similar kinds.

In this particular case, the ten standard HMU classes that are the features of the NMCM were merged into five groups, according to the particular characteristics of this study. It is clear however, that merging may differ or not be needed in other applications.

4.1.6 Decision support systems to evaluate environmental impacts of hydropower peaking operation

The economical and ecological consequences of hydropeaking must be balanced during hydropower operation planning. The complexity of the necessary analysis requires the use of decision support tools.

The NMCM is incorporated in a decision support system for improving hydropower operation planning by environmental impact analysis. It helps decision makers optimizing management issues where hydro-economy and hydro-ecology require opposite management strategies Operation of a real-life hydropower system is modelled and the different proposed flow regimes are evaluated by habitat modelling methods. Three different models were successfully linked for this purpose and created an environment that enables testing and comparing different strategies for power production by means of produced value on one side and distribution of downstream physical habitat on the other side.

This system has been tested on River Nidelva, Norway, and in principle it could be transferred to any other river. The core idea of the system is to relate variations in habitat distribution to the price of the power generation strategy, which is defined by average power production following a given strategy. Habitat evaluation in the first phase of the system is performed by a classical PHABSIM-type analysis and in the second phase by means of the NMCM.

It was found that certain types of background data have different influence on the results and therefore the different results have different validity depending on how they are linked to input data. It was assumed that the minimum level of spatial resolution necessary to generate acceptable HMU maps was not achieved during the data collection campaigns. On the other hand, the elements of the system proved successful and the attempt shows that the core of the problems was probably inherent in data, especially amount of spatial data. The results are used in different ways, HMU maps are generated, HMU distributions are calculated and considering water level variations as describer of one particular environmental factor, potential of stranding of young fish is showed on maps.

The environmental consequences of the proposed flow regimes are compared by both production values and habitat alterations. The experimental studies have shown the possibility and potential of linking different simulation models for environmentally aware hydropower operation planning. The system can be used to simulate value of hydropower production linked with certain physical habitat scenarios and strategies supporting evaluation of river health. The optimisation of the operation plan remains the task of the operators, because value of gained or lost habitat is not discussed in the present study. Legal means however may require maintenance of habitats in the rivers in specific ways.

4.1.7 Major benefits of the developed methodology

1. Habitat quality can be evaluated and numerated in a rapid and effective way on river-scale (which is longer than segment- or section-scale).
2. Habitat assessment is not limited to one particular method, the scaling system allows different philosophies to be tested.
3. Existing micro-scale habitat information and models can be used in this method through upscaling to basin-scale.
4. The method provides capacity for prediction of habitat quality in the range of surveyed flows.

4.2 Future work

Even though the presented work tends to provide a complete solution for the given problem, not all aspects are examined with equal depth and thoroughness. This is due to restrictions in time, budget and technological constrains. The following paragraphs list the issues arose during the study, but which have not been completely solved or analysed.

4.2.1 Habitat analyses

One of the major advantages of the NMCM is the possibility to adapt the method for habitat evaluation. However, this may be a drawback in cases if modern or more advanced techniques are preferred over classical or preliminary ones. Evaluation of the applied habitat modelling techniques is not presented and thereby there is no apparent difference between those from the scaling point of view. Future work should test and emphasize the expected increase in quality of the scaling procedure when incorporating information of environmental indicators into the habitat evaluation phase such as invertebrates, vegetation, guilds or complex ecosystems in addition to common fish sampling data. Such indicators should be tested in new applications and prioritized when habitat processes on river scale are modelled.

4.2.2 Technology

The HMU surveying phase and the interpolation of HMU distribution in the range of surveyed flows could be replaced by modelling HMU variations. Such a model would help overcome the uncertainties related to interpolation of HMU distribution in case of not surveyed flows, as well as it could predict actual locations of selected habitat features. A HMU simulation model would require the mass collection of simple physical data, such as channel topography, water surface elevation and point velocity for characterising water bodies in a cost- and time-effective way. Use of higher order (2D or 3D) hydraulic modelling of river stretches with several km length or river systems would then theoretically allow the unexceptionable simulation of the eight basic HMU types. However, neither the modelling tools nor the data present today allow to construct such a sophisticated system. This is due to limitations in modelling surface flow types and gradient variations in open channel flow. Depth and velocity distributions however are easier to assess but still require higher accuracy in channel topography than what we could reach.

Another technological constrain related to automatic generation of HMU maps exist in data processing because the amount of data produced challenges our methods used in the analysis. In the application example in section 3.2 HMU maps with reduced features (depth and approximated mean velocity only) were generated for selected hours on selected days. A complete habitat prediction would require analysis of much longer series in the order of months or years, to maintain compatibility with the economical results. Generation and analysis of such an amount of spatial data is not possible by means of the tools used in the present study. Maps describing the spatial distribution of the four features of HMUs should be prepared for about each hour in the simulation period for the entire study reach and should be analysed by automatic image processing. Solving this problem would enhance the applicability and power behind the easy and robust scaling solution of the NMCM.

References

Abbott, M.B. (1991). Hydroinformatics. Information technology and the aquatic environment. Aldershot, Avebury Technical.

Ackerman, C.T. (2002). HEC-GeoRAS. Davis, CA, USA, U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC): 154.

Acreman, M.C. (2001). Hydro-ecology : linking hydrology and aquatic ecology. Wallingford, International Association of Hydrological Sciences.

Acreman, M.C. and M.J. Dunbar (2004). "Defining environmental river flow requirements - a review" Hydrology and Earth System Sciences vol. 8(5): 861-876.

Alfredsen, K. (1997). A modelling system for estimation of impacts on fish habitat. 27th International Association for Hydraulic Research Congress: Water for a changing society, San Francisco, IAHR.

Alfredsen, K. (1998a). Habitat : a program system for physical fish habitat assessment. Pages 127-134 in Proceeding of the International Workshop on Environmental Hydrodynamics and Ecological River Restoration in Cold Regions. Norwegian University of Science and Technology, Department of Hydraulic and Environmental Engineering, Trondheim

Alfredsen, K. (1998b). Quantification of impacts of river regulations on fish: An energetic modelling approach. Hydroinformatics 98, Copenhagen.

Alfredsen, K. (1999). An object-oriented framework for application development and integration in hydroinformatics. Department of Hydraulic and Environmental Engineering. Trondheim, Norwegian University of Science and Technology: vii+193+3+3+2.

Alfredsen, K. and Å. Killingtveit (1996). The habitat modelling framework : a tool for creating habitat analysis programs. 2nd International Symposium on Habitat Hydraulics, Québec, Canada, INRS-EAU; FQSA; IAHR-AIRH.

Armitage, P.D. and C.E. Cannan (2000). "Annual changes in summer patterns of mesohabitat distribution and associated macroinvertebrate assemblages." Hydrological Processes vol. 14(16-17): 3161-3179.

Arthington, A.H., J.L. Rall, M.J. Kennard and B.J. Pusey (2003). "Environmental flow requirements of fish in lesotho rivers using the drift methodology." River Research and Applications vol. 19(5-6): 641-666.

Bain, M.B., J.T. Finn and H.E. Booke (1988). "Streamflow regulation and fish community structure." Ecology vol. 69(2): 382-392.

Bain, M.B., A.L. Harig, D.P. Loucks, R.R. Goforth and K.E. Mills (2000). "Aquatic ecosystem protection and restoration: advances in methods for assessment and evaluation." Environmental Science & Policy vol. 3(Supplement 1): 89-98.

Baron, J.S., N.L. Poff, P.L. Angermeier, C.N. Dahm, P.H. Gleick, N.G. Hairston, R.B. Jackson, C.A. Johnston, B.D. Richter and A.D. Steinman (2002). "Meeting ecological and societal needs for freshwater." Ecological Applications vol. 12(5): 1247-1260.

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess and M. Pollock (2004). "The network dynamics hypothesis: How channel networks structure riverine habitats." Bioscience vol. 54(5): 413-427.

Benetti, A.D., A.E. Lanna and M.S. Cobalchini (2004). "Current practices for establishing environmental flows in Brazil." River Research and Applications vol. 20(4): 427-444.

Bisson, P.A. and D.R. Montgomery. 1996. Valley segments, stream reaches and channel units. Pages 23-52 in F. R. Hauer and G. A. Lamberti, eds. Methods in stream ecolology. Academic Press (Elsevier Science USA)

Bisson, P.A., J.L. Nielsen, R.A. Palmason and L.E. Grove. 1981. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62-73 in N. B. Armantrout, ed. Acquisition and utilization of Aquatic Habitat Inventory Information. Proceedings. Western Division of the American Fisheries Society, Portland, USA

Black, J. (2002). A Dictionary of Economics. Oxford, Oxford University Press.

Blöschl, G. (1999). "Scaling issues in snow hydrology." Hydrological Processes vol. 13(14-15): 2149-2175.

Bohlin, T., S. Hamrin, T.G. Heggberget, G. Rasmussen and S.J. Saltveit (1989). "Electrofishing - Theory and Practice with Special Emphasis on Salmonids." Hydrobiologia vol. 173(1): 9-43.

Booker, D.J. (2003). "Hydraulic Modelling of Fish Habitat in Urban Rivers During High Flows." Hydrological processes vol. 17(Part 3): 577-600.

Booker, D.J. and M.J. Dunbar (2004). "Application of physical habitat simulation (phabsim) modelling to modified urban river channels." River Research and Applications vol. 20(2): 167-183.

Booker, D.J., M.J. Dunbar and A. Ibbotson (2004). "Predicting juvenile salmonid drift-feeding habitat quality using a three-dimensional hydraulic-bioenergetic model." Ecological modelling vol. 177(1): 22.

Booker, D.J., D.A. Sear and A.J. Payne (2001). "Modelling Three-Dimensional Flow Structures and Patterns of Boundary Shear Stress in a Natural Pool-Riffle Sequence." Earth surface processes and landforms : the journal of the British Geomorphological Research Group vol. 26(Part 5): 553-576.

Boon, P.J. (2000). "The development of integrated methods for assessing river conservation value." Hydrobiologia vol. 422: 413-428.

BOSS-International (2001). BOSS DAMBRK Reference Documentation, BOSS Inc.

Bovee, K.D. (1982). A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream flow information paper. Washington, D.C., Western Energy and Land Use Team Office of Biological Services Fish and Wildlife Service, U.S. Dept. of the Interior: xx, 248.

Bovee, K.D. (1986). Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. Instream flow information paper. Washington, DC, National Ecology Center Division of Wildlife and Contaminant Research Fish and Wildlife Service U.S. Dept. of the Interior: xxv, 235.

Bovee, K.D. (1996). Perspectives on two-dimensional river habitat models: the PHABSIM experience. 2nd International Symposium on Habitat Hydraulics, Québec, Canada, INRS-EAU.

Bradford, M.J. (1997). "An experimental study of stranding of juvenile salmonids on gravel bars and in side-channels during rapid flow decreases." Regulated Rivers: Research & Management vol. 13: 395-401.

Bratrich, C., A. Frutiger, M. Gessner, E. Hoehn, B. Kiefer, W. Meier, A. Peter, R. Rudel, B. Truffer and B. Wehrli (1999). "ÖKOSTROM": A MULTIDISCIPINARY PROJECT TO REDUCE ENVIRONMENTAL IMPACT OF HYDROPOWER GENERATION. 3rd International Symposium on Ecohydraulics, Salt Lake City, Utah, USA, IAHR.

Bratrich, C., B. Truffer, K. Jorde, J. Markard, W. Meier, A. Peter, M. Schneider and B. Wehrli (2004). „Green hydropower: a new assessment procedure for river management." River Research and Applications vol. 20(7): 865-882.

Brunke, M., A. Hoffmann and M. Pusch (2001). „Use of mesohabitat-specific relationships between flow velocity and river discharge to assess invertebrate minimum flow requirements." Regulated Rivers-Research & Management vol. 17(6): 667-676.

Bryce, S.A. and S.E. Clarke (1996). „Landscape-Level Ecological Regions: Linking State-Level Ecoregion Frameworks with Stream Habitat Classifications." Environmental Management vol. 20(3): 297-311.

Bult, T.P., S.C. Riley, R.L. Haedrich, J. Gibson and J. Heggenes (1999). „Density-dependent habitat selection by juvenile Atlantic salmon (*Salmo salar*) in experimental riverine habitats." Canadian Journal of Fisheries and Aquatic Sciences vol. 56: 1298-1306.

Caissie, D. and N. El-Jabi (1995). „Comparison and regionalization of hydrologically based instream flow techniques in Atlantic Canada." Canadian journal of civil engineering. Revue canadienne de gaenie civil vol. 22(2): 12.

Caissie, D. and N. El-Jabi (2003). „Instream Flow Assessment: From Holistic Approaches to Habitat Modelling." Canadian water resources journal. Revue canadienne des ressources en eau vol. 28(Part 2): 173-184.

Capra, H., P. Breil and Y. Souchon (1995). «A New Tool to Interpret Magnitude and Duration of Fish Habitat Variations.» Regulated Rivers-Research & Management vol. 10(2-4): 281-289.

Capra, H., C. Sabaton, V. Gouraud, Y. Souchon and P. Lim (2003). «A population dynamics model and habitat simulation as a tool to predict brown trout demography in natural and bypassed stream reaches.» River Research and Applications vol. 19(5): 551-568.

CEN-TC230 (2004). EN 14614 - Water Quality - Guidance standard for assessing the hydromorphological features of rivers. Bruxelles, European Committee for Standardization (CEN).

Chow, V.T., D.R. Maidment and L.W. Mays (1988). Applied Hydrology, McGraw-Hill Education (ISE Editions).

CIDE (2001). Cambridge International Dictionary of English. Accessed: 3 May 2004

Cohen, P., H. Andriamahefa and J.G. Wasson (1998). «Towards a Regionalization of Aquatic Habitat: Distribution of Mesohabitats at the Scale of a Large Basin.» Regulated rivers vol. 14(5): 14.

Cortes, R.M.V., M.T. Ferreira, S.V. Oliveira and D. Oliveira (2002). «Macroinvertebrate community structure in a regulated river segment with different flow conditions.» River Research and Applications vol. 18(4): 367-382.

