AMBER

www.amber.international

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689682.

D4.2 Report of Case Studies Demonstrating the Effects of Barrier Removal, Mitigation and Installation

This is version 1.0 of the Report of Case Studies Demonstrating the Effects of Barrier Removal, Mitigation and Installation. This document is a deliverable of the AMBER project that has received funding from the European Union's Horizon 2020 Programme under Grant Agreement (GA) # 689682.

History of changes

Version	Date	Changes	Pages
1.0	19 May 2020		

DISCLAIMER

The opinion stated in this report reflects the opinion of the authors and not the opinion of the European Commission.

All AMBER consortium members are also committed to publish accurate and up to date information and take the greatest care to do so. However, the AMBER consortium members cannot accept liability for any inaccuracies or omissions, nor do they accept liability for any direct, indirect, special, consequential or other losses or damages of any kind arising out of the use of this information.

Executive summary

This is the 2.0 version of the Report of Case Studies on the Effects of Barrier Removal, Mitigation and Installation. This document is a deliverable of the AMBER project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 689682.

Within the AMBER project, a total of seven case-studies were included to provide a practical background for the methods tested and examples from the wide range of barriers found in European rivers and their management. The case studies represent different types of barriers covering a wide geographic range, from Andalusia inSpain to Northern Scotland.

In each case, the AMBER research teams have spent considerable effort to investigate the relevant aspects of the specific barrier and the process involved in management, be it mitigation/modification, removal or construction. A range of research methods have been used, some of which have been developed through the AMBER project, and the methods used are described, and to some extent evaluated, in this report. Two case studies deal with installation of new barriers (Hydropower dams), three cases studies, modifications of already existing dams and two case studies review the effects of barrier removal. From the installation of new barriers case studies, one of the planned dams was cancelled after a long decision process, mainly due to pressure from NGOs and environmentalists, while the other was postponed, and a more environmentally friendly plan for the river agreed upon. Three large dams were undergoing modifications to mitigate adverse effects, and the AMBER studies provided important information to help design changes that will have substantial positive influence on connectivity. In the case study of barrier removals, the planned removal of a large dam in the Blackwater River in Ireland was unfortunately substantially delayed, so the evaluation of impacts could not be performed as planned. However, a range of relevant studies were carried out at this location.

In the case of barrier removals in small rivers, a substantial number of actual dam removals were described and before and after measurements of habitat and fauna were used to evaluate the effects of the removals. The studies of cases where both social- and natural science was used, provided the AMBER research team with a vast range of experience in terms of new methods, obtained results and insight into the processes involved in barrier management. Much of this experience has been transformed into scientific papers, but in this report, almost all of what has been learned in the seven case studies is compiled.

The case studies demonstrate the wide range of issues associated with barriers in rivers and the loss of connectivity they can cause. Each case study is quite unique, with different biology, hydrology and society/culture, so it is clear that one general step-by-step solution will not solve all problems. The case studies show that a deep involvement from citizens, stakeholders, NGOs and researchers can really influence decisions on infrastructure that will impact our environment for decades to come.

Authors

Brian Coghlan (IFI), Barbara Morrissey (UHI),César Rodriguez Ruiz (AEMS), Ciara Fleming (IFI), Damian Bubb (DU), Eric De Oliveira (EDF), Eric Verspoor (UHI), Euan Bowditch (UHI), Eva Garcia-Vasquez (UNIOVI), Eduardo Dopico (UNIOVI), Fabien Henault (EDF), Iwona Pińskwar (ERCE), James Barry (IFI), James King (IFI), Janusz Ligięza (SSIFI) Jeroen Tummers (DU), Jocelyn Rancon (CNSS), Katarzyna Suska (SSIFI), Karol Ławniczak (ERCE), Kim Aarestrup (DTU), Kim Birnie-Gauvin (DTU), Lucio Marcello (UHI), Mairi Innes (UHI), Małgorzata Łapińska (ERCE), Martyn C. Lucas (DU), Matthieu Le Brun (EDF) , Niels Jepsen (DTU), Paweł Buras (SSIFI), Paweł Prus (SSIFI), Piotr Dębowski (SSIFI), Piotr Parasiewicz (SSIFI), Samantha Beck (UHI), Samy More (EDF), Sara Garrido Espinosa (AEMS), Silvia Carvalho (UHI), Stéphane Tétard (EDF), Wiesław Wiśniewolski (SSIFI), Zbigniew Kaczkowski (ERCE) for the AMBER Consortium.

Acknowledgements

Thanks to Paul Gaffney, Mark Taggart and Hugh Cheape for their contribution to Case Study 4: Quoich Dam, Upper River Garry, of water quality analysis reports and historical monographs for the River Garry catchment.

Edited by Niels Jepsen and Victoria Hurst-Brown.

Contents

1 INTRODUCTION

Barriers are ubiquitous in today's rivers. Be it to provide energy, flood control or recreation, barriers have altered the natural course of rivers over the past centuries (Nilsson et al. 2005). Following the realization of the effects of barriers, especially on migratory fish species, an era of engineered-solution surfaced to improve fish passage (Silva et al. 2018; Birnie-Gauvin et al. 2019). Thus far, these solutions have had underwhelming effects, and barriers continue to threaten the livelihood of freshwater ecosystems as a whole. Yet, in many countries, hydropower dams, water supply dams and flood control dams continue to be approved and constructed. In few nations are barriers slowly and painstakingly being removed.

In WP4, more practical, empirical experiences with barrier management and the use of various methods are described. Here, we wanted to move away from the laboratories and the theoretical models and into the real world. While acknowledging that it is not easy to study an often very long process like dam removal, dam installation or dam mitigation in a short project like AMBER, we set out to implement some of the methods as well as have the opportunity to study actual (engineering) projects and the ecological effects of these.

The case studies were not selected on the basis of criteria chosen by AMBER, but were mainly those available where partners had a chance to follow the process closely. Projects with modifications or removal of large dams are not common in the EU, and with the short duration of this project, the number of such potential cases was very limited. This is not the case in respect of the removal of small dams, where Denmark in particular is carrying out a significant number of barrier removals in lowland rivers every year, mainly to fulfil the requirements of the WFD. Thus, due to dam removal in lowland rivers in Denmark and in small rivers in the UK, it was possible to make analyses on a more generic basis regarding the applicability of methods, and on the outcome of the removal projects. However, It is clear from this work that experiences from one case cannot just be transferred to others; each dam project is unique, and so the applicability of methods varies, making it important to have a large toolbox and an open mind.

Here, we report on the seven AMBER case studies to showcase the effects of barrier installation, barrier mitigation and barrier removal using a variety of tools (some of which were developed in WP2 and WP3). We report on the process that took place from an adaptive management perspective.

2 METHODS TO EVALUATE EFFECTS OF BARRIERS

2.1 Remote sensing: using drones to map habitat and geomorphology

The commercialisation of small drones, which can be purchased and operated by private citizens, has opened a broad range of applications. Relatively cheap, off-the-shelf drones were used to survey rivers and stream stretches in the UK, Scotland, Spain, Poland, Denmark and Ireland. Four "DJI Phantom" drones were used to provide images of the areas surveyed and give information on local geomorphology (vegetation, substrate type, river morphology and hydrology). Remote sensing offers a cost-effective method to monitor rivers, especially in areas that are hard to access where bringing lots of equipment would be difficult, though drones remain constrained in their range, flight times, and by weather conditions. Ranges of drone surveys are often limited to the viewable area, because it is difficult and risky to operate a drone out of sight. Weather conditions also limit drone use to clear days with little wind and no rain. Such conditions are relatively rare in locations like Denmark and Scotland. Many headwater streams have trees along both banks, or run in forested areas, where the use of drones is practically impossible. One serious limitation can be local rules and regulations prohibiting the use of drones in certain areas, as was the case in Case Study 2 (Guadalhorce), where it proved impossible to perform a planned drone survey because of restrictions and bureaucracy.

Despite constraints, remote sensing using drones can be useful under certain specific conditions, generally in concert with other tools. Extensive surveys of habitats that include defining substrate type (sediments for example) require very clear water for detection by drones, something rarely the case in small, lowland rivers. In the Polish study of the large River Vistula, information obtained from drone surveys provided data that would have been very difficult or impossible to obtain from a boat or bank-based surveys. Images from the drones were used to compare before and after removal and provide nice images that communicate a clear message. But in terms of use for habitat mapping, sites that fit very specific descriptions are needed for it to be useful, and it was never used as a “stand-alone” mapping tool in AMBER.

Thus, when appropriate, a few hours of drone flying can replace multiple days of fieldwork and often provide better data, for example, for the analysis of macrophyte cover or counts of salmonid spawning redds. The general impression from the tests of drone surveys is that it is very useful in combination with ground measurements in stream surveys.

2.2 eDNA tool kit

The use of eDNA has gained much attention during the last decade and holds much promise for aquatic monitoring. The method requires less fieldwork compared to traditional sampling methods, thus saving resources. The AMBER eDNA tool was tested in Case Study 1, the River Nalón in Spain, where it proved more sensitive than the traditional macroinvertebrate sampling. A cost-benefit analysis shows that the metabarcoding approach is more expensive than conventional techniques for determining macroinvertebrate communities but requires fewer sampling and identification efforts. Our results suggest that metabarcoding is a useful tool for alternative assessment of freshwater quality. The method is generally most useful for species presence/absence studies, not just of fish but also of other aquatic taxa, including invertebrates and amphibians, but also plants. Careful interpretation of results is crucial, and it is important to note that failure to detect DNA from one species does not equal absence and that quantitative information cannot yet be expected from most analyses. In a situation where the relevant DNA sequences are well defined, the method can be used to give an overview of the distribution of aquatic species in relation to the location of barriers as well as of species richness. When species assemblages differ significantly up and downstream from a given barrier, this can indicate loss of connectivity. The results from the River Garry (Case Study 3), where attempts were made to assess the presence of Atlantic salmon smolts in certain areas, were inconclusive and highlight the shortcomings of a method still under development.

2.3 Electrofishing surveys

Electrofishing surveys have been used for decades to assess riverine fish populations and are performed throughout the EU. The European Committee for Standardisation (CEN) standards EN 14962 and EN 14011, specify the methods to be used for sampling fish according to the WFD. For wadable streams, it involves single pass electrofishing, with the optional use of block or stop nets.

These surveys are low-cost and take relatively little effort. In contrast to assessing species via eDNA approaches, electrofishing surveys can provide information not only on presence/absence of species, but also on the individuals (size and sex for example), age structure and density. Further, the information is obtained in real-time – no further analysis in the laboratory is necessary. These surveys can be performed at multiple locations, both below and above barriers, and over various lengths of time to evaluate the effects of construction, mitigation or removal (BACI approach – before-after-control-impact approach).

In larger rivers and reservoirs, electrofishing (from a boat) has significant limitations and will provide a much more qualitative assessment of fish populations, leaving out most bottom dwelling fish, as these are rarely caught. However, different variations of the method were used in the Irish Case Study, where the Clondulane and Fermoy impounded areas were sampled using boom boat electro fishing in the deep, impounded channel segments and conventional boat- based or wading- electric fishing in natural sections, depending on water depths. With the right equipment and valid estimations of efficiency, fish abundance and size distribution can be monitored even in deep, impounded areas.
Also, in the River Vistula, electrofishing from a boat was used to obtain population estimates of fish. Here only small-scale equipment was used, but still provided a useful overview of the abundance and size distribution of most fish species.

The method has been extensively used to evaluate the effects of dam removal in the case studies from Denmark and England and used to describe the fish population at the weirs in the Blackwater River in Ireland. In the small, species poor, lowland streams of Denmark, where brown trout is the dominant species, the density of YoY trout can be used as indicator of stream quality. In Denmark, a density of > 80 YoY trout or salmon/m2 is required to achieve good ecological status in accordance with the WFD. This level of density is hard to reach if connectivity is compromised reducing salmon, sea- or lake-trout access to spawning areas, so the density indicator does provide information on both habitat quality and connectivity.

In brief, electrofishing is a well-tested tool which can provide good information about fish communities with relatively little effort/resource use in many situations, when appropriately used.

2.4 Telemetry

Telemetry is one of the best approaches to study the impacts of barriers on fish movement and survival. Telemetry has provided invaluable detailed information on behaviour and helped scientists to pinpoint bottlenecks or areas of particular interest surrounding a given barrier. Indeed, the evaluations of salmonid fish migrations up and downstream through hydropower dams in the River Columbia in the USA have been the main driver for development of modern telemetry systems. During the last three decades, aquatic telemetry has developed from being a novel, experimental method to become widespread as a standard tool to monitor fish movements, numbers and survival. Today, PIT-technology, radiotelemetry and acoustic telemetry are used in most areas in fish investigations for a wide range of purposes.

In the French case study in the River Allier, acoustic telemetry was used to provide detailed information on the downstream movement of salmon smolts through the Poutes dam and reservoir. Here wild and hatchery smolts were tagged and followed through three years under various management regimes and different environmental conditions. The results were analysed in-depth, and the conclusions were rather easily translated into management recommendations, giving better survival and passage of the smolts, thus mitigating some of the negative effect of the barrier.

In Ireland, acoustic telemetry should have been used to monitor sea lamprey migration through a dam, but it was not possible to carry out as only two were caught, so instead resident dace and trout were tagged and followed. The result from that study demonstrated how barriers to migration can induce artificially high residency or localised movement within the impounded habitat. The results indicate that the displacement patterns observed are primarily driven by foraging activity which in turn are influenced by seasonal changes and the onset of potential spawning periods and/or change to overwintering behaviour.

Determining where fish are distributed across days and seasons is valuable for understanding their ecology, evolution and conservation. These data have given novel insight into the patterns effecting fish behaviour in a lowland riverine impounded habitat and has provided descriptive information on brown trout and dace spatial distribution. From a barrier management perspective, these data can feed into stock status monitoring in impounded habitats and also increase the understanding of how barriers influence fish populations. One of the assets of telemetry is that the results are often very clear and self-explanatory and thus very useful in adaptive management where laymen (NGOs) are involved in decisions affecting, for example, fish migration. Simple studies on fish survival and behaviour during up and downstream passage of obstacles and impoundments have and will play an important role in barrier management. In excess of 500 European eel were PIT tagged in the Munster Blackwater in one year and repeat annual surveys examined of growth rate and residency in an extended area of impounded river.

The study of the River Vistula employed PIT- telemetry to monitor fish passage through a fish ladder at a major hydropower plant. The technology is used widely and well suited to monitor passage through narrow areas like fishways. PIT tags are small (enabling tagging of small individuals) and cheap (enabling tagging many individuals) making the method well suited for studies of a wide range of species and sizes of fish. The method is based on on Passive Integrated Transponders (PIT) with radio frequency identification (RFID) signals that are inserted into a fish and the fish is then detected when passing a loop antenna system in the fishway. A total of 880 fish of 12 species were tagged in the Vistula and the movement in the fishway and passage success was monitored.

2.5 MesoHABSIM

Habitat mapping and modelling has been a widely used tool in river studies for some decades and exploited for a variety of purposes. Its main application has been for deciding minimal flow for regulated rivers, where models have predicted how the (fish) habitats are impacted by reductions in flow. A minimal threshold is then determined (expressed in the percentwise reduction of essential habitat) and the legal limits for water abstraction or hydropower-spill is set. For larger constructions or modifications, habitat modelling is important to simulate the effect of such engineering work.

The Mesohabitat Simulation Model (MesoHABSIM) is an approach used to model instream habitats at the river and site-specific scale. It encompasses a computer model, Sim-Stream, which predicts the quantity of habitat for aquatic communities in rivers and streams for watershed management scenarios. MesoHABSIM enables research and forecasting in relation to river systems on the catchment scale. The system is based on a data resolution that reflects animal responses to changes in the external environment and its effective extrapolation to a scale that allows planning and management. An appropriate extrapolation framework is based on a structured approach for selection of representative location and watershed area transformation of flow values. The basic steps in the development of this system are to define biological targets and appropriate scale to identify habitats that significantly differ in the composition of fish community (Aadland 1993, Lobb and Orth 1991).

Advanced habitat time series analysis applied in the model allows the establishment of common denominator metrics such as Habitat Stress Days or Community Habitat Structure Alterations that can be used in quantitative scenario comparisons within River Restoration Analysis framework (Parasiewicz et al. 2012). Because the model was created on the basis of GIS, it is characterized by flexibility in the simulation of morphological changes, allowing a set of reference conditions to be defined and the analysis of the effect of potential actions (such as dam removals) to compensate for habitat shortages in the river to be evaluated. The final elements of the methodology are indexes and tools enabling the transference of results to operational activities in the comparison of different planning scenarios; the latter is particularly useful in adaptive management. Like all habitat models, MesoHABSIM requires quite intensive data collection, which can be well supported by drone imagery and other rapid assessment techniques developed during the AMBER project, reducing effort to reasonable level.

The biggest application of habitat models is for providing clear, quantitative assessment results from potential or actual mitigation actions, and so providing strong support in the decision-making processes.

Habitat mapping and modelling was used in four of the seven case studies, and proved quite challenging due to the need for standardised data, collected under various flow regimes. The use of the model is demonstrated in detail in Case Study 5, the River Vistula. The model was also applied in three other Case Studies: The River Guadalhorce In Spain; the Munster Blackwater in Ireland and the Gear Garry in Scotland. In each case, the different aspects of the barrier's impact on habitat have been described. On the River Vistula, the habitat structure up and downstream of the dam differed from the structure predicted by the Fish Community Macro Habitat Model (FCMacHT), and lowering the dam connected with restoration measures downstream was established as the ecologically most effective alternative. On the River Guadalhorce and the Gear Garry, the habitat structure downstream of the dam closely resembled the expected target, and most habitat improvements can be accomplished by more sophisticated flow regulations. On the River Guadalhorce, maintaining the appropriate flows in the channel downstream of the dam in a less erratic and more controlled fashion is a recommended action. On the Gear Garry, the disturbed water quality and sediment supply strongly affect salmonid spawning grounds, and more frequent channel-forming flows would offer an improvement. At the Munster Blackwater, where Fermoy Dam is partially breached, the model documented that the most ecologically appropriate action is further dam demolition connected with habitat improvement actions in adjacent areas.