Crowder, D.W. (2002). Reproducing and Quantifying Spatial Flow Patterns of Ecological Importance with Two-Dimensional Hydraulic Models. Blacksburg, Virginia Polytechnic Institute and State University: 170.

Crowder, D.W. and P. Diplas (2000). "Evaluating spatially explicit metrics of stream energy gradients using hydrodynamic model simulations." Canadian Journal of Fisheries and Aquatic Sciences vol. 57(7): 1497-1507.

Davies, N.M., R.H. Norris and M.C. Thoms (2000). "Prediction and assessment of local stream habitat features using large-scale catchment characteristics." Freshwater Biology vol. 45(3): 343-369.

Dovciak, A.L. and J.A. Perry (2002). "In Search of Effective Scales for Stream Management: Does Agroecoregion, Watershed, or Their Intersection Best Explain the Variance in Stream Macroinvertebrate Communities?" Environmental Management vol. 30(3): 365-377.

Duel, H., G.E.M. van der Lee, W.E. Penning and M.J. Baptist (2003). "Habitat Modelling of Rivers and Lakes in the Netherlands: An Ecosystem Approach." Canadian water resources journal. Revue canadienne des ressources en eau vol. 28(Part 2): 231-248.

Dunbar, M., A. Gustard, C.T. Ackerman and C.R.N. Elliott (1998). Overseas approaches to setting River Flow Objectives. R & D Technical reports. Bristol, Environment Agency: 82.

Dunbar, M.J. and M.C. Acreman. 2001. Applied hydro-ecological science for the twenty-first century. Pages 1-17 in M. C. Acreman, ed. Hydro-ecology: Linking Hydrology and Aquatic Ecology. IAHS, Wallingford, UK

EAMN (2004). State-of-the-art in data sampling, modelling analysis and applications of of river habitat modelling. Bruxelles, European COST Action 626.

EC (2000). Directive of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. 2000/60/EC. Luxembourg. Vol. 1997/0067: 151.

Emery, J.C., A.M. Gurnell, N.J. Clifford, G.E. Petts, I.P. Morrissey and P.J. Soar (2003). "Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design." River Research and Applications vol. 19(5-6): 533-549.

ESRI (1996). ArcView GIS. Redlands, CA, USA, Environmental Systems Research Institute Inc.: Software manual and tutorial.

Farhar, B. (1993). Trends in Public Perceptions and Preferences on Energy and Environmental Policy: Executive Summary. Golden, CO, National Renewable Energy Laboratory, Department of Energy, USA.

Flodmark, L.E.W., H.A. Urke, J.H. Halleraker, J.V. Arnekleiv, L.A. Vøllestad and A.B.S. Poléo (2002). "Cortisol and glucose responses in juvenile brown trout subjected to a fluctuating flow regime in an artificial stream." Journal of Fish Biology vol. 2002(60): 238-248.

Frissell, C.A., W.J. Liss, C.E. Warren and M.D. Hurley (1986). "A Hierarchical Framework for Stream Habitat Classification - Viewing Streams in a Watershed Context." Environmental Management vol. 10(2): 199-214.

Frutiger, A. (2004). "Ecological impacts of hydroelectric power production on the River Ticino. Part 2: Effects on the larval development of the dominant benthic macroinvertebrate (Allogamus auricollis, Trichoptera)." Archiv Fur Hydrobiologie vol. 159(1): 57-75.

Gazetteer (1995). The Gazetteer for Scotland. Accessed: 26 April 2005. http://www.geo.ed.ac.uk/scotgaz/gaztitle.html

Gibbins, C.N., H.J. Moir, J.H. Webb and C. Soulsby (2002). "Assessing discharge use by spawning Atlantic salmon: A comparison of discharge electivity indices and PHABSIM simulations." River Research and Applications vol. 18(4): 383-395.

Gippel, C.J. and M.J. Stewardson (1998). “Use of wetted perimeter in defining minimum environmental flows.” Regulated Rivers: Research & Management vol. 14(1): 53-67.

Gordon, N.D., T.A. McMahon, B.L. Finlayson and C.J. Gippel (2004). Stream hydrology: an introduction for ecologists, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.

Gore, J.A., D.J. Crawford and D.S. Addison (1998). “An analysis of artificial riffles and enhancement of benthic community diversity by physical habitat simulation (PHABSIM) and direct observation.” Regulated Rivers-Research & Management vol. 14(1): 69-77.

Gouraud, V., J.L. Bagliniegravere, P. Baran, C. Sabaton, P. Lim and D. Ombredane (2001). “Factors regulating brown trout populations in two French rivers: application of a dynamic population model.” Regulated Rivers: Research & Management vol. 17(4): 557-569.

Habersack, H.M. (2000). “The river-scaling concept (RSC): a basis for ecological assessments.” Hydrobiologia vol. 422(1): 12.

Halleraker, J.H., S.J. Saltveit, A. Harby, J.V. Arnekleiv, H.P. Fjeldstad and B. Kohler (2003). “Factors influencing stranding of wild juvenile brown trout (*Salmo trutta*) during rapid and frequent flow decreases in an artificial stream.” River Research and Applications vol. 19(5-6): 589-603.

Hamill, L. (2001). Understanding Hydraulics. Bristol, Palgrave.

Harby, A., K. Alfredsen, H.P. Fjeldstad, J.H. Halleraker, J.V. Arnekleiv, P. Borsányi, L.E.W. FLODMARK, S.J. Saltveit, S. Johansen, K. Clarke and D.A. Scruton (2001). Ecological impacts of hydro peaking in rivers. Hydropower in the new Millennium: Proceedings of the 4th International Conference on Hydropower Development, Hydropower ‘01, Bergen, Norway, Balkema.

Harby, A. and J.V. Arnekleiv (1994). Biotope improvement analysis in the River Dalåa with the River System Simulator. 1st international symposium on habitat hydraulics, Trondheim, Norway.

Harby, A., J.H. Halleraker, K. Alfredsen, J.V. Arnekleiv, S. Johansen and S.J. Saltveit (1999). Impacts of hydropeaking on Norwegian riverine ecosystems. 3rd International Symposium on Ecohydraulics, Salt Lake City, Utah, USA, IAHR.

Hardy, T.B. (1995). Habitat typing and habitat mapping. Workshop on advanced techniques for instream flow assessments, Prague, Czech Republic.

Hardy, T.B. (1998). “The Future of Habitat Modeling and Instream Flow Assessment Techniques.” Regulated rivers vol. 14(5): 16.

Hardy, T.B. and R.C. Addley. 2001. Vertical integration of spatial and hydraulic data for improved habitat modelling using geographic information systems. Pages 65-75 in M. C. Acreman, ed. Hydro-ecology: Linking hydrology and aquatic ecology. IAHS, Wallingford

Hawkins, C.P., J.L. Kershner, P.A. Bisson, M.D. Bryant, L.M. Decker, S.V. Gregory, D.A. McCullough, C.K. Overton, G.H. Reeves, R.J. Steedman and M.K. Young (1993). “A hierarchical approach to classifying stream habitat features.” Fisheries vol. 18(6): 3-11.

Hayes, J.W., J.D. Stark and K.A. Shearer (2000). “Development and test of a whole-lifetime foraging and bioenergetics growth model for drift-feeding brown trout.” Transactions of the American Fisheries Society vol. 129(2): 315-332.

HEC-USACE (1995). HEC-DSS User’s Guide and Utility Program Manuals

HEC-USACE (1998). River Analysis System, User’s Guide. Davis, CA, USA, U.S. Army Corps of Engineers, Hydraulic Engineering Center (HEC).

HEC-USACE (2002). HEC-RAS River Analysis System, Hydraulic Reference Manual. Davis, CA, USA, U.S. Army Corps of Engineers, Hydraulic Engineering Center (HEC)**:** Hydraulic Reference Manual.

HEC-USACE (2003). HEC-DSS Microsoft Excel Data Exchange Add-In. Davis, CA, USA, U.S. Army Corps of Engineers, Hydraulic Engineering Center (HEC)**:** User’s Manual and Installation Guide.

Heggenes, J. (1996). “Habitat selection by brown trout (*Salmo trutta*) and young Atlantic salmon (*S-salar*) in streams: Static and dynamic hydraulic modelling.” Regulated Rivers-Research & Management vol. 12(2-3): 155-169.

Heggenes, J., A. Harby and T. Bult (1996). Microposition choice in stream-living Atlantic salmon (*Salmo salar*) parr and Brown trout (*Salmo trutta*): Habitat-hydraulic 3-dimensional model and test. 2nd International Symposium on Habitat Hydraulics, Québec, Canada, INRS-EAU.

Helland-Hansen, E., T. Holtedahl and K.A. Lye (1995). Environmental Effects. Trondheim, Norwegian University of Science and Technology, Deprtment of Hydraulic and Environmental Engineering.

Inoue, M. and S. Nakano (1999). «Habitat structure along channel-unit sequences for juvenile salmon: a subunit-based analysis of in-stream landscapes.» Freshwater Biology vol. 42(4): 597-608.

Johnson, R. and P. Kuby (2004). Elementary Statistics. Belmont, Brooks/Cole-Thomson Learning.

Jorde, K. (1996). Ecological evaluation of instream flow regulations based on temporal and spatial variability of bottom shear stress and hydraulic habitat quality. 2nd International Symposium on Habitat Hydraulics, Québec, Canada, INRS-EAU.

Jorde, K. and M. Schneider (2000). The CASiMiR habitat simulation model (personal communication). P. Borsányi. Stuttgart, Germany.

Jowett, I.G. (1993). „A method for objectively identifying pool, run and riffle habitats from physical measurements.“ New Zealand journal of marine and freshwater research vol. 27(2): 241-248.

Kalma, J.D. and M. Sivapalan (1995). Scale issues in hydrological modelling. New York, Publication Chichester Wiley.

Karr, J.R. (1991). „Biological Integrity - a Long-Neglected Aspect of Water-Resource Management.“ Ecological Applications vol. 1(1): 66-84.

Katopodis, C. (2003). „Case Studies of Instream Flow Modelling for Fish Habitat in Canadian Prairie Rivers.“ Canadian water resources journal. Revue canadienne des ressources en eau vol. 28(Part 2): 199-216.

Kemp, J.L., D.M. Harper and G.A. Crosa (2000). «The habitat-scale ecohydraulics of rivers.» Ecological engineering vol. 16(1): 17-29.

Kershner, J.L. and W.M. Snider. 1992. Importance of habitat-level classification system to design instream flow studies. Pages 179-193 in P. J. Boon, P. Carlow and G. E. Petts, eds. River conservation and management. John Wiley & Sons

Killingtveit, Å. (1999). River System Simulator models : an introduction to the nMAG model for simulating reservoir and hydropower operation. Trondheim, Norwegian University of Science and Technology (NTNU) Department of Hydraulic and Environmental Engineering.

Killingtveit, Å. (2004). nMAG2004 - A computer program for hydropower and reservoir operation simulation. Trondheim, Department of Hydraulic and Environmental Engineering, Norwegian University for Science and Technology (NTNU)**:** Users’ manual.

Killingtveit, Å. and A. Harby (1994). The River System Simulator : report from testing. Nordisk hydrologisk konferanse, Tórshavn, Danmark, Koordineringskomitéen for Hydrologi i Norden.

Killingtveit, Å. and N.R. Sælthun (1995). Hydrology. Trondheim, Norwegian University of Science and Technology.

King, J., C. Brown and H. Sabet (2003). “A scenario-based holistic approach to environmental flow assessments for rivers.” River Research and Applications vol. 19(5-6): 619-639.

King, J. and D. Louw (1998). “Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology.” Aquatic Ecosystem Health and Management vol. 1(2): 109-124.