2.6 Surveys of Ecosystems Services

Surveys to identify and rank the benefits and adverse effects of a given barrier will be an important source of information in adaptive barrier management, particularly in the case of large, important dams/structures. Very often, these can be reduced to benefits of a continuous, naturally flowing river versus the benefits of a barrier with respect to a service such as hydropower or a reservoir as a source of water for agriculture or industry.

In several of the Case Studies, AMBER social surveys were carried out to understand societal attitudes toward dams and to estimate how much they mean to different people. For example, in the case of the River Nalón, a dam was planned, but the project was not carried out because public opinion was against this, and because the ecosystem services of a free river were ranked higher than that of a dammed river with a large reservoir. Thus, Ecosystem Services Surveys (ESS) can be important for decision support. In the Guadalhorce Case study, analyses of ESS was also carried out and made a difference in the decision about the construction of the dam. In cases of smaller streams with smaller barriers, like the Case Studies in Denmark and the UK, making such surveys is not as relevant, because few stakeholders/interests are involved and because there are insufficient resources to do so.

3 EFFECTS OF BARRIER INSTALLATION, MITIGATION AND REMOVAL

Using the 7 case studies carried out as part of AMBER, we report on the general and overall impacts of barrier installation, mitigation and removal from an environmental and social perspective. Below are the main messages from the case studies. Detailed summaries on the case studies are provided in the Appendix section and an overview is provided in **Table 1**.

3.1 Methods used

Table 1. Overview of the main methods used in each of seven case studies.

Case	Drone	eDNA	E-fishing	Telemetry	ESS	MesoHABSIM	Social survey
1 Nalón		X			X		X
2 Guadalhorce	(X)	X			X	X	X
3 Allier		X		X			
4 Garry	X	X			X	X	X
5 Vistula	X	X	X	X		X	
6 Blackwater	X		X	X		X	
7 Small rivers UK and DK	X		X			Habitat surveys	

3.2 Barrier installation

Barrier installation clearly alters connectivity, by affecting the flow of water and sediment, but also by affecting the ease of access to habitats by the organisms that inhabit the river.

The case study on barrier installation failed because the plan to build a major dam in a Spanish river was abandoned, mainly due to lack of public support. The most obvious reason to build new dams in the future will be the need to store water for human, urban and rural use. The need for stored water is only expected to increase as climate change intensifies and will be most pronounced in the Mediterranean area. The need for dams for excluding unwanted species (moving upstream) is discussed in-depth in another AMBER deliverable and can be a reason for establishing (or keeping) dams in very special cases. If a new dam is to be installed, be it for hydropower, flood control or water storage, it is imperative that an open and transparent decision process is used, where stakeholders can get involved. The case of the dam on the River Nalón demonstrates that if the decision does not involve stakeholders (including the general public), it may end with conflicts and eventually cancellation. In the case of the Guadalhorce, the planned modifications to the lower river became the focus of much study/survey/discussion in the local community. Here, the citizens were involved and their feeling about the project and dams in general were expressed. Interestingly, there was a general positive perception of dams and the benefits they brought about. The use of decision-support tools is clearly very important in cases of dam planning and should always be used. Even in situations where a new dam is being build, mitigation measures for reducing the negative impact (loss of connectivity) are easier and cheaper to implement in the planning phase than after construction. There are a few examples in the world of hydropower stations, built in a way to minimally affect the connectivity of a river (i.e. The Falkenberg (Herting) station in Sweden) and these should be used as inspiration for new projects, where connectivity is crucial.

3.3 Barrier mitigation

Barrier mitigation, often regarded as restoring connectivity through installations such as fish ladders, can provide access to *some* fish, but is never as good as their removal. Mitigation can take different forms and measures include different forms of fish ladders and eel pass for upstream migration, bypass facilities for downstream migrating fish, spill of water to facilitate downstream migration, capture and transport of fish around barriers, compensatory stocking of hatchery fish, bypass streams, rock ramps, fish elevators and even fish canons.

Most mitigation measures reflect the desire to keep some level of connectivity while at the same time retaining the main purpose of the dam, be it hydropower, water storage or flood control. To achieve both goals, high head dams often requires major modifications and/or may lead to loss of income for a power plant or other facility. Thus, it is very important that as much experience as possible is consulted before making such costly modifications. There are a vast number of very costly fish passage facilities around the world, not the least in Europe, of which very few (if any) really solved the problems of lost connectivity.

In the AMBER Case Study of the large Poutes Dam in France, the choice of mitigation measure was based on detailed surveys on site and the solution to provide better passage for at least Atlantic salmon. In the case of the River Vistula in Poland, the upstream fish passage near the Włocławek Dam was studied, and it was clear that only very few of the upstream migrating fish managed to use the fishway and for downstream migrants there was no passage, except through the turbines.

3.4 Barrier removal

The AMBER Barrier Atlas, and the results from the AMBER Barrier Tracker show very clearly that there is a high density of barriers in most EU rivers. Of these, most are small, and most are obsolete. Thus, there is huge potential for barrier removal projects throughout the EU. Full barrier removal is always the best option for rivers and the organisms that live within them and unless there are important economic, cultural or security values associated with a dam, removal should be the number one option.

The dams removed within the AMBER project have all been relatively small and none of them has been an active hydropower dam. The planned removal and mitigation at two large dams on the River Blackwater in Ireland did not happen and thus could not be studied by WP4 as planned. However, the removal of 10 barriers in UK and 12 in Denmark provided a good opportunity to perform before and after surveys and evaluate some of the effects of removal. The assessments made on the (short-term) effect of barrier removal demonstrate that these effects vary widely from site to site, but that in the Danish lowland streams, a swift and significant response by the fish community is seen in respect of trout density. In the UK, in small streams with a higher gradient, the same response has not been seen. This lack of similar positive response may be attributed to the general connectivity of the streams and the differing fish populations in the stream. However, there were substantial improvements at nearly all sites with regard to the quality and variation of the habitats upstream of the removed dams. Interestingly, there were two Danish sites where a dam was replaced by an "engineered", steep riffle-like stream stretch, designed to keep the stream in place, which did not show any improvement in fish abundance.

4 LESSONS LEARNED

- Take a holistic perspective. All the integrated effects of barriers influence the inputs to ecosystem services. Restoring natural river fuction will benefit biology, but all the pieces fit together.
- River size influences the choice of methods and the process for mitigation.
- Do not engineer too much.
- Adaptive management; it is a benefit in most cases, but cost and time can limit use.
- Bureaucracy, time, unpredictability; there is a general need for stronger enforcement/legislation.
- Local interests in keeping the status quo is very often a hindrance to dam mitigation/removal.
- Size matters. What works for small Danish rivers does not necessarily work for the River Vistula. One size does not fit all and there is no tool or method for everywhere.
- Legacy: Overall message about time scales; how long do you expect for a river to recover, depending on size.
- Despite opposition in the planning phase, the experience from most barrier removals show great satisfaction from most stakeholders and the public after restoration.

Building barriers started many centuries ago in Europe,hence, the shifting baselines syndrome thrives in river management, with some of the negative effects lost through the generations since modifications were made, and as such, are unappreciated today. This is probably also why a large number of barriers that exist today have no use anymore,and just add to the threatened and deteriorating status of freshwater ecosystems. Barriers takemany forms, have many effects, with some obvious and some more complicated. Hence, a one-size fits all approach is bound to fail, and each case will likely have to be explored on its own. It is important to look at the integrated effects caused by the barrier because the biological systems in rivers are complex and collated inputs to ecosystem services must be appreciated. Failing to do so may result in missing important opportunities as well as waste of precious time and money.

While biology is complicated, at the heart of all biology in rivers lies hydromorphology, the basics for creating the habitat necessary for river life to thrive. Hence, hydro-morphology is one of the obvious factors to measure when looking at barrier effects, and if choosing the right biological variables (so-called indicator species), it is possible to integrate much of the effects over time without having to measure everything. However, these metrics will depend on the place itself in terms of climate, geography and biology. For example, there may very likely be different optimal ways to approach intermittent vs perennial rivers as well as smaller vs larger rivers. In addition, picking the right biological indicators may be a challenge, for example in cases where the best indicator(s) has gone extinct (like often the case with salmonids), what methods to use will also depend on the situation at hand; in some places electrofishing may be the best option, sometimes telemetry, sometimes drones surveys and sometime e-DNA or a combination thereof.

Restoring part of the natural river function will benefit biology, but all the pieces fit together and the classic way of approaching barriers by engineering a solution will in many cases not fix the challenges, but rather postpone a sufficient solution to further delay or detriment to the environment. Another important point is that most rivers hold several barriers generating a negative cumulative effect. This necessitates setting a priority for getting the optimal solutions at play from the beginning, or restoring river function is bound to fail. Many barriers have been modified (for example, fish passes and bypass channels) several times over several decades, but proper ecosystem function was not attained until the full removal of the barriers. It is the clear perception from the project that wherever possible, a return to the original condition (full removal) is the preferred solution. There is very convincing evidence suggesting this is by far the best solution in terms of restoring natural river function, not only to historical levels, but in fact superseding historical levels. In smaller rivers, the effect may be relatively fast (1+ generation time for indicator species if they are not extinct), but it should be acknowledged that in larger systems it may take longer.

Where removal is not feasible, adaptive management may be a useful tool to generate an acceptable outcome. However, adaptive management is not a magic wand and it is quite expensive to apply in terms of both cost and time. Hence, adaptive management may be an appropriate tool in cases of larger barriers (or when many barriers in the same river are treated together, for example,on a whole river basis). Other unpredictable factors are bureaucracy, lack of local appreciation for the overall effects and general unpredictability in natural systems. Here surveys of ecosystem services may be a good tool to clarify and elaborate on the services rendered (or lacking) by the barrier(s). The experience from countries at the forefront of restoration is that very often local needs and wishes take precedence from the overall goal, often without proper knowledge of the potential solutions. An often-encountered challenge is local people claiming barriers are of high cultural-historical value and claiming a need to maintain everything as it is. This makes it difficult for authorities and stakeholders to collaborate on a solution. Very often, the experience is that these perceptions can be modified and most of the local needs and wishes can be accommodated while still being able to restore the full river function. It may also work the other way around, making local people aware of the ecosystem services actually provided by the river (as in the River Nalon). However, the experience is that to achieve these goals there may be a need for stronger enforcement/legislation to give the necessary motivation to attain the goal of restoring river function. It is also necessary to make sure other legislation does not prevent the goal of reaching free passage for both fish and invertebrates. It is also the experience that in most places where barriers have been removed (or mitigated), local opposition disappears afterwards, and even goes as far as the local stakeholder claiming it was their own idea to remove or mitigate the barriers.

It is the authors hope that the experiences gained through these case studies may be of help and inspiration for people working with barriers, providing a diverse barrier background and the methods to address the challenges. With the right approach, it is in fact often possible to actually attain river ecology “as good as the old days” and sometimes even better than in these old days.

5. CASE STUDIES

A1. BARRIER INSTALLATION

A1.1 CASE STUDY 1: Calaeo Dam, River Nalón

The River Nalón has seven large dams and reservoirs built between 1960 and 1970, two of them (Tanes and Rioseco) within a protected area upstream - Redes Natural Park, that is a Natura 2000 site and Reserve of the Biosphere (**Figures 1.1.1** to **1.1.3**). A new dam (Caleao) was planned upstream within the protected area, for water and energy supply, including water supply for steel companies (specifically Arcelor-Mittal), and for compensatory flows to maintain biodiversity (enhancing water quality up to be suitable for salmonids downstream). The project was cancelled officially after a decision of Asturias Parliament in 2018, within the AMBER project lifetime.

The societal implications and socio-economic impact of the stakeholders involved in the final resolution of the conflict created around the Caleao dam, including AMBER researchers, are enormous. The cancellation of the dam project has already mobilized 60 million euros that will be employed by the public water consortium of the Asturias region (CADASA) for alternative water supply to steel companies of a lower environmental impact. This action implies the safeguarding of the Redes Natural Park and represents a milestone for conservationists and naturalists, as well as for the general public conscious about the environment. The contribution of AMBER to the impacts already produced, and the positive impacts that will follow in the region of Asturias, is difficult to quantify because the participative approach undertaken implies the involvement of many factors, including stakeholders and the civil society. We believe that AMBER researchers have contributed, perhaps modestly, to create a state of opinion favourable for the cancellation of the Caleao dam project. It is likely the public pressure based on objective information -including AMBER results- helped the politicians and CADASA to find an alternative source of water supply for the Arcelor-Mittal steel company.

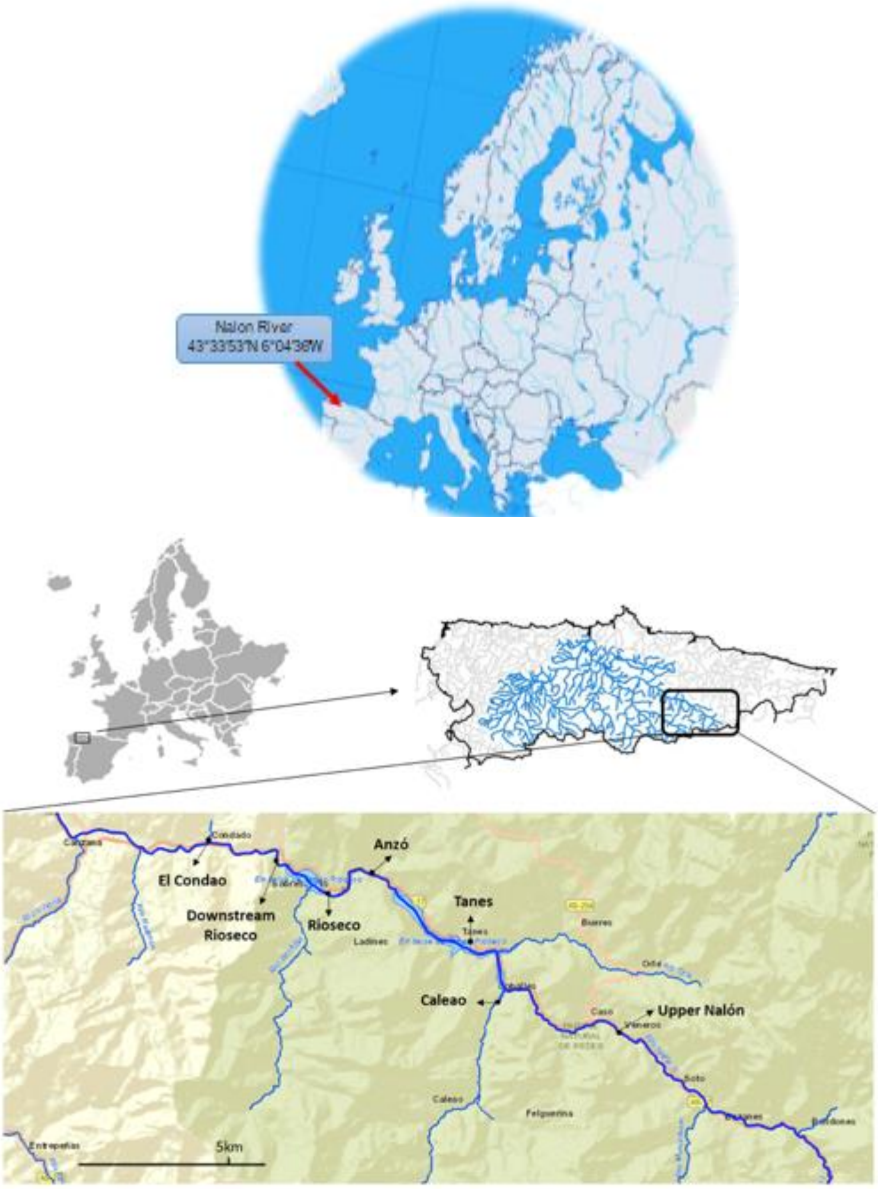


Figure 1.1.1. Map of the case study river with a zoom on the upstream area where Caleao is located. Sampling locations where eDNA was collected are indicated.

Figure 1.1.2. Obstacle in the River Nalón for industrial use (thermal powerstation).

Figure 1.1.3. Rioseco reservoir within the Biosphere Reserve and Natural Park of Redes, Upper River Nalón.

A1.1.1 The history of Caleao dam project: 1998-2015 conflict

The Caleao dam was jointly promoted by the Regional Government of Asturias and CADASA (Asturias water consortium). Its construction was approved in the Spanish Royal Decree – Law 9/1998. The project was initially submitted in 2001 and was rejected for inclusion in the Spanish Hydrological Plan, Law 10-2001 of 5 of July, where it was not mentioned explicitly. In 2004 it was proposed again in the Spanish national Parliament and in the Asturias regional parliament. A public debate was opened that year.

A civil platform was created in 2006 for defending the Natural Park of Redes (UNESCO Biosphere Reserve since 2001) and the valley of Caleao. Its website can be found at: http://defensa-redes.blogspot.com/search/label/Plataforma (in Spanish only, as most online documents reported hereafter, the case study being located in Spain). They camped by the river from 24 to26 September 2006 to hold a Conference of protest against the dam plans, and, the Platform stated, were boycotted by the Asturias government who sent Guardia Civil (a branch of Spanish police) to control the activities and prevent public demonstrations. Two NGOs of the platform submitted initial allegations against the project draft –before its inclusion in FEDER operational program: ANA (Amigos de la Naturaleza de Asturias) and La Cirigüeña.

The project was included in 2007 in the EU FEDER operational program for Asturias region 2007-2013. Programa Operativo del Feder para Asturias 2007/2013 http://ec.europa.eu/regional_policy/en/atlas/programmes/2007-2013/spain/operational-programme-asturias. On page 130 of this program it is stated: "*Los cuatro proyectos mencionados por La Cirigüeña (el embalse de Caliao, ….. no recibirán financiación ni del FEDER ni del Fondo de Cohesión, por lo que las alegaciones contra estos proyectos no han sido consideradas*." The translation reads: "*The four projects mentioned by La Cirigüeña (Caleao reservoir, … will not receive funding from FEDER nor the Cohesion Funds, so the allegations against these projects were refused*".

In 2007 and 2008, the Conferences against the plans and for protecting the Biosphere Reserve were held again, with no reports of interference from the regional government. In the revised hydrological plan of the Occidental Cantabric region where Asturias is included (Plan Hidrológico de la Demarcación Hidrográfica del Cantábrico Occidental), National Water Council 13 December 2012, the construction of Caleao dam was subsumed in the measure named "Improvement of water supply of the central zone of Asturias". The plan continued and was presented publicly and in writing. It remained deposited in the headquarters of the Regional Government for public consultation and allegations by any private party, public institution, NGO, or individual. On 30 June 2015, the period of allegations expired. The Spanish national 2015-2021 Hydrological Plan studied the allegations and refused them, thus the project passed to the next phase as Approved. The construction of the Caleao dam was foreseen any time within the next years, and by 2021.