Kocik, J.F. and C.P. Ferreri (1998). "Juvenile production variation in salmonids: population dynamics, habitat and the role of spatial relationships." Canadian Journal of Fisheries and Aquatic Sciences vol. 55(0): 191-200.
Lamouroux, N., H. Capra and M. Pouilly (1998). "Predicting Habitat Suitability for Lotic Fish: Linking Statistical Hydraulic Models with Multivariate Habitat Use Models." Regulated rivers vol. 14(1): 12.
Lechovicz, M.J. (1982). "The sampling characteristics of electivity indices." Oecologia vol. 52: 22-30.
Leclerc, M., A. Boudreault, J.A. Bechara and G. Corfa (1995). "Two-Dimensional Hydrodynamic Modeling: A Neglected Tool in the Instream Flow Incremental Methodology." Transactions of the American Fisheries Society vol. 124(5): 645-662.
Leclerc, M., A. Saint-Hilaire and J. Bechara (2003). "State-of-the-Art and Perspectives of Habitat Modelling for Determining Conservation Flows." Canadian water resources journal. Revue canadienne des ressources en eau vol. 28(Part 2): 135-152.
Leonard, P. and D.J. Orth (1986). Habitat-use guilds and selection of instream flow target species. Workshop on the development and evaluation of habitat suitability criteria, Fort Collins, Colorado, USA, U.S. Department of the Interior, Fish and Wildlife Service, Research and development.
Lobb, M.D. and D.J. Orth (1991). «Habitat Use by an Assemblage of Fish in a Large Warmwater Stream.» Transactions of the American Fisheries Society vol. 120(1): 65.
Lonzarich, D.G., M.R. Lonzarich and M.L.J. Warren (2000). «Effects of riffle length an the short-term movement of fishes among stream pools.» Canadian Journal of Fisheries and Aquatic Sciences vol. 57: 1508-1514.
Luz, L.d. and D.P. Loucks (2003). «Developing habitat suitability criteria for water management: a case study.» International Journal of River Basin Management vol. 1(4): 283-295.
Maddock, I. (1999). «The importance of physical habitat assessment for evaluating river health.» Freshwater Biology vol. 41(2): 373-391.
Maddock, I. and D. Bird (2000). The application of habitat mapping to identify representative PHABSIM sites on the River Tavy, Devon, UK. 2nd International Symposium on Habitat Hydraulics, Québec, Canada, INRS-EAU; FQSA; IAHR-AIRH.
Maddock, I.P., M.A. Bickerton, R. Spence and T. Pickering (2001). «Reallocation of compensation releases to restore river flows and improve instream habitat availability in the Upper Derwent catchment, Derbyshire, UK.» Regulated Rivers-Research & Management vol. 17(4-5): 417-441.
McCartney, M.P. and C.T. Ackerman (2001). "Managed flood releases as an environmental mitigation option." Hydropower & Dams vol. 1(1): 74-80.
Microsoft (2004). "Encarta Dictionary: English (North America)."
Minitab (2003). MINITAB Statistical Software. Pennsylvania, USA, State College.
Morrison, H.A. (2000). Frameworks and models for assessing the effects of hydropeaking on the productivity of aquatic ecosystems, Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences: 56.
MPE (2004). The energy sector and water resources in Norway. Facts 2004. H. Opsund, Ministry of Petroleum and Energy: 112.
Newson, M., D. Archer and C. Newson (2002). Expanding the definition of 'natural' instream physical habitat: flow variability and biotope diversity in a representative selection of UK river 'types'. Environmental flows for river systems, 4th International Symposium on Ecohydraulics, Cape Town, South Africa.
Newson, M.D. and C.L. Newson (2000). "Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges." Progress in physical geography vol. 24(Part 2): 195-218.
NRFA (2005). National River Flow Archive of the UK. Accessed: 26 April 2005. http://www.nwl.ac.uk
Olsen, N.R.B. (1999). Computational Fluid Dynamics in Hydraulic and Sedimantation Engineering. Trondheim, NTNU, IVM.
Olsen, N.R.B. (2002). Hydroinformatics, fluvial hydraulics and limnology. Trondheim, Department of Hydraulic and Environmental Engineering Norwegian University of Science and Technology.
Padmore, C.L. (1998). "The role of physical biotopes in determining the conservation status and flow requirements of British rivers." Aquatic Ecosystem Health and Management vol. 1(1): 25-35.
Parasiewicz, P. (1996). "Estimation of physical habitat characteristics using automation and geodesic-based sampling." Regulated Rivers-Research & Management vol. 12(6): 575-583.
Parasiewicz, P. (2001). "MesoHABSIM: A concept for application of instream flow models in river restoration planning." Fisheries vol. 26(9): 6-13.
Parasiewicz, P. (2003). "Upscaling: Integrating Habitat Model into River Management." Canadian water resources journal. Revue canadienne des ressources en eau vol. 28(Part 2): 283-300.
Pasternack, G.B., C.L. Wang and J.E. Merz (2004). «Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California.» River Research and Applications vol. 20(2): 205-225.
Pearsall, J. (2001). Concise Oxford Dictionary. Accessed: May 2004
Peter, A., G. Holzer, R. Mueller and M. Schneider (2004). Spawning habitat requirements of European grayling (Thyallus Thymallus) and modelling of habitat changes in a lake outflow (AAre River) using a 2-dimensional hydraulic model. Fifth International Symposium on Ecohydraulics, Madrid, Spain, IAHR.
Petts, G.E. (1990). «Regulation of Large Rivers - Problems and Possibilities for Environmentally-Sound River Development in South-America.» Interciencia vol. 15(6): 388-395.
Petts, G.E. (1996). «Water allocation to protect river ecosystems.» Regulated Rivers-Research & Management vol. 12(4-5): 353-365.
Piddington, K. (1991). Environmental Assessment Sourcebook (Vol. 1-3). WORLD BANK TECHNICAL PAPER. Washington, D.C., The Word Bank, Environment Department: 246 + 302 + 256.
Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks and J.C. Stromberg (1997). "The natural flow regime." Bioscience vol. 47(11): 769-784.
Pollard, S. (2002). Setting our sites on the right scale: a comparison of IFIM and a new approach, the Geomorphological-Biotope assessment (GBA), in the Marite River. Environmental flows for river systems, 4th International Symposium on Ecohydraulics, Cape Town South Africa.
Raven, P.J., N.T.H. Holmes, P. Charrier, F.H. Dawson, M. Naura and P.J. Boon (2002). "Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods." Aquatic Conservation-Marine and Freshwater Ecosystems vol. 12(4): 405-424.
Raven, P.J., N.T.H. Holmes, F.H. Dawson, P.J.A. Fox, M. Everard, I.R. Fozzard and K.J. Rouen (1998). River habitat quality, the physical character of rivers and streams in the UK and Isle of Man. River Habitat Survey Report, Environment Agency United Kingdom.
Reiser, D.W., T.A. Wesche and C. Estes (1989). "Status of Instream Flow Legislation and Practices in North-America." Fisheries vol. 14(2): 22-29.
Rosgen, D.L. (1985). A stream classification system. Symposium on Riparian ecosystems and their management: Reconciling conflicting uses, Tucson, USA.
Rosgen, D.L. 1996. Applied river morphology. Pages 4-1--5-34 in Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado, USA
Rowlands, I.H., P. Parker and D. Scott (2002). "Consumer Perceptions of 'Green Power'." Journal of Consumer Marketing vol. 19(2): 36-48.

Rüther, N. (2004). Applied Computational Fluid Dynamics of Flow in a Rough, Natural Open Channel Bend. Trondheim, Department of Hydraulic and Environmental Engineering, The Norwegian University of Science and Technology.

Saltveit, S.J., J.V. Arnekleiv, J.H. Halleraker and A. Harby (1999). Experimental Studies on the effect of rapid flow decreases on juvenile atlantic salmon (*Salmo salar*) and Brown Trout (*Salmo trutta*). 3rd International Symposium on Ecohydraulics, Salt Lake City, Utah, USA, IAHR.

Saltveit, S.J., J.H. Halleraker, J.V. Arnekleiv and A. Harby (2001). "Field experiments on stranding in juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) during rapid flow decreases caused by hydropeaking." Regulated Rivers-Research & Management vol. 17(4-5): 609-622.

Sauvage, S., S. Teissier, P. Vervier, T. Ameacuteziane, F. Garabeacutetian, F. Delmas and B. Caussade (2003). "A numerical tool to integrate biophysical diversity of a large regulated river: hydrobiogeochemical bases. The case of the Garonne River (France)." River Research and Applications vol. 19(2): 181-198.

Scatena, F.N. (2004). "A survey of methods for setting minimum instream flow standards in the Caribbean Basin." River Research and Applications vol. 20(2): 127-135.

Schneiders, A., E. Verhaert, G. De Blust, C. Wills, L. Bervoets and R. Verheyen (1993). "Towards an ecological assessment of watercourses." Journal of Aquatic Ecosystem Health vol. 2: 29-38.

Schwiebert, E.G. (1978). Trout. New York, E.P. Dutton.

Scruton, D.A., L.M.N. Ollerhead, K.D. Clarke, C. Pennell, K. Alfredsen, A. Harby and D. Kelly (2003). "The behavioural response of juvenile Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) to experimental hydropeaking on a newfoundland (Canada) River." River Research and Applications vol. 19(5-6): 577-587.

Sempeski, P., P. Gaudin and E. Herouin (1998). "Experimental study of young grayling (Thymallus thymallus) physical habitat selection factors in an artificial stream." Archiv für Hydrobiologie vol. 141(3): 321-332.

Shaw, E.M. (1994). Hydrology in practice. London, Chapman & Hall.

Shirakawa, N. and N. Tamai (2003). "Use of economic measures for establishing environmental flow in upstream river basins." International Journal of River Basin Management vol. 1(1): 15-19.

Stalnaker, C.B., B.L. Lamb, J. Henriksen, K.D. Bovee and J. Bartholow (1995). The Instream Flow Incremental Methodology. A primer for IFIM. Biological report. Fort Collins, Colorado, USA, U.S Department of Interior, National Biological Service.

Steele, R.J. and K.E. Smokorowski (2000). Review of literature related to the downstream ecological effects of hydroelectric power generation, Ministry of Supply and Services Canada**:** 55.

Straton, A. (in press) A complex systems approach to the value of ecological resources. Ecological Economics.

Takahashi, G. (1994). Basis for classification of riffle-pool components and its application. 1st international symposium on habitat hydraulics, Trondheim, Norway.

Tanaka, S.K. and J.R. Lund (2003). "Effects of increased delta exports on sacramento valleys economy and water management." Journal of the American Water Resources Association vol. 39(6): 1509-1519.

Tennant, D.L. (1976). "Instream flow regimens for fish, wildlife, recreation and related environmental resources." Fisheries vol. 1(4): 6-10.

Tharme, R.E. (2003). "A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers." River research and applications vol. 19(5-6): 397-441.

Thoms, M.C. and F. Sheldon (2002). "An ecosystem approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology." Geomorphology vol. 47(2-4): 153-168.

Tickner, D., P.D. Armitage, M.A. Bickerton and K.A. Hall (2000). "Assessing stream quality using information on mesohabitat distribution and character." Aquatic Conservation-Marine and Freshwater Ecosystems vol. 10(3): 179-196.

Townend, J. (2002). Practical statistics for environmental and biological scientists. Chichester, John Wiley & Sons Ltd.

Ureña, J.M.d., Ed. (1999). River design and environmental protection in Europe, Universidad de Cantabria.

Valentin, S., F. Lauters, C. Sabaton, P. Breil and Y. Souchon (1996). "Modelling temporal variations of physical habitat for brown trout (*Salmo trutta*) in hydropeaking conditions." Regulated Rivers-Research & Management vol. 12(2-3): 317-330.

Van Winkle, W., H.I. Jager, S.F. Railsback, B.D. Holcomb, T.K. Studley and J.E. Baldrige (1998). "Individual-based model of sympatric populations of brown and rainbow trout for instream flow assessment: model description and calibration." Ecological Modelling vol. 110(2): 175-207.

Vanderploeg, J.A. and D. Scavia (1979). "Two electivity indices for feeding, with special reference to zooplankton grazing." Journal of the Fisheries Board of Canada vol. 36: 362-365.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing (1980). "River Continuum Concept." Canadian Journal of Fisheries and Aquatic Sciences vol. 37(1): 130-137.

Vehanen, T., A. Huusko, T. Yrjana, M. Lahti and A. Maki-Petays (2003). "Habitat preference by grayling (Thymallus thymallus) in an artificially modified, hydropeaking riverbed: a contribution to understand the effectiveness of habitat enhancement measures." Journal of Applied Ichthyology vol. 19(1): 15-20.

Vismara, R., A. Azzellino, R. Bosi, G. Crosa and G. Gentili (2001). "Habitat suitability curves for brown trout (*Salmo trutta fario L.*) in the River Adda, Northern Italy: comparing univariate and multivariate approaches." Regulated Rivers: Research & Management vol. 17(1): 37-50.

Ward, J.V. (1989). "The 4-Dimensional Nature of Lotic Ecosystems." Journal of the North American Benthological Society vol. 8(1): 2-8.

Wathne, M. (1992). River system simulator : the development of a decision support system. Trondheim, Norwegian Hydrotechnical Laboratory.

Yevjevich, V. and Ö. Starosolszky (1998). "Controversies between water resources development and protection of the environment." Journal of hydraulic research. Journal de recherches hydrauliques vol. 36(1): 135-138.

Supporting information

The appendices contain a brief hydrological description of the river sections mentioned in the text, then a short summary of the projects the work partly or fully contributed to and finally a list of the utilized models and software packages are mentioned.

A.1 Field descriptions

This chapter provides some hydrological description of the catchments and rivers that played some role in the development, analyses or testing phases of the method. There are five rivers considered in Norway and two in the United Kingdom. Table A.1.1 shows some general information about these.

Table A.1.1: Study sites

River	Catchment area (km^2)	Specific discharge ($l/s/km^2$)	Start of observation period of discharge measurements	Length of study section for the present work (km)
Nidelva (N)	3661	28.95	1882	0.05 and 10
Orkla (N)	3346	22.65	1913	0.05 and 20
Ingdalselva (N)	102	25.23	2002	15
Surna (N)	~1219	47.98	1966	15 and 25
Nausta (N)	~315	89.27	1964	15
Water of Tarf (UK)	(732)*	(26.30)*	(1976)*	0.5
Cruick Water (UK)				0.3

* The values in (brackets) refer to the North Esk River, of which both Water of Tarf and Cruick Water are tributaries

A.1.1 Nidelva

Nidelva is one of the largest rivers in Central Norway ("Midt-Norge") and its hydrological regime is heavily modified. Regulation of the river started as early as in the 18th century, when the government of Trondheim enforced the embankments to prevent erosion at some places. Later in the middle of the 20th century, a large hydropower system was built utilizing the Nidelva and Nea catchments. Figure A.1.1 shows the actual catchment after the current regulation. High point is on the SE corner (bottom left) of the map.