A1.1.2 The way to Caleao dam cancellation: citizen initiatives and political negotiations

After its approval, the dam project continued to be much contested by ecological and conservationist associations (**Figure 1.1.4**). The reason being the projected dam would affect the Natural Park of Redes (Natura 2000, LIC, ZEPA, Biosphere Reserve) and several protected species within. A conflict between companies of ecological tourism and the new dam was also expected.

Figure 1.1.4. Caleao protest camp – a banner against the project.

On May 11, 2018, the Asturias Parliament (Junta General del Principado de Asturias) approved a Resolution for the Asturias Regional Government to officially announce to the Caleao dam project in the Plan of Water Supply. The discussion, arguments, and voting results can be found in the Record of Sessions of the Junta General del Principado de Asturias, X Legislatura, Series P, number 167, available athttp://anleo.jgpa.es:8080/documentos/Diarios/PDF/10J167.pdf. The proposition was presented by Izquierda Unida party, on the basis of a new Agreement between CADASA (water consortium) and the multinational steel and mining company Arcelor-Mittal which has investments and interests in Asturias. In that agreement, there is a plan of exploitation of the River Narcea (a branch of the Nalón-Narcea basin) channel, that includes special costs of water for its factory in Veriña (Asturias). Since one of the reasons for building the dam was water supply for steel companies, the Caleao dam project was traded with CADASA for the new agreement.

https://www.20minutos.es/noticia/3337826/0/junta-insta-al-principado-incluir-renuncia-expresa-al-embalse-caleao-plan-abastecimiento/

"La Junta General del Principado de Asturias ha aprobado este viernes una moción presentada por Izquierda Unida para instar al Gobierno del Principado a presentar, antes de octubre, el Plan Director de Abastecimiento 2017-2037 con la renuncia "expresa" a la construcción del embalse de Caleao y de cualquier otra infraestructura hidráulica similar. Durante la defensa de la propuesta, el diputado de IU Ovidio Zapico ha incidido en la necesidad de cerrar, así, cualquier posibilidad de nuevas infraestructuras hidráulicas, al mostrarse "innecesarias" para garantizar el suministro de agua en Asturias. Izquierda Unida formula esta moción tras el reciente convenio suscrito entre el Consorcio de Aguas (Cadasa) y la multinacional siderúrgica ArcelorMittal para poder explotar el canal del río Narcea desde Quinzanas (Pravia) hasta la estación de tratamiento de agua potable de Ablaneda. A cambio, ArcelorMittal obtendrá unas tarifas de consumo de agua en "mejores condiciones" para su factoría de Veriña". The translation reads: "*The Junta General del Principado de Asturias has approved this Friday a motion presented by Izquierda Unida to urge the Government of Asturias Principality to present, before October, the Supply Master Plan 2017-2037 with the "express" resignation to the construction of Caleao dam and any other similar hydraulic infrastructure. During the defense of the proposal, the IU Deputee Ovidio Zapico has emphasised the need of so closing any possibility of new hydraulic constructions that have been shown "unnecessary" for ensuring water supply in Asturias. Izquierda Unida formulates this motion after the recent agreement subscribed between the Water Consortium*

(CADASA) and the steel multinational ArcelorMittal for exploiting the channel of Narcea River from Quinzanas (Pravia) to the drinking water treatment plant of Ablaneda. In compensation, ArcelorMittal will obtain water consumption rates in ¨better conditions" for its factory in Veriña".

Following the political decision adopted in the Parliament, the budget project of Asturias Principality for 2019 presented by the Regional Government on December 7 in 2018, and approved November 27 in 2018 in the Junta General del Principado, recognizes the so called Pacto del Narcea (Narcea Agreement) between Arcelor-Mittal and CADASA, and liberates for free CADASA's use of the 60 million euros retained for the construction of Caleao dam. The document can be found at: https://www.asturias.es/webasturias/GOBIERNO/ACTUALIDAD/pdfs/2018/2018_12_07_itv_consejero_infraestructuras_presu_2019.pdf.

With this final disposition the project of the Caleao dam can be considered definitively cancelled within AMBER lifetime.

A1.1.3 AMBER contribution to the Caleao solution

Several tools developed in AMBER were applied in the upper zone of the River Nalón, focused on the uppermost reservoirs and the area where Caleao dam was projected. Here we applied the molecular toolkit (D2.5), educational materials, estimated ecosystem services provided by the dams, carried out the AMBER social survey (D3.5) for understanding society attitudes towards dams, and networked with stakeholders for publicizing the results obtained with these tools, contributing to the conflict resolution. The World Fish Migration Days of 2016 and 2018 were chosen for organizing AMBER public activities to involve the local society in the issue of river barriers and connectivity. Next, we will explain the activities developed and some results obtained.

A1.1.4 AMBER molecular toolkit in the River Nalón

The molecular tools applied were Barcoding for individual species identification, Genotyping for lineage determination in brown trout, Specific markers for species detection and Quantification from environmental DNA (eDNA), and Metabarcoding for inventory of the community from eDNA. The results have been published and are fully accessible in open access journals.

The first study objective was to use qPCR on eDNA to assess the presence of invasive north American native rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) in the upstream part of the River Nalón. This trout is one of the most widely farmed fish species in the world. It was first introduced in Spain in the late 19th century for sport fishing and nowadays is the main freshwater fish farmed in the country. On the other hand, the European native brown trout (*Salmo trutta* L.) is catalogued as vulnerable in Spain. We employed two eDNA based methods (qPCR and nested PCR-RFLP) to detect salmonid species from the Biosphere Reserve and Natural Park of Redes (Upper Nalón Basin, Asturias), where brown trout is the only native salmonid. The sampling area located upstream the impassable dams of Tanes and Rioseco contains one rainbow trout farm.

Employing qPCR methodology, brown trout eDNA was detected from all nine sampling sites surveyed, while the nested PCR-RFLP method failed to detect it from two sampling points. Rainbow trout eDNA was detected from both techniques at three sites in the river branch where the rainbow trout farm is located, both upstream and downstream the farm (**Figure 1.1.5**). Salmonid habitat units and water quality were high from the area studied. Unreported escapes from the farm are a likely explanation of these results. Since salmonid habitat is abundant and the water quality high upstream of the dams, the establishment of rainbow trout populations would be favored if escapes are recurrent.

Environmental DNA has here proved to be a valuable tool for species detection in freshwater environments, and the probe-based qPCR highly sensitive technique for detection of scarce species. We would recommend this method for routine monitoring and early detection of introduced species within natural reserves. More importantly regarding the case study, this technique based on eDNA revealed that the River Caleao still contains only the native brown trout species and could be considered free of the exotic species.

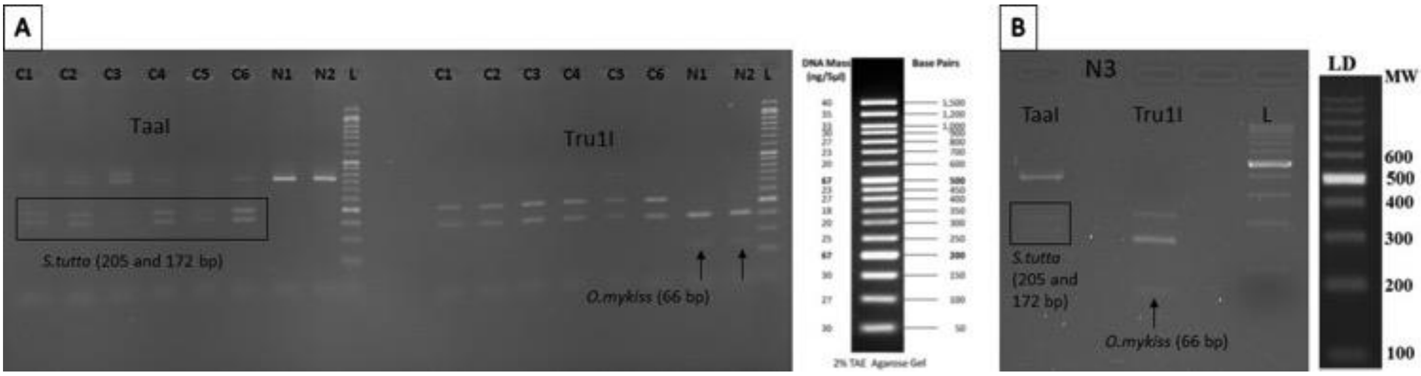


Figure 1.1.5. RFLP results of *Salmo trutta* and *Oncorhynchus mykiss* in the Upper Nalón. Fragments of both species are indicated (c1-c6: sampling points in Caleao River; n1-n3: sampling points in the River Nalón, L: Ladder to measure fragments 'size; Taal and Tru1I Restriction enzymes).

A second application of the eDNA AMBER tool was aimed at macroinvertebrate community study. To reduce human impact on water bodies, the EU has established an essential regulatory framework for protection and sustainable management (WFD; 2000/60/EC). In this strategy, reliable and economic bioindicators are a fundamental component. Benthic macroinvertebrates are the group most commonly used as bioindicators through all EU countries. However, their conventional assessment currently entails serious cost-efficiency limitations. In this study, we have tested the reliability of metabarcoding as a tool to record river macroinvertebrates using samples from a mock community (in vitro validation) and eDNA extracted for field validation from water from six sites within the case study area of the Upper River Nalón. Two markers (V4 region within the nuclear 18S rDNA and a fragment of the mitochondrial COI gene) were amplified and sequenced using an Illumina platform. The molecular technique has proven to be more sensitive than the visual one. A cost-benefit analysis shows that the metabarcoding approach is more expensive than conventional techniques for determining macroinvertebrate communities but requires fewer sampling and identification efforts. Our results suggest that metabarcoding is a useful tool for alternative assessment of freshwater quality. In the same study we have demonstrated a clear discontinuity in the whole community diversity due to the presence of dams, with a particular alteration in the river zone located between Tanes and Rioseco dams, named Anzó (**Figure 1.1.6**), where the biotic diversity is very poor.

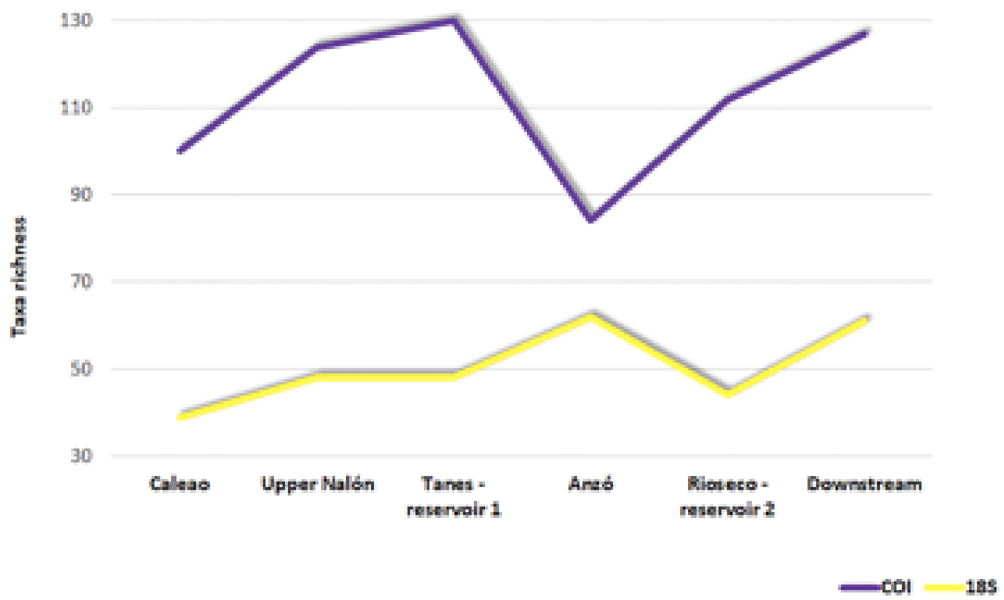


Figure 1.1.6. Genus richness at the six sampling points analyzed in this study within the River Nalón using COI and 18S metabarcodes. *From: Fernandez et al. (2018).*

The water quality was measured employing the molecular toolkit for inventorying macroinvertebrate families and calculate the index IBMWP, used in Spain for accomplishing the European Water Framework Directive monitoring water quality in the rivers. We validated the molecular method through a comparison with the index obtained conventionally (physical sampling of macroinvertebrates). The two approaches gave similar results that revealed a clear deterioration of water quality in the zones affected by dams (**Figure 1.1.7**).

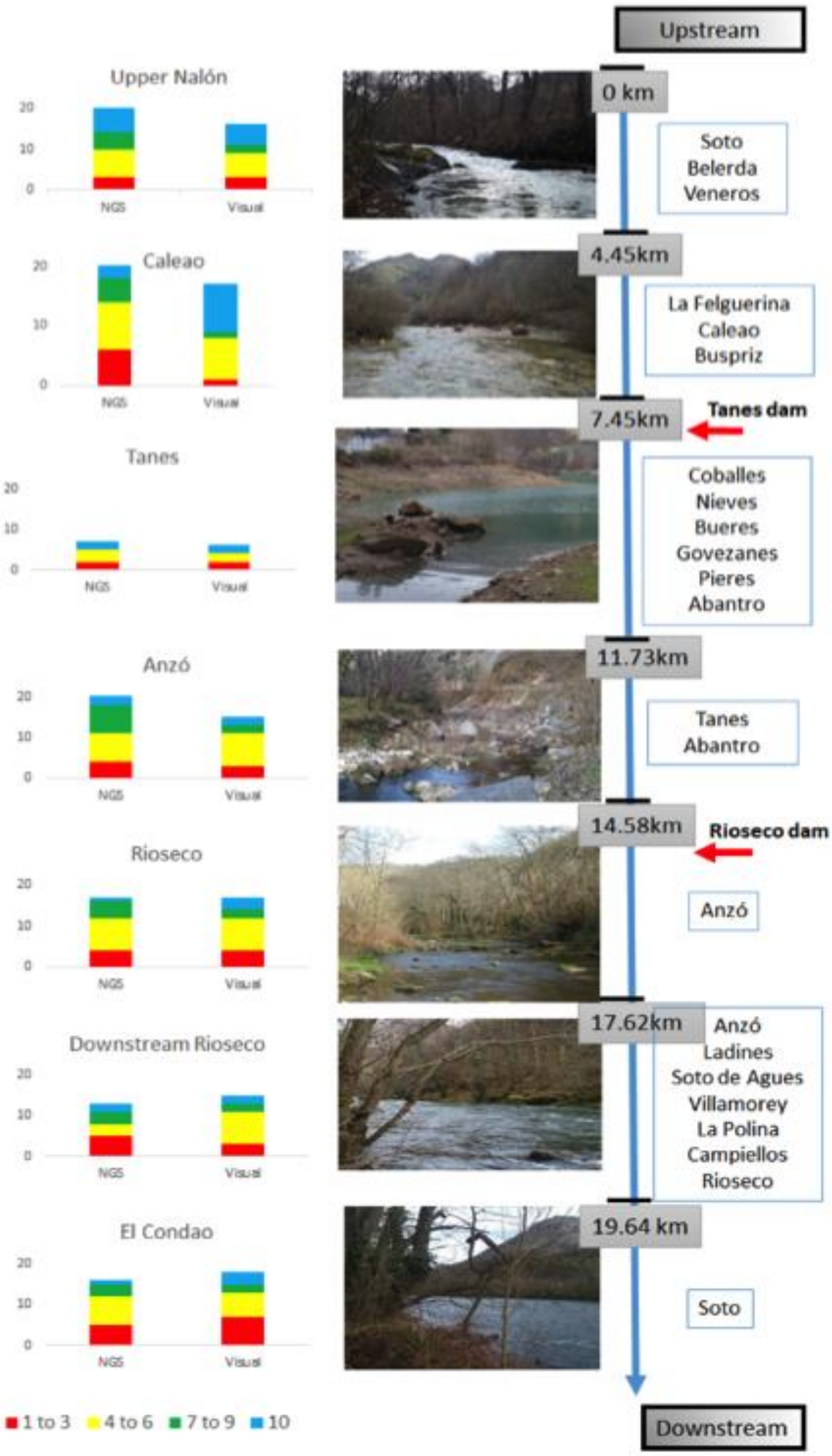


Figure 1.1.7. Number of macroinvertebrate families in each sampling point within the River Nalón, with their IBMWP index score (1 to 10, for most to least tolerant families so worst to best water quality) in different colors. Results from eDNA (HTS) and morphological traits (Visual). Villages discharging along the surveyed river sectors at right. The dams are marked with red arrows. The distance (km) between the Upper Nalón point and the rest of the sampled points is shown

It can be seen that the effects of the dams are enormous. The point located in Tanes reservoir had a very limited amount of macroinvertebrate families. Upstream communities exhibit a clearly better status of water quality, with more indicators of good environmental health (in blue and green in **Figure 1.1.7**). This emphasizes the negative impact of river barriers, especially in short rivers like those of the regions within the Atlantic Arc like Asturias. The results obtained in Caleao, precisely in the point where the new dam was planned, were very good. If constructed, the dam would have impacted very negatively the environmental status within this Natura 2000 protected area.

The eDNA results of this case study have been partially published in Fernandez et al. (2018a, 2018b).

A1.1.5 AMBER tool for estimating ecosystem services in the River Nalón

The ecosystem services provided by the River Nalón were estimated using the ESS tool proposed in the WP2 (**Table 1.1.1**).

Table 1.1.1. Ecosystem services and disservices provided by the River Nalón dams. In blue, provision; in green, regulation; in brown, cultural.