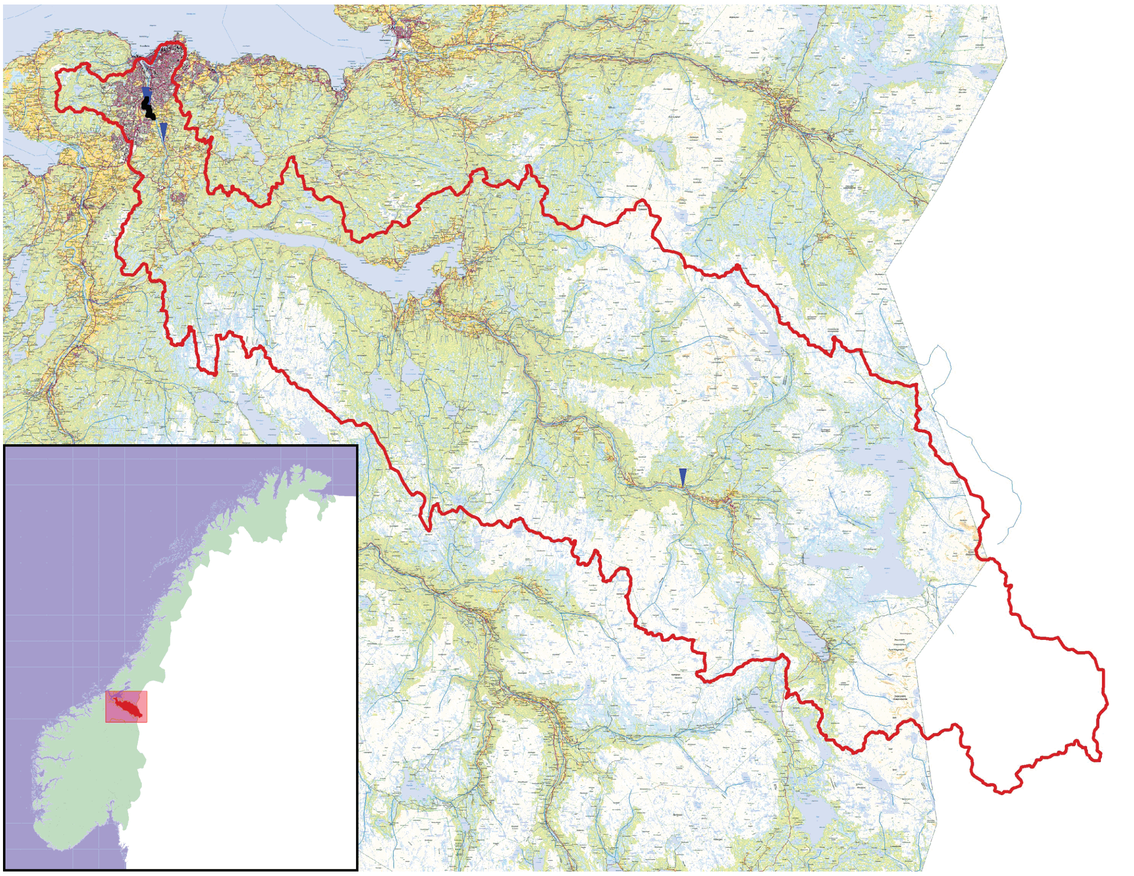


Figure A.1.1: Map of the Nea-Nidelva catchment. The blue triangles indicate gauging stations, while the black line mark the study reach

Figure A.1.3 shows flow duration curves at a hydrological observation station marked by the blue triangle most downstream (top right on the map) on Figure A.1.1. Experiments and field trips related to the present work were carried out in its close neighbourhood, at the lower section of the river, downstream from the outlet of the last (lowest) two power stations.
Nidelva was used in three stages of the development of the NMCM. The first case was the pilot study of the method for its first practical application (section 2.1.2, Figure A.1.2 top right). The second time Nidelva utilized was in relation with the description of HMUs by statistical means based on point samples of describing parameters (section 2.1.5, Figure A.1.2 bottom right). The last case was one of the applications of the method linking hydropower economy to river ecology (section 3.2, Figure A.1.2 top right). The first and third case used the same study reach, which started downstream of the outlet of Nedre Leirfoss and Bratsberg power stations and ended upstream of Sluppen Bridge. For the second study, we utilized a side channel on the left side of the island at Trekanten site, which was comparable in size to the other UK rivers used in this particular study (see section A.1.5 for description of the UK sites).

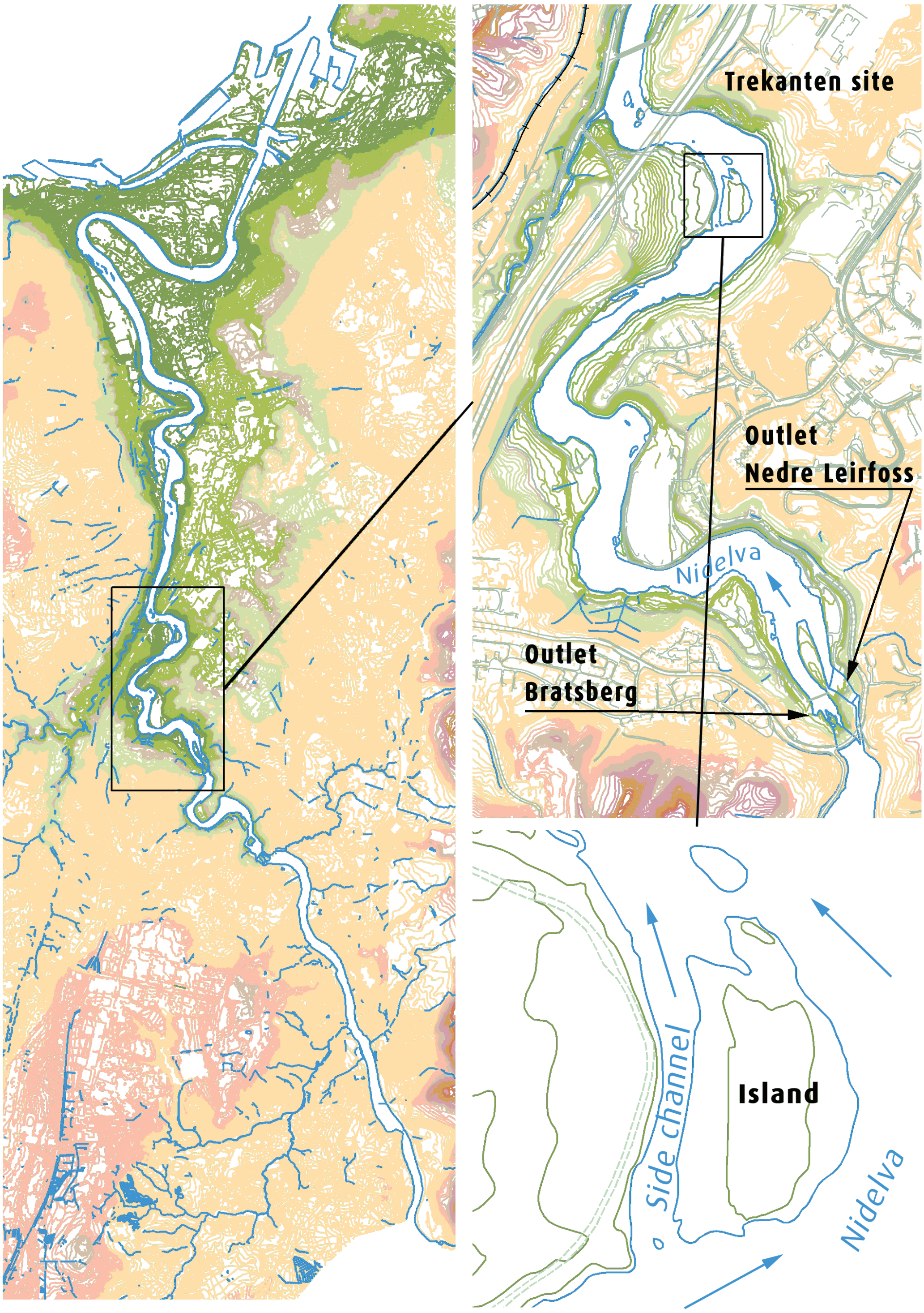


Figure A.1.2: Map of the Nidelva study reaches. The left map shows the lower section of Nidelva in the Trondheim area. The upper right map shows the study reach used in the pilot study of the NMCM and in the application study of the NMCM. The lower right map shows the study reach used for the analysis of the hydromorphological picture of HMUs.

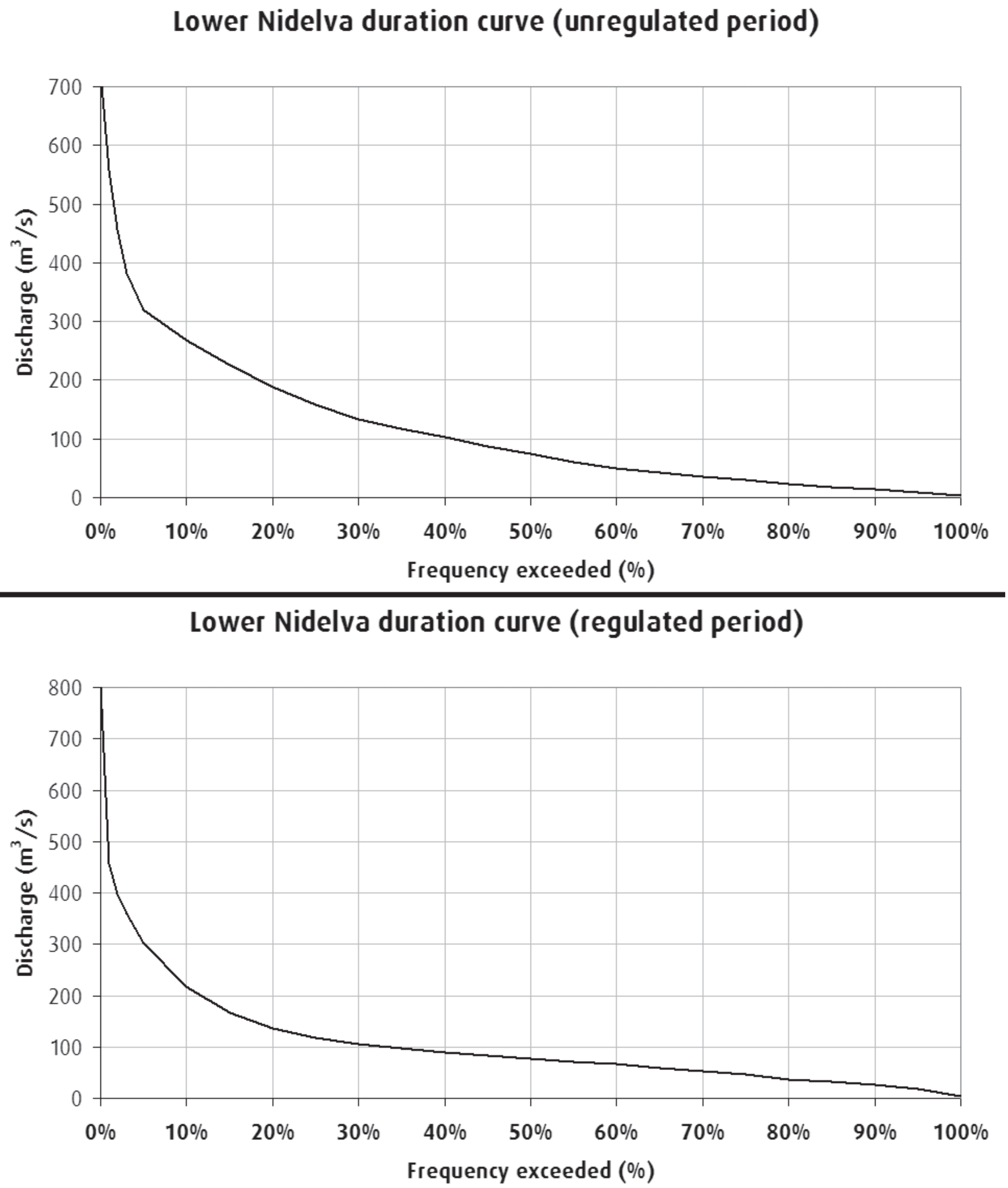


Figure A.1.3: Flow duration curves in the regulated and unregulated periods in lower Nidelva, Rathe measurement station (observations from 1 January 1881, regulated from 20. August 1902, mean in regulated period 102 m^3/s, in unregulated period 112 m^3/s)

A.1.1.1 The Nea-Nidelva hydropower system

The system includes 10 power stations, 7 reservoirs and their related transfer connections. Geographically the catchment extends from inside Sweden to the coast at Trondheim. Figure A.1.4 shows the schematic of the hydropower system. Blue trapezoids mark the reservoirs, black squares water transfer points between separate catchments and grey squares the power stations. The study reach starts downstream from the outlet of Bratsberg and Nedre Leirfoss power stations, marked by the green square (control point) on the scheme.

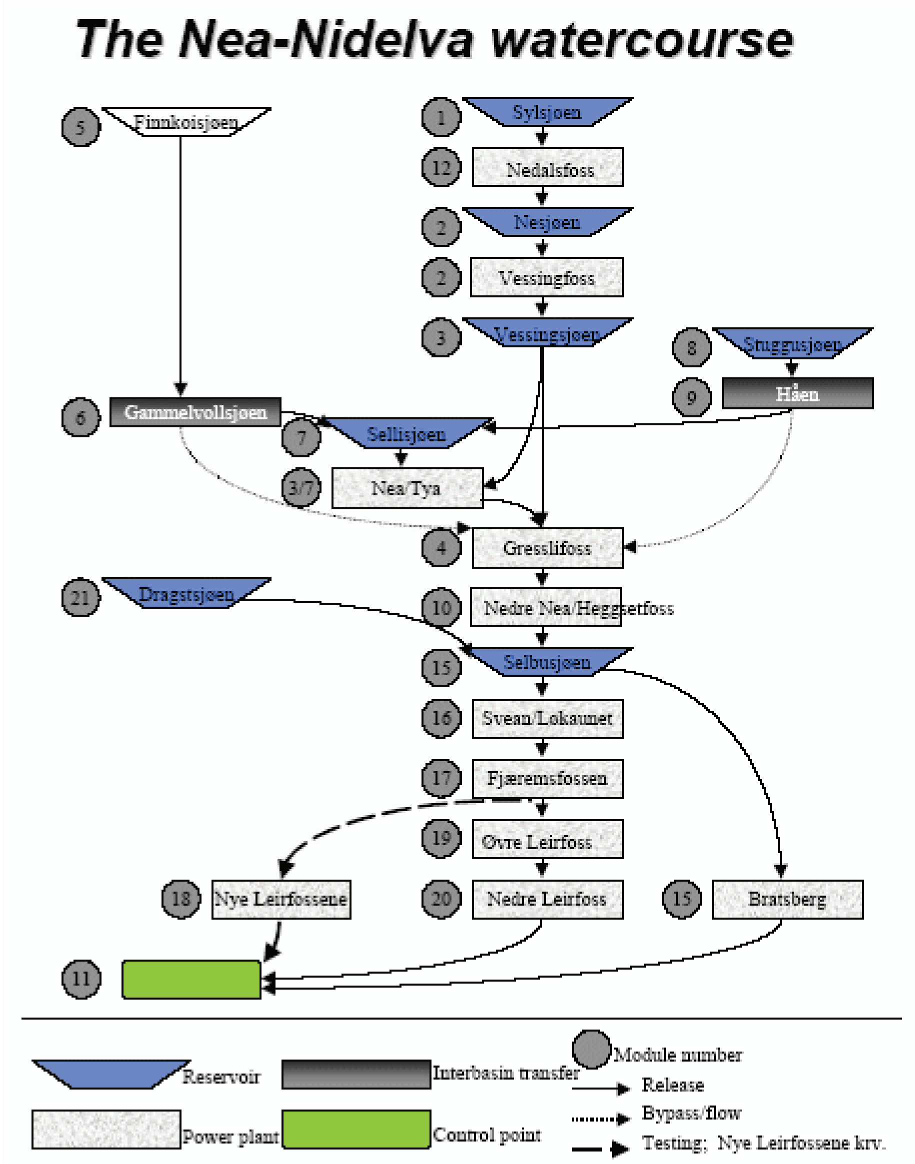


Figure A.1.4: The Nea-Nidelva hydropower system, from Killingtveit (2004)