		Ecosystem Service change	
	Categories of benefits	**Above the dam**	**Below the dam**
	Reared animals and their outputs	-1	0
	Wild plants and animals	-1	-1
	Aquaculture	0	0
	Surface water for drinking	1	0
	Ground water for drinking	0	0
	Materials / biomass from plants, algae and animals	-1	-1
	Surface water for non-drinking purposes	1	0
	Ground water for non-drinking purposes	0	0
P	Energy	1	0
	C sequestration/ storage /accumulation by ecosystems	1	0
	Dilution by water	0	1
	Mediation of smell/noise/visual impacts	-1	-1
	Erosion protection	0	-1
	Flood protection	0	1
	Hydrological cycle and water flow maintenance	0	1
	Drought prevention	1	0
	Soil formation - decomposition and fixing processes	1	0
	Micro and regional climate regulation	1	0
	Chemical condition of freshwaters	-1	-1
regulation	Maintaining nursery populations and habitats	-1	-1
	Experiential use of plants, animals and landscapes in different environmental settings	0	0
	Physical use of landscapes in different environmental settings	1	1
	Scientific	0	0
	Educational	1	1
	Heritage, cultural	-1	0
	Entertainment	1	0
	Aesthetic	-1	0
	Symbolic	0	0
	Sacred and/or religious	0	0

In summary (**Figure 1.1.8**), the ecosystem services provided by the dams in this case study are negative regarding provision of goods, regulation and cultural services upstream. Of special importance is the impeded access to valued fish species such as European eel and Atlantic salmon. The regulation of river flow and others downstream are positive, especially for the prevention of floods in the river valley. Some cultural benefits would be the use of reservoirs for angling and leisure activities like kayaking and bathing.

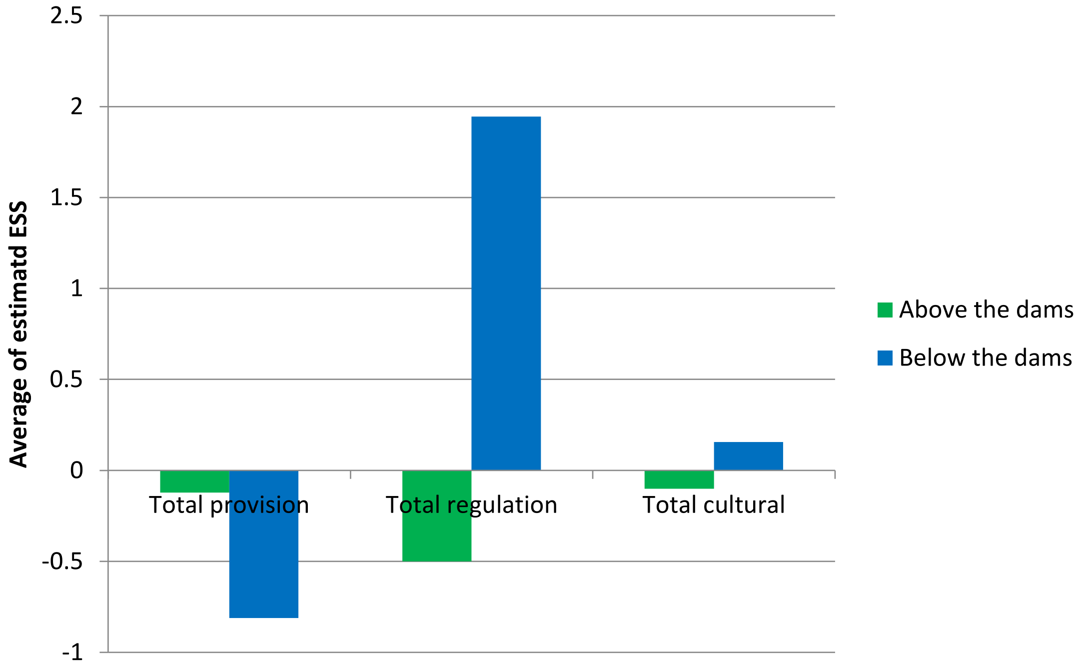


Figure 1.1.8. Average estimated values of provision, regulation and cultural services provided upstream and downstream by Upper River Nalón dams.

From these results, that indicate clearly the negative impacts of dams on ecosystem services upstream, it could be inferred that the Caleao dam projected in the upper part of the River Nalón basin would have threatened the river ecosystem services inside the Biosphere Reserve and Natural Park of Redes.

A1.1.6 Quantification of costs and benefits of dams in the River Nalón

This task was done using the AMBER tool questionnaire designed for the "Social survey on attitudes toward dams and reservoirs" (D3.5). The questionnaire was administered in this case study. Dam acceptance was investigated through different questions (items) Likert-scaled, plus one multiple-choice question and one item based on willingness to pay. In this report, we will give some results of the latter as an example. In this questionnaire the item number Q3 was formulated as "What taxes percentage (%) you pay yearly would you allocate to: a) Building structures to facilitate fish migration; b) Improving the economic efficiency of the reservoir (leisure, fishing, water reserves…); c) Improving waters connectivity / rivers reconnection; d) Contributing to dam and reservoirs demolition; e) Building new dams and reservoirs". The willingness to pay gives an estimate of the public economic valuation of ecosystem services. In the River Nalón case study (N = 299), more than 70% of the respondents were willing to increase their taxes by more than 0.5% to restore river connectivity, while the percentage of respondents that choose the same increase for demolishing obsolete or unused dams was much lower: 46% (**Figure 1.1.9**). The results indicate that the general public in the region of the case study gives a real economic value to the actions aimed at improving river status and dam efficiency, and not so much to drastic actions on the dams such as demolitions or constructions of new ones. The proportion of respondents not willing to pay for these actions was higher than for the other, less drastic actions aimed at improving river environment and dam uses.

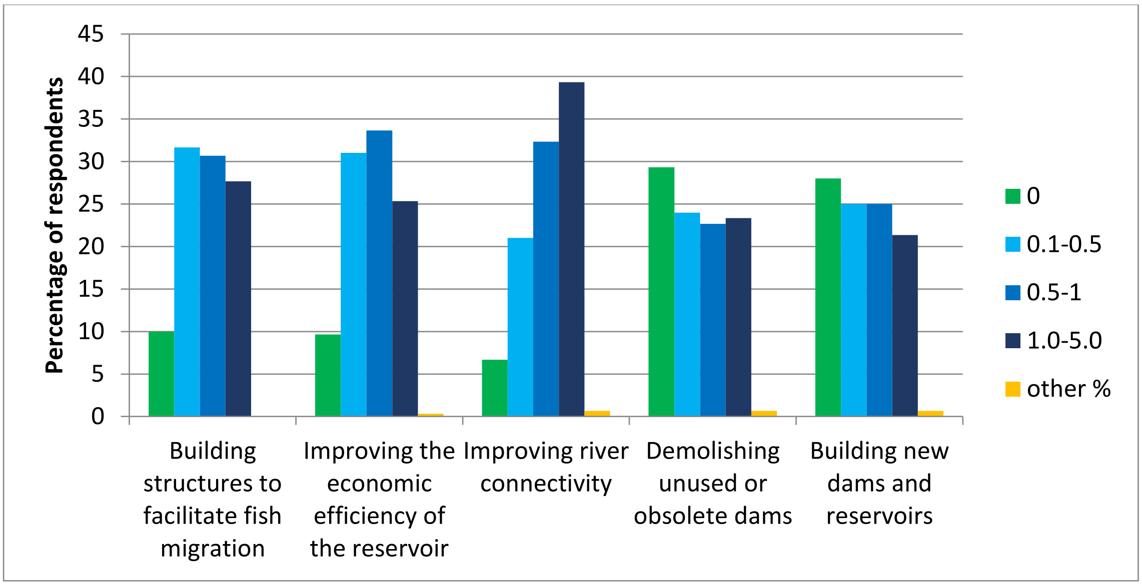


Figure 1.1.9. Proportion of respondents willing to increase their taxes by a percentage for actions to improve River Nalón features.

Regarding dam acceptance, the proportion of participants choosing each of the five options offered was: They should be eliminated, 1%; I would prefer them out of the area where I am living, 10.3%; Should be modified for having less ecological impact, 45.7%; Should be maintained as they are today, 20.3%; More dams and reservoirs are needed to provide more services, 22.7%. These results show an acceptance of dams by 43% of the participants, and a rejection by 11.3% in this case study.

A1.1.7 Trial of the AMBER BARRIER TRACKER app

The AMBER Barrier Tracker app for smartphones was assayed in the River Nalón by AMBER researchers. In total there are seven dams and reservoirs officially inventoried in the River Nalón. In this trial, 20km of the river were surveyed for barriers and the results introduced in the website of AMBER, within the Citizen Science section.

In total we found 63 barriers higher than 1m within the river sector surveyed (**Figure 1.1.10**). This shows the need for considering all the barriers in official inventories and highlights the importance of AMBER project.