A.1.2 Orkla

The Orkla River is situated in the central part of Norway. With its 3346 km^2 large catchment, it is the third largest river flowing to the Trondheim Fjord. Ureña (1999) provides extensive details of the Orkla catchment. The sources of Orkla are situated about 1000 m above see level, close to the Oppdal ski resort area. The catchment shape is elongated and its average slope is 6‰. Over 50% of the area is above timberline (which is at 600-700 m. a. s. l. here). The amplitude temperature (the temperature difference between the warmest month and the coldest month) is 15 C^o close to the sea and 20 C^o in the mountains. Precipitation is distributed unevenly, ranging from 500 mm to 2000 mm (from inland zones to the coast). The number of days with snow cover varies from 150 to 225 in the region. See Figure A.1.5 for geographical information on the river system. The mean annual discharge at the outlet to the fjord is 71 m^3/s. From the hydrological point of view, the river shows "nival" characteristics with a dominating spring flood caused by melting snow. There are gauging stations along the river that along with the five operating power plants give detailed hydrological information of the river system.

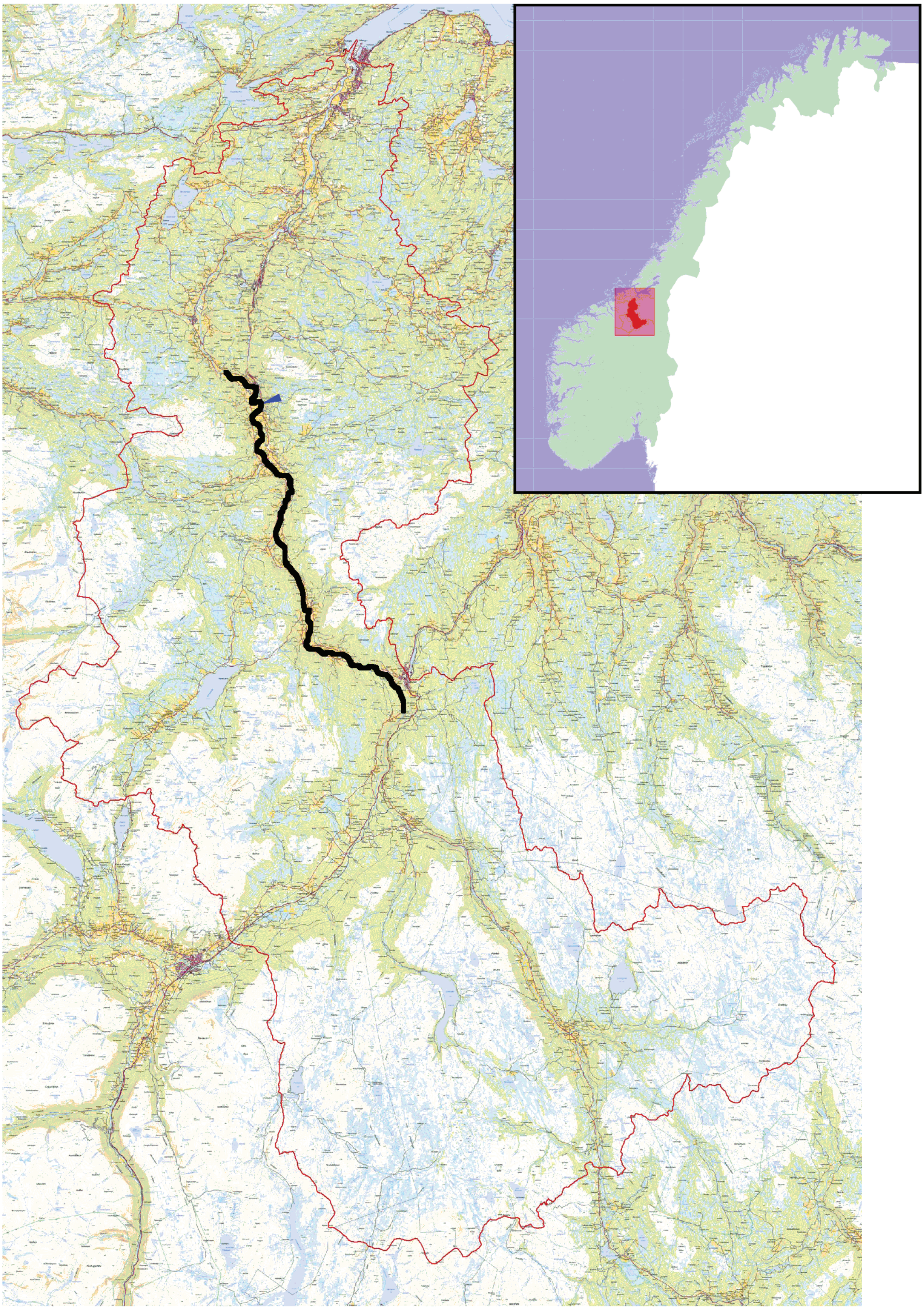


Figure A.1.5: The Orkla catchment. The blue triangle indicate a gauging station, while the black line mark the study reach

Figure A.1.6 shows flow duration curves at a hydrological observation station marked by the blue triangle on Figure A.1.5.

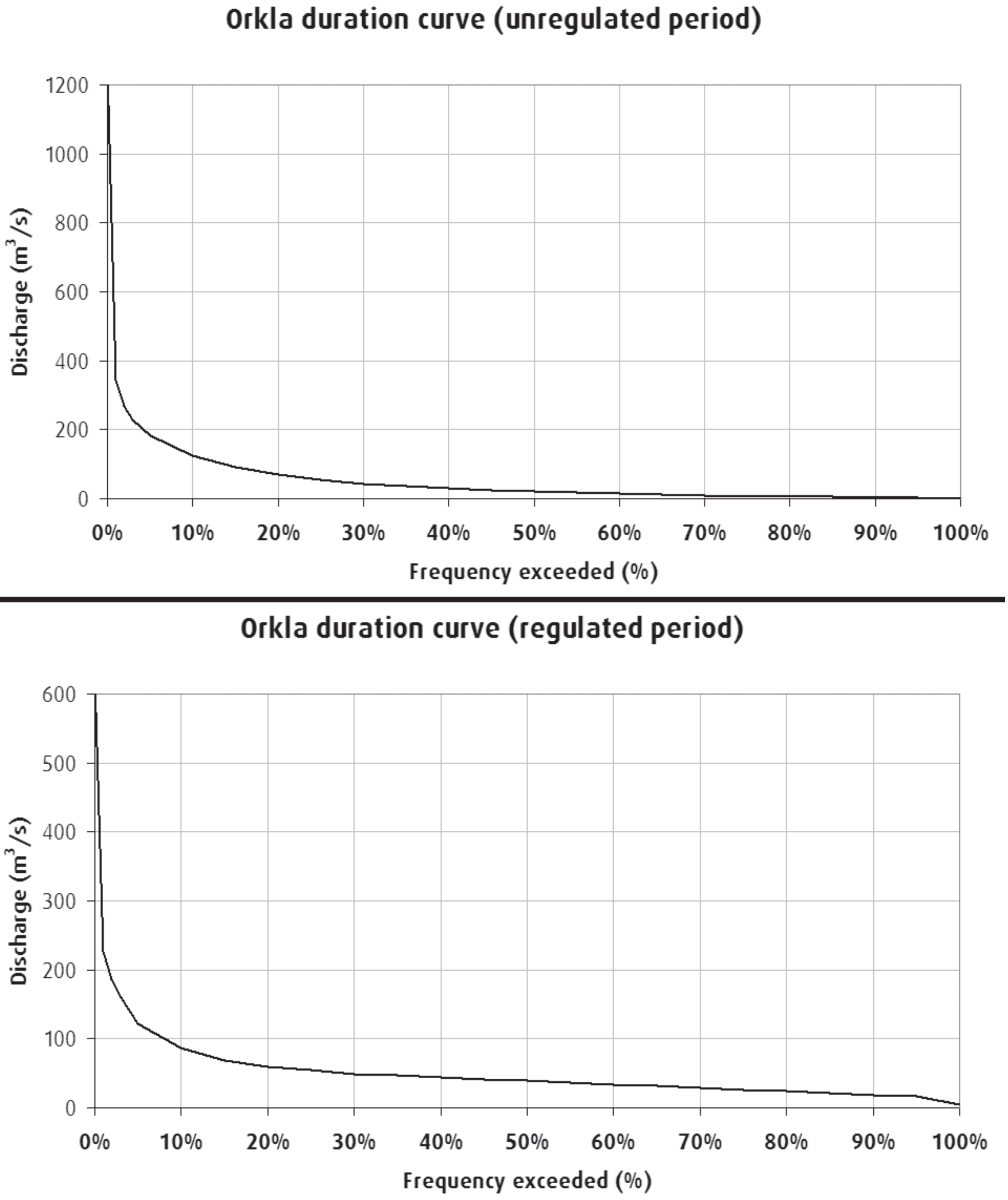


Figure A.1.6: Flow duration curves in the regulated and unregulated periods in Orkla, Syrstad measurement station (observations from 1 January 1912, regulated from 1. May 1982, mean in regulated period 49 m³/s, in unregulated period 47 m³/s)

Water quality is monitored regularly at several gauging and meteorological stations in the last 20-30 years to present time. An extract of the detailed description of the river by Ureña (1999) is presented below. Landscape along the river shows differences from upstream to downstream parts. There are three significantly different parts, the upper, the middle, transition and the lower regions. The lower part can be identified from its wide and flat valley and a considerable amount of farmlands. Upstream the transition zone follows between the lower and the middle regions, where river valley is steeper than in the neighbouring zones. Few agricultural areas and large forests surround the narrowing basin. Then just like at the lower region, the middle region is wide and flat again and farmers occupy the floodplain. This region is slightly scattered by short rapids in the river, where the valley narrows as well. Finally, in the upper region where the gradient of the riverbed is high, the valley forms a typical “V” shape (caused by erosion).

During the regulation of the river, the major changes in the catchment and in the floodplain were due to hydropower development. The whole development lasted from 1978 to 1985. Three power plants utilize water from tributaries, while other two are located on the main river. Agricultural activities also affect the area, mostly at the lower region. Other changes are related to flood embankments, roads, etc. Finally, gravel mining and flood protection measures alter the riverbed. At downstream sections of the stream, gravel extraction was so intensive that riverbed has been lowered by roughly 2 meters. This activity has led to stability problems on the embankment, larger erosion and decrease of fish habitat.

There was a strong public debate regarding the Orkla regulation project, first because of the dismay of effects on salmon fishing and secondly because of suspected changes of local climate. After a ten year long monitoring of the environment salmon habitat seems to be even better than before the project and so far no significant changes in the climate can be noted.

A.1.3 Ingdalselva

Ingdalselva drains to the fjord of Trondheim and is situated north from the catchment of Orkla (see Figure A.1.7). Discharge is measured regularly since May 2002, close to the outlet to the fjord (blue triangle on the map). The upstream border of the study reach is Sagfossen at Husdalen. The river here flows mostly northwards to the confluence of Ingdalselva and Grostadtjørna, where it turns in NE direction. The downstream end of the reach is at the urban area of Øvre Ingdal.

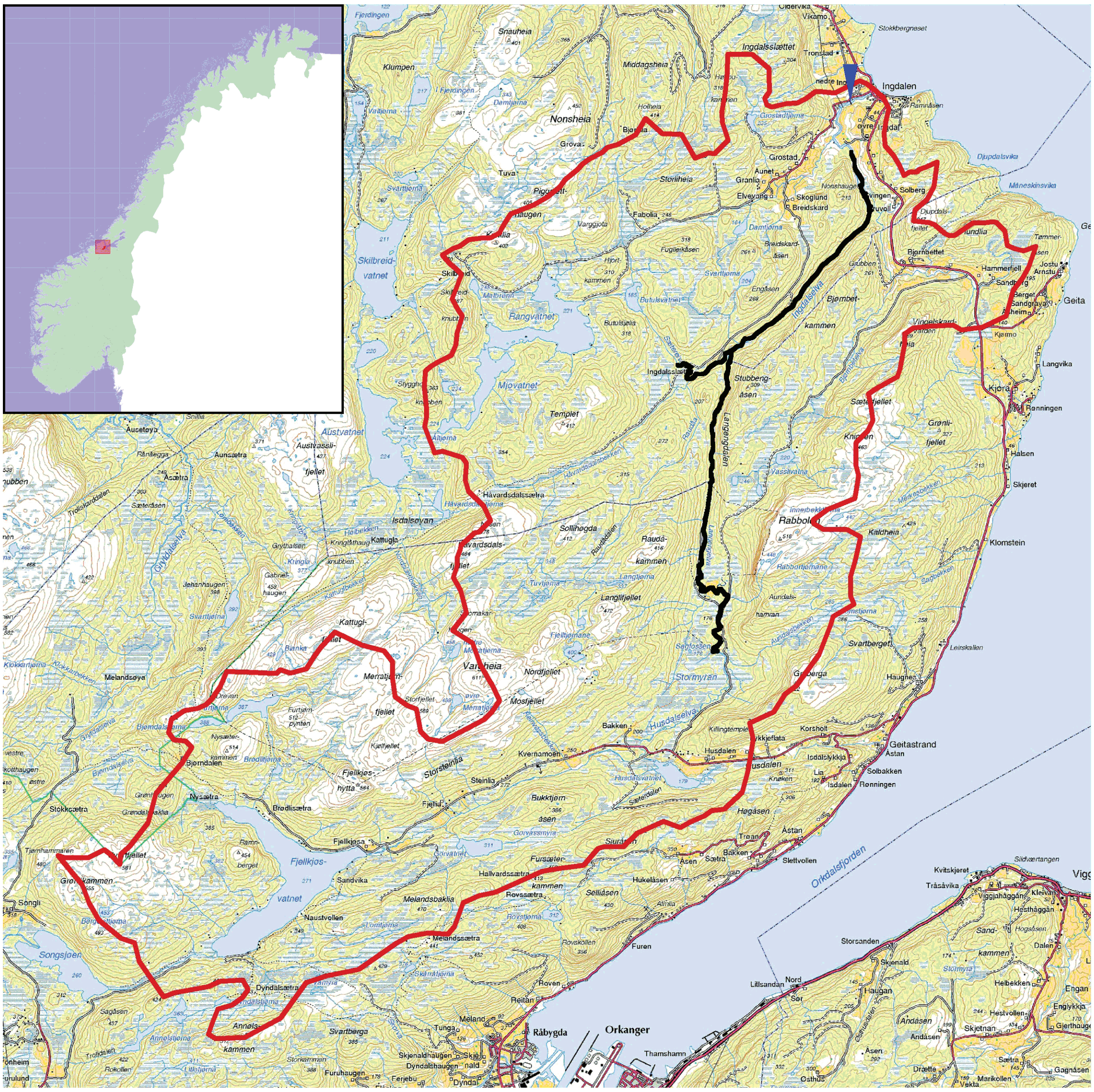


Figure A.1.7: Ingdalselva catchment. The blue triangle indicate a gauging station, while the black line mark the study reach

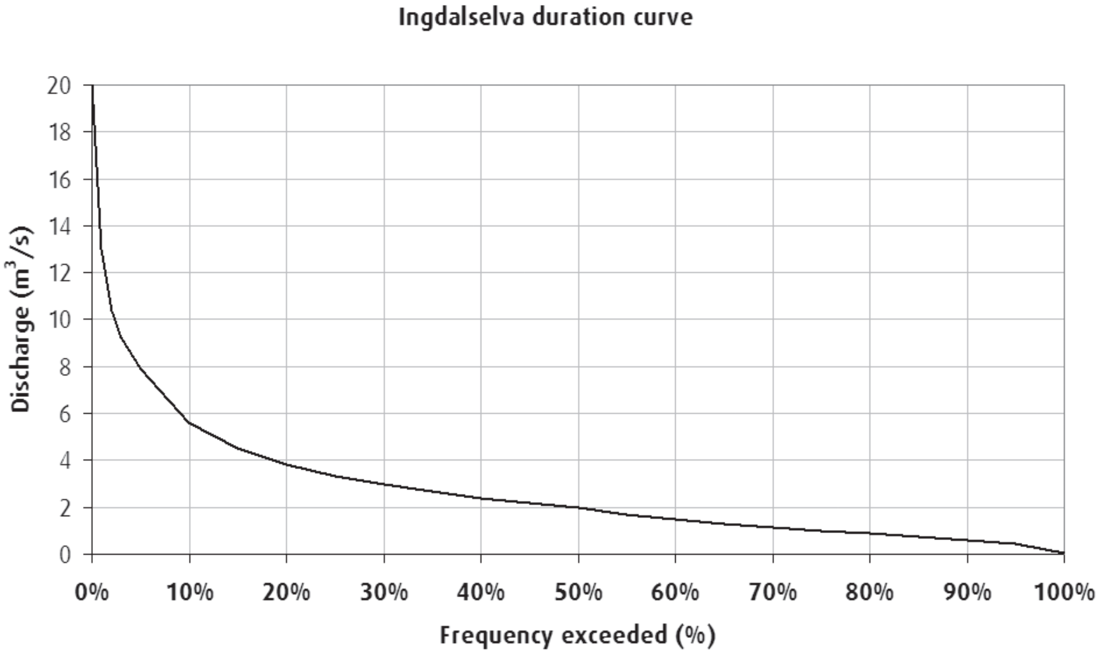


Figure A.1.8: Flow duration curve of Ingdalselva, Ingdalsfoss measurement station (observations from 1 May 2002, unregulated, mean in observation 2.5 m^3/s)

A.1.4 Surna

Surna is a river situated SW from Trondheim, flowing from east to west. It has been regulated for hydropower use since 5 July 1968, which regulation is now planned to be revised. The hydropower outlet divides the river into two easy to distinguish parts, referred to as the lower and the upper reaches hereafter. The two overlapping blue triangles on the middle of Figure A.1.9 mark the point of discharge form Trollheim power station. The upper reach is a mountainous reach with summer low flow and flood in springtime, less effected by the regulation opposed to the lower reach. That, on the contrary is more severely effected by reduced flows and accidental (opposite or negative) peaking. This accidental peaking is caused by malfunction of the installed machinery, when production of power is stopped abruptly and since the bypass channel is much longer than the channel through the power station, it can take more than an hour before bypass water reaches the natural river channel at the power station outlet. Figure A.1.9 shows the regulated river basin of Surna.

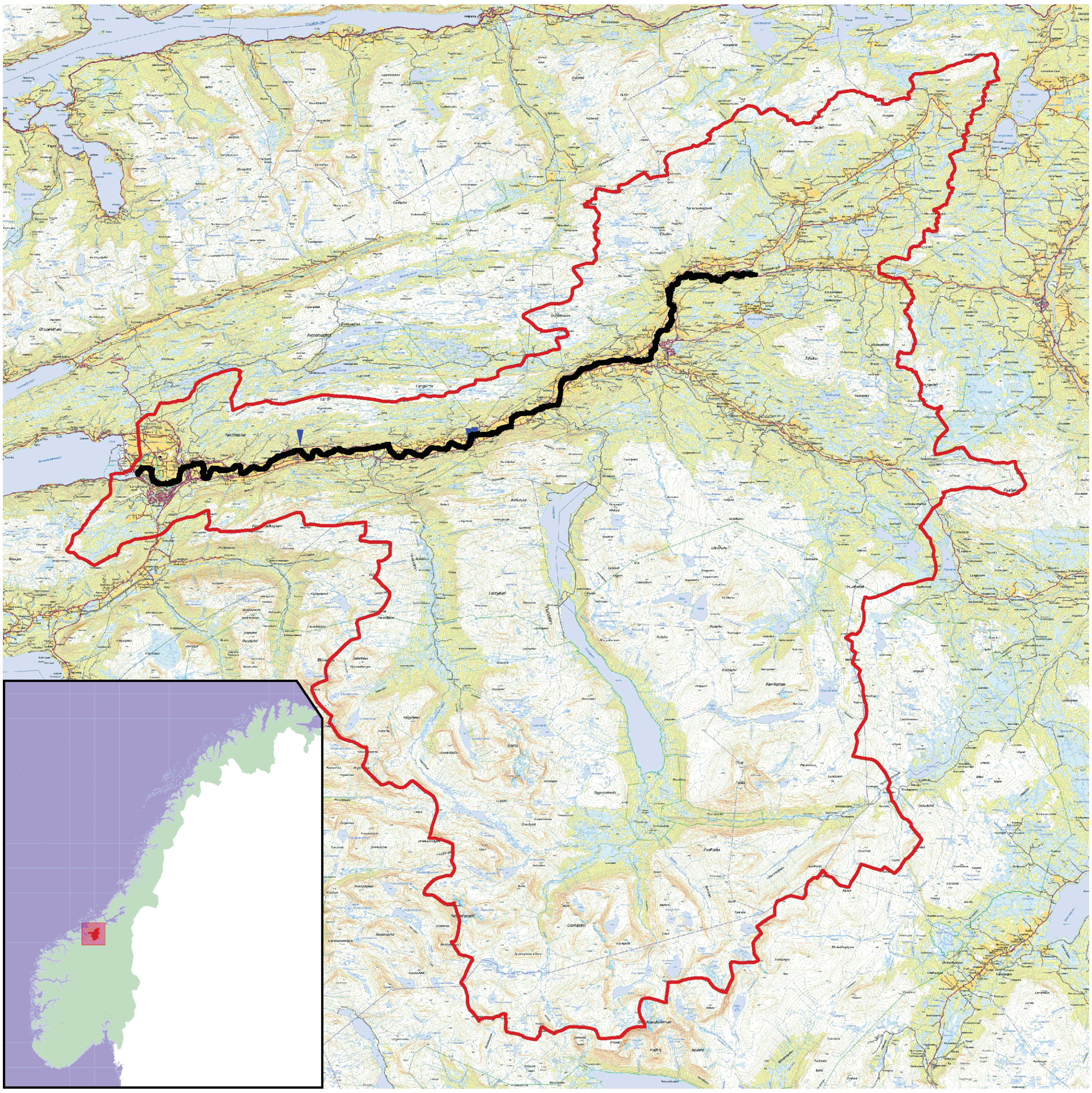
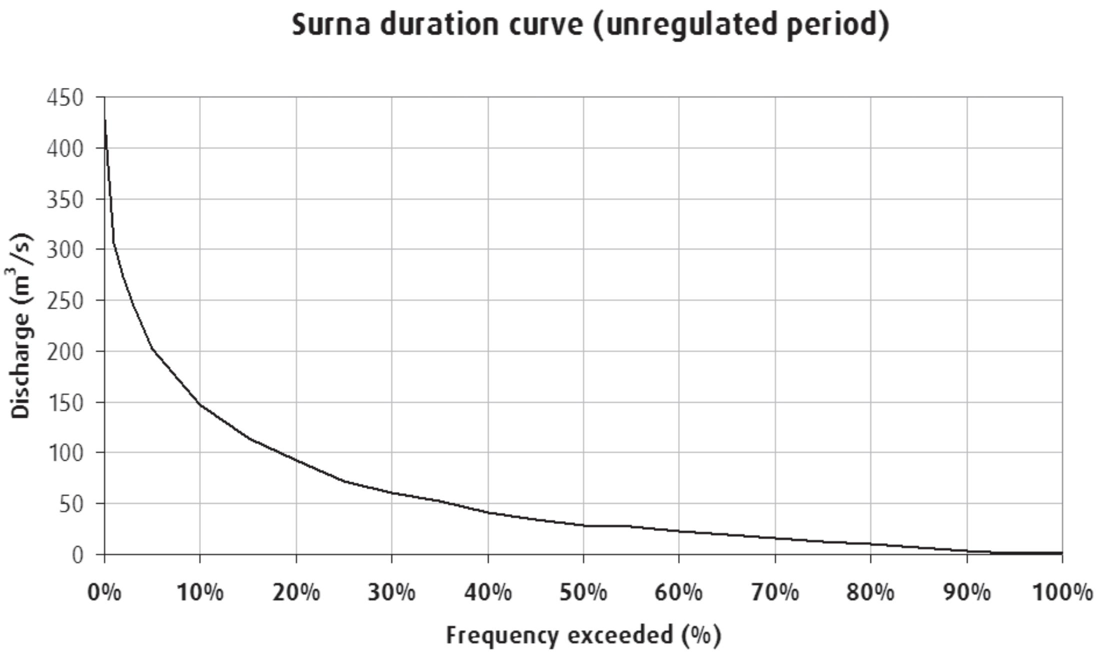


Figure A.1.9: The map of Surna catchment. The blue triangles indicate gauging stations, while the black line mark the study reach

Duration curves are shown on Figure A.1.10 based on data from the measurement station situated few kilometres downstream from the hydropower outlet (leftmost blue triangle on the map).



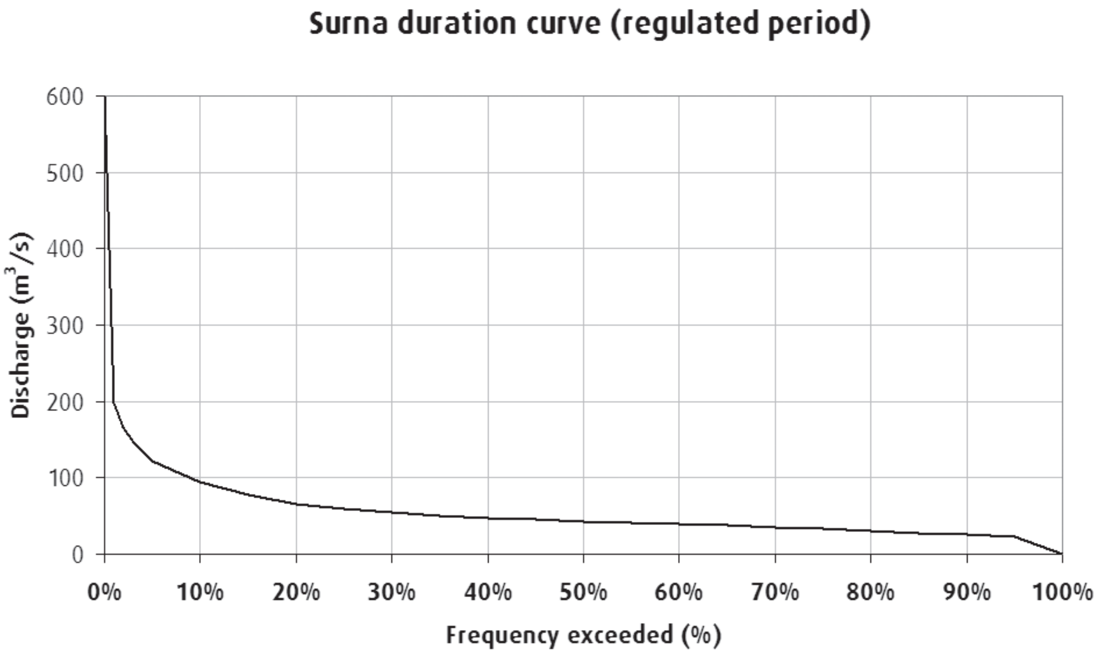


Figure A.1.10: Flow duration curves in the regulated and unregulated periods in Surna, Honstad measurement station (observations from 21 June 1965, regulated from 5. July 1968, mean in regulated period 53 m^3/s, in unregulated period 56 m^3/s)

A.1.5 Cruick Water and Water of Tarf

Figure A.1.12 shows the rough geographical location and the surroundings of the two sites. Water of Tarf is a creek in west Dumfries and Galloway that rises in New Luce Parish to the west of Craigairie Fell. The Gazetteer (1995) tells that it flows generally south eastwards for most of its course until a short distance beyond Tarf Bridge near Mark of Luce it turns north eastwards for just over 5 km-s before joining the River Bladnoch just east of Kirkcowan. Its total length is about 27 km. The geology is intrusive igneous rising steeply to 742 m above sea level, although downstream the river runs over metamorphic rocks and old red sandstone in the lower reaches. Land use is almost entirely rough grazing with little tree cover. The flow is unregulated and fully natural. The area is all part of a large estate and is relatively isolated. River Bladnoch is a tributary of the North Esk, which is on the northern edge of the Tayside region of Scotland.

The study site is situated ~250 m above sea level at the sharp turn mentioned above and has a catchment area of approximately 15 km^2. The study site is accessed from the North Esk valley via Tarfside, from south.

Cruick Water is a lowland river and it flows directly into the North Esk a few km-s downstream from our study site. The Gazetteer (1995) informs us that it is stream in Angus and it rises on Mowat's Seat in the Braes of Angus. It flows south into the valley of Strathmore then east to join the River North Esk at Stracathro. It has a total length of 26 km. Underlying geology is Lower Old Red Sandstone, land use is predominantly forest and pasture in the catchment.

The study site is situated ~50 m above sea level at Newtonmill and is accessed directly from the 8996 road between Brechin and Edzell. Our investigations covered the reach downstream from the bridge with a length of about 300 m downstream.

Both the Water of Tarf and Cruick Water are ungauged, but NRFA (2005) provides public gauging data of the North Esk close to its outlet to the sea, north of Montrose.

Figure A.1.11 shows the flow duration curve calculated from measured data at gauging station 013007 Logie Mill, North Esk.

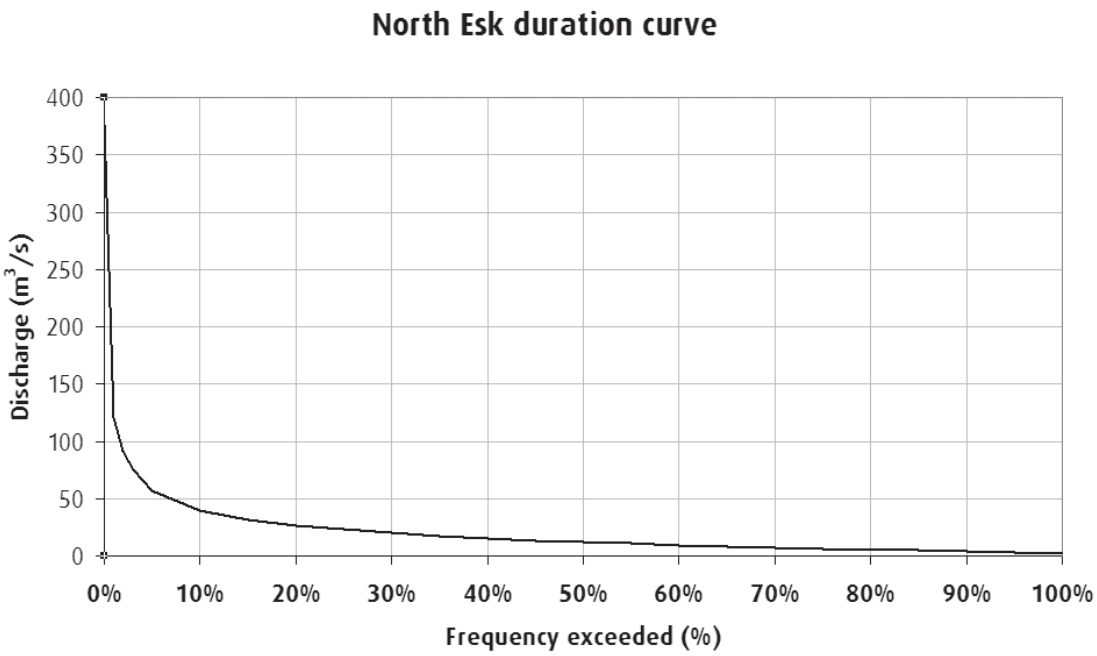


Figure A.1.11: Flow duration curve of North Esk, Logie Mill measurement station (observations from 1 January 1976, mean in observation 19 m³/s)

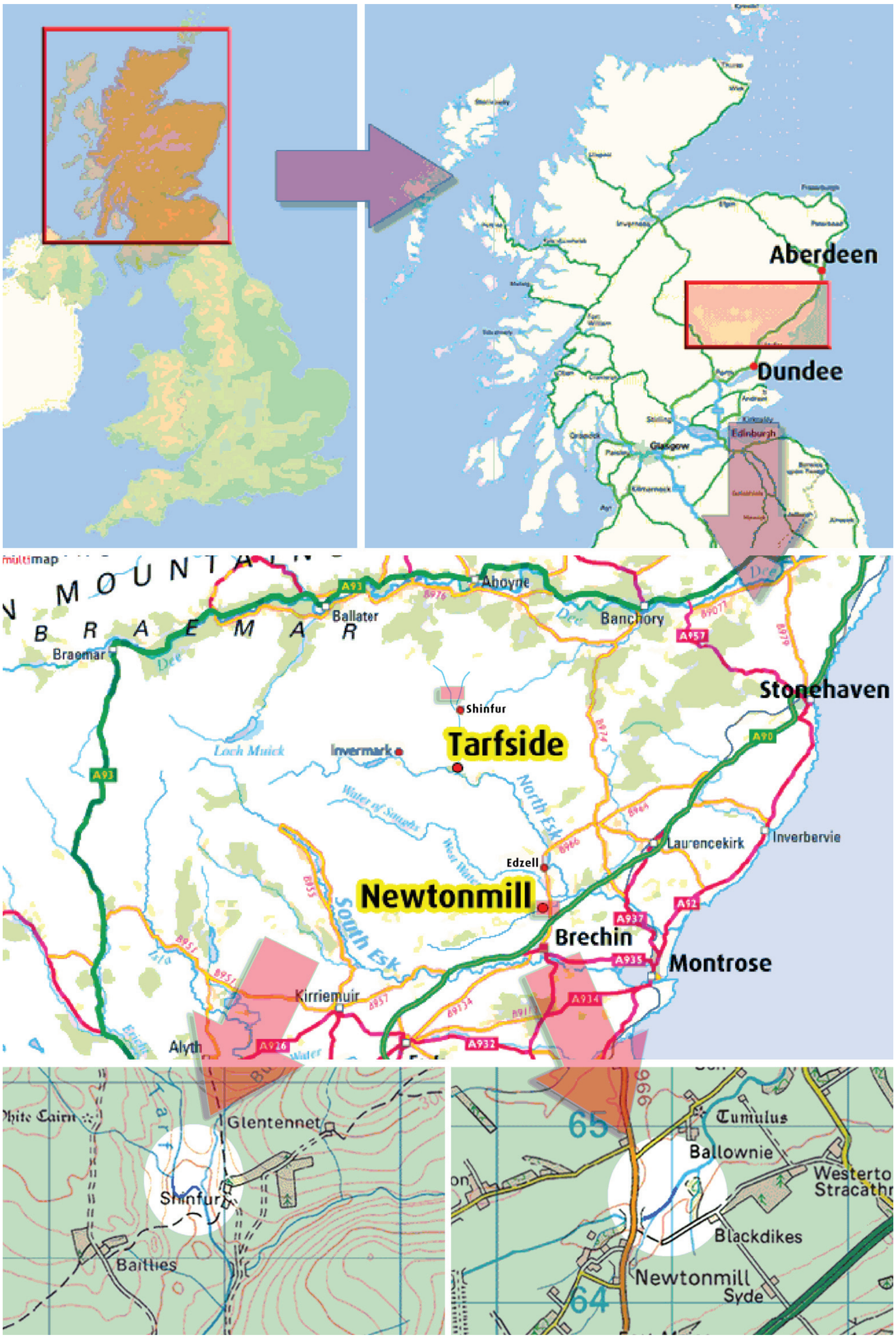


Figure A.1.12: Water of Tarf (bottom left) and Cruick Water (bottom right) sites in Scotland. The maps are published for non-commercial but only educational use by courtesy of http://www.multimap.com

A.1.6 Nausta

River Nausta is situated in west Norway and is famous of its natural salmon and trout production. The unregulated river rises on the east part of the catchment (left part of the map), flows westwards, then turns in SW direction and finally drains into Førdefjord from the north. The study reach is bordered by Naustdalfoss waterfall downstream and Fimland bridge upstream. Hovefoss gauging station is marked by a blue triangle on the map, at the lower third of the study reach.

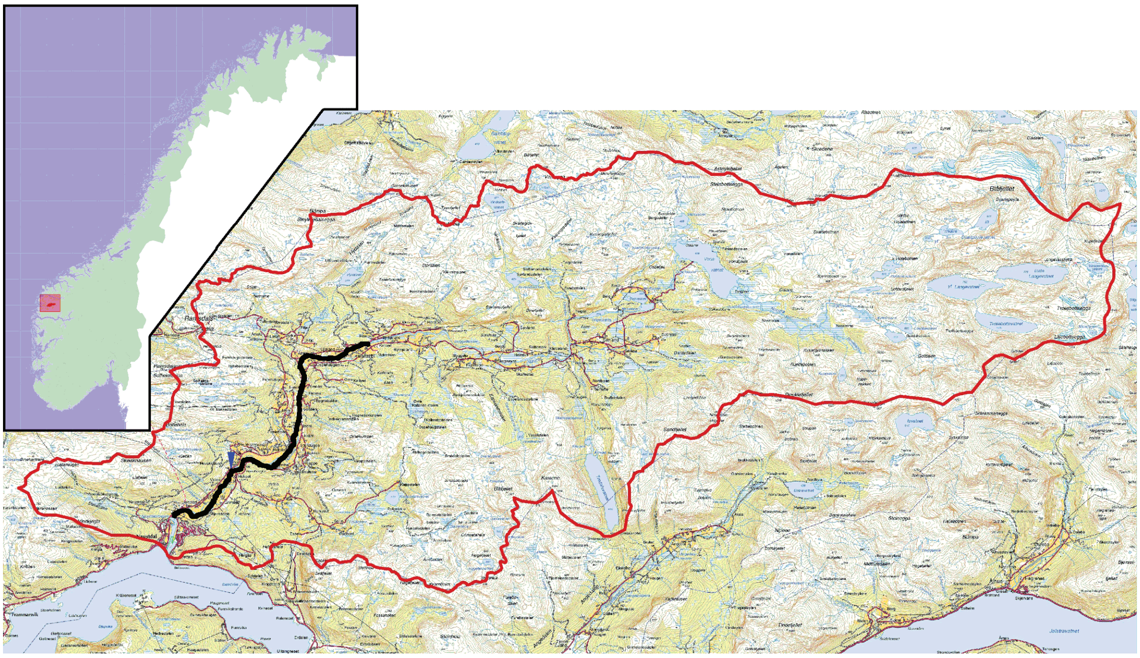


Figure A.1.13: Nausta catchment overview map. The blue triangle indicate a gauging station, while the black line mark the study reach

Figure A.1.14 shows the flow duration curve in the observation period. The measurement station is situated at the lower part of the reach, marked by a blue triangle on the map. Wet spring-early summer and low flows mostly occurring in winter characterise the river. Floods are distributed throughout the whole year, slightly higher in the autumn then in other periods.

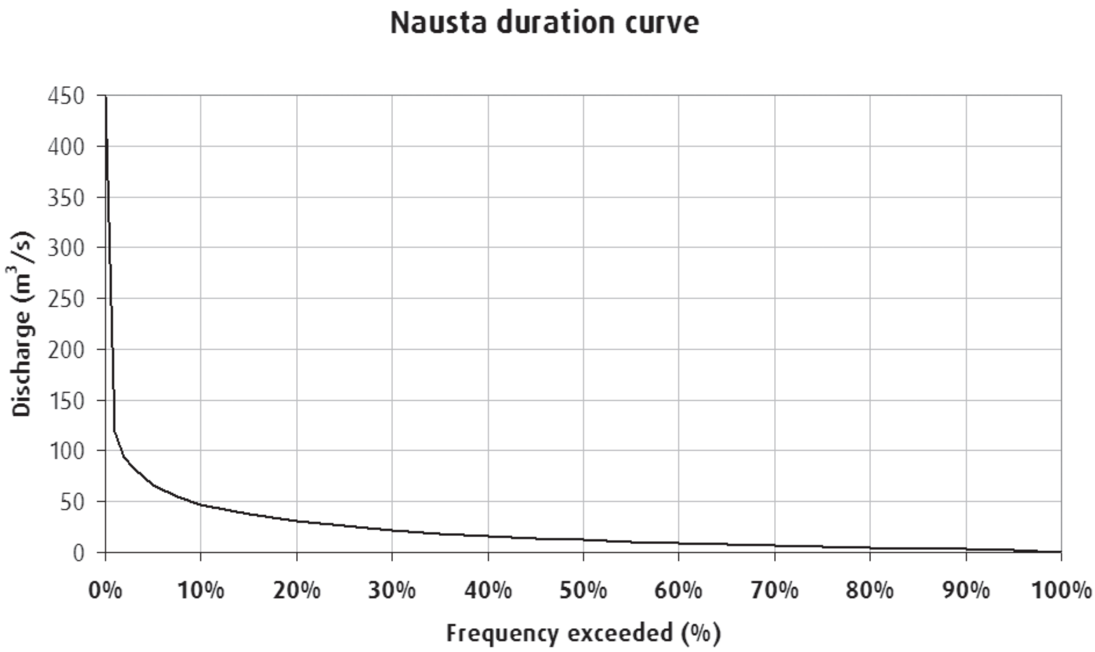


Figure A.1.14: Flow duration curve of Nausta, Hovefoss measurement station (observations from 29 November 1963, unregulated, mean in observation 20 m³/s)

A.2 Related projects

Development of the Mesohabitat Tool was practically organized as parts of two larger projects. These provided frameworks and financial support for the approach, setting convenient focus and proposed outcomes at different stages of the work.

A.2.1 The EFFEKT project

This project was run by the Norwegian Research Council together with several research companies, institutes and educational organizations such as SINTEF, NTNU, LFI, NINA, NIVA and was aiming to analyse the issues related to the impacts from hydro-peaking on riverine ecosystems. The project aimed to develop methods and models to assess impacts from increased peaking hydropower production on the riverine ecosystem.
There is a strong fear of destroying the living conditions in rivers, which are used for hydropower production. Electric power from water is produced in Norway for a long time though, the problem has risen only recently, because the power market was highly regulated before and market forces could not act freely on economical basis. Today it is possible selling and buying power for significant amount of money and thereby the amount of peaking is increased. At the same time downstream of power plants stranding of fish appear and the public expressed its demands to investigate and solve the undesirable situation. There are no legal regulations concerning hydro peaking presently, but it is very likely that in the close future the Norwegian Parliament will entertain the subject. So the privately owned power companies will than have to operate their plants in an environmentally sound way and this project was dealing with parts of the problem. Several sub-questions are touched. The sub-projects were the following:

- Stranding of juvenile fish in peaking rivers
- Physical habitat for juvenile fish and invertebrates during hydro peaking
- Fish behaviour during hydro peaking
- Hydro peaking and water vegetation. Case study in Mandal river system
- Smolt production in peaking rivers

A.2.2 The Mesohabitat project

The less useful but full name of this project was the "Functional links between mesohabitat classes, food consumption growth and production of Atlantic Salmon"
The main objective of this study was to establish functional links between major habitat classes in salmon rivers and the performance of fry and parr in these habitats in order to assess the importance of variation in habitat quality within and among rivers for smolt production. The main objective was attained through the following sub objectives:
To develop methods for scaling up from established microhabitat models to mesohabitat classes that can be applied in practical river characterisations.
To estimate and compare relative growth, food consumption and growth efficiency of fry and parr in different habitat classes within and among rivers.
Several rivers were pointed out, to test the capabilities of and to improve the method. These were the following (Table A.2.2):

Table A.2.2: Description of study sites

River	Location (km from Trondheim)	Mean Flow (m^3/s)	Catchment (km^2)	Length of Study section (km)	Details of study section
Lower Nidelva	In Trondheim	94,91	3125 (Inter-connected catchment)	10	30 cross sections
Orkla	200 south-west	67,19	3053	20	15-20 cross sections
Ingdalselva	50 west	2,62	102	15	10-15 cross sections

A.3 Utilized models and software

This section provides background information about all major utilized models and software packages. Not all details and aspects of these are listed here, instead, the features and describers related to the present work are discussed briefly.

A.3.1 Population model - Norsalmod

The salmon population model NORSALMOD is developed to simulate the population development of Atlantic salmon from spawning to out-migrating smolt controlled by physical and biological factors. The model can handle multiple year-classes simultaneously. The two main components are:
A temperature based growth and development model that simulates egg maturation, alevin development and parr growth using temperature formulations. Work is done to develop this model to suit different temperature regimes found in various Norwegian rivers. The setup includes data for size distributions in each year-class and it computes the number of smolts from each year-class.
A habitat based distribution and mortality model that uses a meso-habitat characterization of the river to predict spawning areas, parr distribution, parr movement and habitat suitability. Data from the functional links programme are be used to characterize the available habitats depending on biological criteria. The meso-habitat method classification method used in the population model will be simplified in order to operate on fewer numbers of classes.
In addition, the model consists of a temperature component and a hydraulic component that handles flow routing and stage computations at certain locations. Since one of the objectives of the development is to describe effects of river regulations on the salmon population the base structure can also handle reservoirs with gates, spillways and release plans. The base structure of the method is shown on Figure A.3.15.

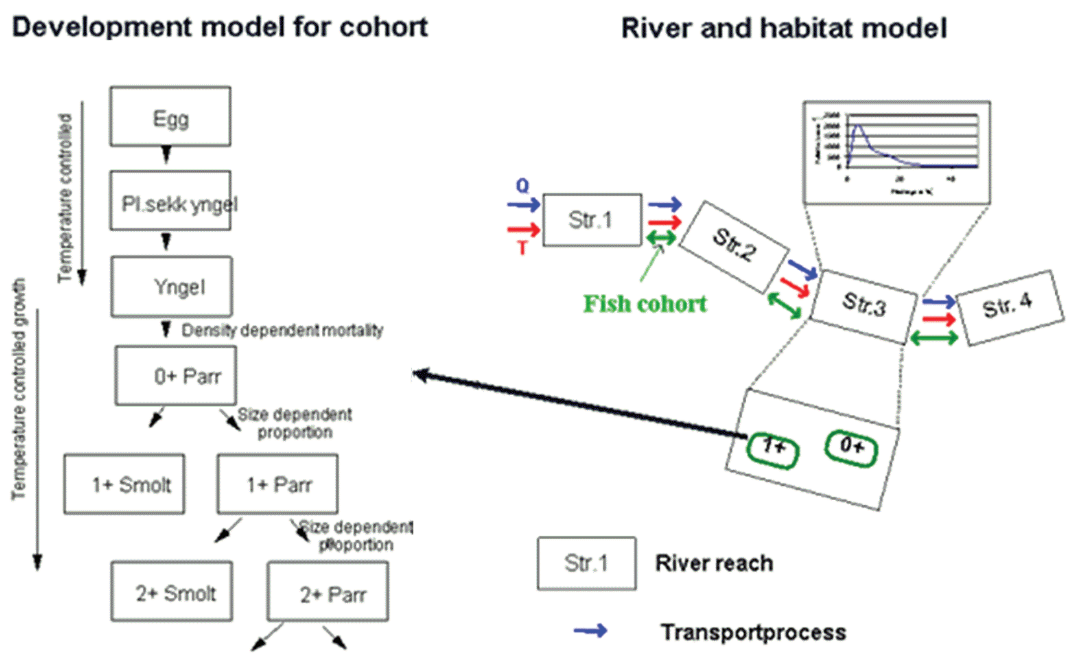


Figure A.3.15: Norsalmod population model (courtesy of Knut Alfredsen, NTNU)

A.3.2 The nMag model

This is the second version of the original ENMAG model, which was developed in 1984-86 at the Norwegian Hydrotechnical Laboratory. User documentation is provided in Killingtveit (2004). The major difference between ENMAG and nMag is that this latter can handle more than one reservoir. The main components of the hydropower system are the:

- reservoir;
- power plant;
- interbasin transfer; and
- control point.

By defining the internal links and providing the necessary and optional data that describe each component, the model can calculate power production, water release, spillage and other values at them. For example in the case of a "Power Plant" component, the necessary data are:

- addresses of turbine water, bypass release, flood spill;
- maximum capacity (m^3/s); and
- energy equivalent (kWh/m^3).

Optional data are for example:

- nominal head (m);
- intake and tailwater levels (m.a.s.l.);
- head loss coefficient (s^2/m^5);

- peaking schedule;

Simulations can be organized according to monthly, weekly, daily or hourly time-steps. Runoff data from the sub-catchments and daily/annual price variations should be presented as input. Peaking is defined by hourly ratios of proposed daily loads, while seasonal variations can be described by their relationship to one another (since total runoff cannot be foreseen).

A.3.1 Boss DAMBRK

This programme was designed to predict flood wave propagation in a river channel. BOSS-International (2001) provides further information on the software. The flood source can be, for example, a dam failure with breach development or simply a given inflow hydrograph. At the outlet of the channel, for example, a stage hydrograph can be described to ensure a proper boundary condition at the downstream end of the model. The channel is defined by cross sections (geometry, friction, distances from one another, etc.). Flood routing follows the initialisation of the starting conditions and results in stage and discharge time series for the cross sections.

Serious limitations of the system are the limited number of graph-points allowed for specifying the inflow hydrograph, the method of describing the cross sections and the strong sensitivity to backwater effects. Characteristic points of which DAMBRK accepts only 30 specify the inflow hydrograph. Therefore the simulation period is restricted if there are significant variations in the inflow. The programme can handle only symmetric cross-sections, so the actual cross-section must be converted accordingly. Computational problems can often occur where there is a local depression in the channel, so where slopes are negative in the downstream direction between two cross sections.

A.3.2 Habitat

The first version of the program was created as the habitat modelling part of the River System Simulator in 1996. Alfredsen (1998a) gives details on the program. It was used to describe channels with respect of their suitability for fish life. The main purpose within RSS was to minimize the negative environmental impacts of regulations or power production on fish production. The version used here can handle various types of input sources such as HEC-2/HEC-RAS, SSIIM and more. One-, two- and three-dimensional modelling results can be handled. The user interface is a control file for the major module; the user gives various options and switches that influence the programme input, operation and results. These results can be further analysed by the presentation module (Habplot) or other means. The system is able to create classical preference curves (habitat classification curves), WUA (weighted usable area) curves, habitat time series, habitat plots and –in a preliminary form– habitat patches (indices).

A.3.3 ArcView

The general use desktop GIS package from ESRI is used here for generation of channel geometry and for display and analysis of hydraulic simulation results. General information about the software is provided in ESRI (1996). ArcView 3.3 features integrated charts, maps, tables, mapping and analysis capabilities for both vector and raster data. Default capabilities are expanded through extensions, of which “3D Analyst”, “Spatial analyst” and “HEC-GeoRAS” are used. Data classification possibilities include equal area, equal interval, natural breaks, standard deviation, data normalization. Conversion between vector data, grids, graticules, are possible.
Analysis capabilities comprise spatial queries, buffering, geoprocessing for performing spatial operations such as dissolve, merge, clip, intersect and union and data aggregation. Data can be read from ESRI Shape files, “ArcInfo Coverages”, PC ARC/INFO Coverages, AutoCAD (DXF and DWG), MicroStation (DGN and MSG), TIFF 6.0 (including GeoTIFF) and so on. The extensions used allow data support for TIN, GRID (as raster data), DOQ, IRS-1C, Landsat TM, RPF, SPOT, GeoSPOTV formats. Data features are divided to geometry, display and attribute groups, which are stored in separate files. It is also possible to edit them separately. This triple set of features are referred to as the ArcView Shape files. Editing features are less flexible as in a general CAD environment, but possible with little workarounds.

A.3.4 HEC-RAS

The abbreviation stands for Hydraulic Engineering Center, River Analysis System and is described in . HEC is an institute within the United States Corps of Engineers and has been developing this package for several years. With version three, dynamic (time-dependent) simulations were made possible. HEC-RAS performs one-dimensional hydraulic calculations for a network of natural and/or constructed channels. The system presently contains two one-dimensional hydraulic analysis components for steady and unsteady flow simulations. A key element is that both components use a common geometric data representation and common geometric and hydraulic computation routines. It also contains several hydraulic design features. Data communication is allowed by either simple ASCII or binary type input/output files (with predefined structure), or by the HEC-DSS data storage platform. Generation of the model is not fully automatic, input data are converted to files under separate categories of so called “projects”. These include plan, geometry, steady flow data, unsteady flow data and sediment data of which each is stored in separate files. Output data is primarily written to binary files, but can be transferred to HEC-DSS type databases as well. In addition to the regular and DSS data input/output communication and channel geometry can be retrieved from several other formats, including GIS, Mike 11, HEC-2, USACE and so on. GIS format here refers to ArcView/HEC-GeoRAS generated channels on TIN terrain models. Read HEC-USACE (1998), (2002) for further information.

A.3.5 HEC-GeoRAS

This package is distributed as an extension for ArcView 3.2. HEC-GeoRAS, described by Ackerman (2002), is a set of procedures, tools and utilities for processing geospatial data in ESRI’s ArcView GIS software package using a graphical user interface. This interface allows the preparation of geometric input data for HEC-RAS as well as simulation results exported from HEC-RAS. A digital terrain model (DTM) of the river system in TIN format is needed. Channel geometry is then generated by drawing a series of 2D line themes. These are the “Stream Centerline”, “Flow Path Centerlines”, “Main Channel Banks” and “Cross Section Cut Lines” (these are the “RAS Themes”. Additional possibilities include information on “Land Use”, “Levee Alignment”, “Ineffective Flow Areas” and “Storage Areas”. Hydraulic simulation results, like water surface profile data and velocity data are exported from HEC-RAS. ArcView GIS 3.2, for Windows and 3D Analyst Extension is required. Spatial Analyst extension is recommended.

A.3.6 HEC-DSS

HEC-DSS stands for HEC data storage system and it stores data in a way useful for inventory, retrieval, archiving and model use. HEC-USACE (1995) provides further information. The original fields of application were water resource applications. Interaction is allowed with the database by utilities that allow entry, editing and display of information independently from each other, or application programs that are able to communicate with the data base (where the these utilities are coded in the application or included as libraries).
The most important uses are storage and maintenance of data in one centralized location (common database), providing input or output for application programs, transferring data between application programs and displaying data in graphs or tables.

The HEC-DSS MS Excel Data Exchange Add-In, described in more detail in HEC-USACE (2003), is a Visual Basic application for reading and writing regular-interval time series or paired data directly from/to Excel to/from a HEC-DSS database file. Irregular-interval time series data utilities are not yet available.