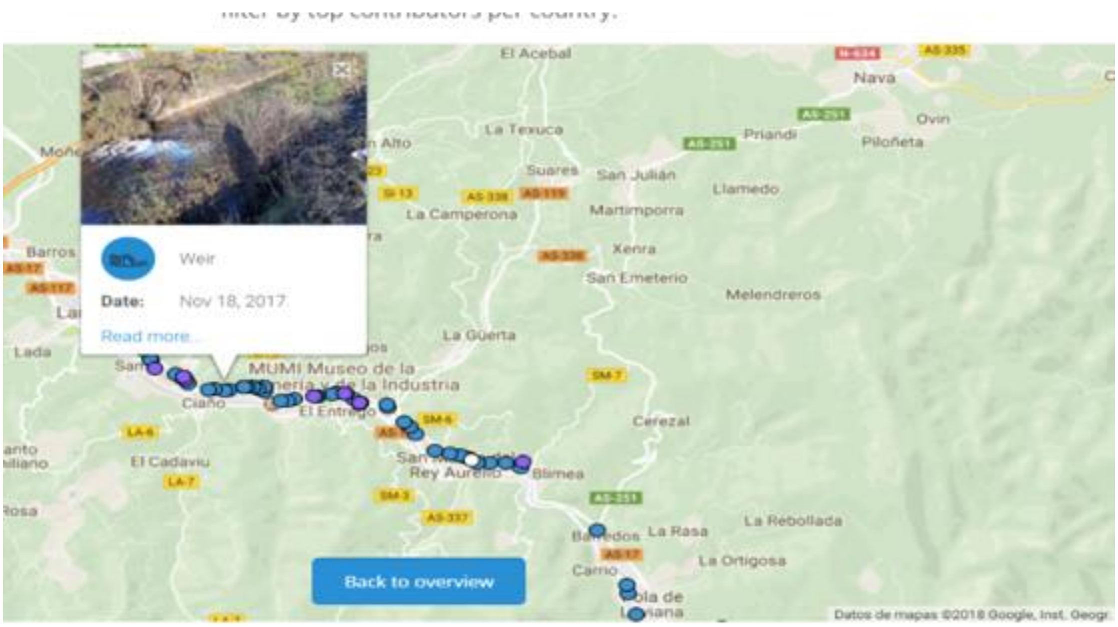


Figure 1.1.10. View of the barriers inventoried in the River Nalón with the Barrier Tracker app.

A1.1.8 Aid in conflict resolution.

AMBER researchers approached stakeholders including local authorities, hydropower companies, fishermen associations, education sectors, local schools and the general public, and organized events within the World Fish Migration Days in 2016 and 2018. The general message transmitted from AMBER was the importance of river connectivity and environmental quality. The AMBER project, the work of the researchers and the results in the Upper River Nalón case study were publicized by media in the region and at a national level, and AMBER was one of the voices taken into account in the debate between 2016 and 2018. The public involvement is demonstrated in **Table 1.1.2**, where there are some links to Spanish national and Asturias regional and local news, including TV, where this AMBER case study is mentioned.

Table 1.1.2. Examples of news appeared in Spanish media where the AMBER project is mentioned in relation with the River Nalón case study. Links are provided (all accessed in August 2019).

- https://docplayer.es/74718256-El-proyecto-amber-y-el-alto-nalon.html
- http://www.lacuencadelnalon.es/periodicos/lcn151.pdf (page 24)
- http://www.territoriopesca.com/dejalo-fluir/
- http://www.rtpa.es/asturias:La-Universidad-de-Oviedo-presenta-el-proyecto-Amber-en-Sobrescobio_111463837284.html
- http://agencias-origin.abc.es/agencias/noticia.asp?noticia=2209909
- https://www.iagua.es/noticias/espana/universidad-oviedo/16/05/25/amber-inventario-pantanos-y-kit-molecular-evaluaran
- https://www.lavozdeasturias.es/noticia/asturias/2016/05/25/impuesto-linaje-trucha-exotica-autoctona-asturiana/00031464171435895420698.htm
- http://www.ipacuicultura.com/noticias/en_portada/49012/la_universidad__de_oviedo_participa_en_un_proyecto_europeo_para_analizar_los_ecosistemas_de_los_embalses.html
- http://www.adecagua.es/nt-15-188/Un-inventario-de-pantanos-y-un-kit-molecular-evaluaran-la-salud-de-los-embalses-europeos
- https://www.catalunyavanguardista.com/chequeo-a-los-embalses-espanoles/
- http://www.asturiasmundial.com/noticia/85513/uniovi-lidera-proyecto-europeo-investigar-ecosistemas-embalses/
- https://documentslides.org/the-philosophy-of-money.html?utm_source=el-proyecto-amber-y-el-alto-nalon

The work within Caleao dam project was logically focused on the Upper River Nalón, where the reservoirs of Rioseco and Tanes are located (**Figure1.1.11**) and the Caleao dam was projected.

Figure 1.1.11. Photos of Rioseco (left) and Tanes (right) reservoirs.

The World Fish Migration Day of 2016 was the opportunity for playing the AMBER education game “Fish Gymkhana” in the area of the case study. All the children of Rioseco village, and their parents, did participate in the activity (**Figure 1.1.12 A, B, C**). We ended in the tail of Rioseco reservoir and enjoyed some snacks, soft drinks and sweet treats offered by the City Council.

Figure 1.1.12. Children of Rioseco village and their parents playing the AMBER educational game Fish Gymkhana in 2016 during the World Fish Migration Day. They were looking for clues and following a path near the reservoir while learning about the life and habitat of native brown trout.

The World Fish Migration Day of 2018 was employed for presenting AMBER results to the local community, including the results obtained with the molecular tools that were appreciated by the audience, especially those referred to the water quality and the brown trout. The children of the zone engaged in an AMBER education game, which attracted a lot of attention from the young (**Figure 1.1.13**). We also planned a gymkhana, but it was cancelled due to bad weather. The media were present and part of the activity with recorded after obtaining the parents' permission.

Figure 1.1.13. Rioseco children getting prepared for engaging in activities in the World Fish Migration Day. Above, AMBER researchers explaining the game; below, being interviewed by journalists of the regional TV.

A.1.2 CASE STUDY 2. River Guadalhorce (Andalusia, Spain)

The River Guadalhorce emerges and travels its first 4 kilometres through the province of Granada, then runs through the province of Malaga for 150km to its mouth. The basin covers an area of 3,157km2.

This river is the central fluvial basin of south Mediterranean Spain. It is the longest river in the Andalusian Mediterranean Basin, and the second largest, after the River Guadiaro. The irregular regime alternates between frequent droughts and occasional flash floods that cause extensive damage and threaten human lives. The climate of the Guadalhorce river basin is framed in the Mediterranean type, with hot summers and winters between mild and cold - in the low and high part of the basin, respectively - and average temperatures between 15 and 17ºC; annual rainfall less than 600mm, with irregularly distributed rains, although often concentrated in intense storms for a few days throughout the year, with prolonged droughts in summer. According to the Spanish Environmental Ministry, it belongs to the Mediterranean low-altitude axes.

The main course of the Guadalhorce, along with its tributaries Guadalteba and Turón, forms the head of the basin. Downstream it receives numerous tributaries, the most important the right Rivers Grande and Campanillas, in addition to many strongly seasonal ravines.

The river supplies water and electricity to the city of Malaga via four hydropower stations on the same number of dams and reservoirs that also regulate water flow. Its channel has been diverted in Malaga city to prevent inundations and decrease flood risk.

A.1.2.1 Hydrological and regulatory characteristics of the Basin

The average flow of the Guadalhorce at the mouth is $8m^3/s$. However, it is a very torrential basin where the current flow can vary significantly throughout the year. In periods of heavy rains and heavy storms, the flow can reach incredible values. In the floods of 1989, they exceeded $2000m^3/s$ at the mouth, more than 250 times the average flow.

The river supplies electricity to the city of Malaga via four hydropower stations on the same number of dams and reservoirs that also regulate water flow. We must bear in mind that hydroelectric use is very abundant in Spain. Most of the approximately 1,300 large dams that exist in Spanish rivers have hydroelectric power among their primary uses. However, it is not the first use.

The three main reservoirs of the basin, Conde de Guadalhorce ($66,5hm^3$), Guadalhorce ($126hm^3$), and Guadalteba ($153hm^3$) are located at the confluence of the Guadalhorce with its tributaries Turón and Guadalteba (see **Figures 1.2.2 to 1.2.4** below). The construction of these 3 reservoirs determined the agricultural development and industry of the whole valley and the water supply to the city of Malaga. All three have the same multiple uses with the following order of priority: Supply - Irrigation - Energy. For Hydrological Planning, the Guadalhorce is part of the SERRANIA DE RONDA, I-4 River Basin of the Guadalhorce and Guadalmedina rivers.

Figure 1.2.2: "Conde del Guadalhorce" Dam.

Figure 1.2.3: "Guadalteva" Dam.

Figure 1.2.4: "Guadalteva" reservoir.

Apart from the impact on the river ecosystem associated with the barrier effect, these large reservoirs generate potentially high pressure on the ecological state of the water body by regulating the downstream flow. The Hydrological Plan (see **Figure 1.2.6** for graphic information of the works included in the Guadalhorce Plan) shows that values of the regulation index of up to 650% are estimated against the total contribution in the natural regime. However, the degree of real alteration would depend on the operating regime of all the reservoirs. It should be noted that the artificial fluctuation of the level in the Reservoir "Tajo de la Encantada" (see **Figure 1.2.5**) due to the day-night hydroelectric exploitation cycle is cited among the most critical hydromorphological alterations in the water masses of the Andalusian Mediterranean basins and have motivated the designation of it as highly modified.

Figure 1.2.5: "La Encantada" ("El Chorro") Dam.

In turn, regulation from these large reservoirs determines the classification of water bodies corresponding to the middle and lower Guadalhorce basin as highly modified masses: about 35km of river, between the "La Encantada" cliff and Jévar and then between Jévar and the River Grande, as well as the more than 15km of Lower Campanillas downstream of the Casasola dam. In a subsequent evaluation of the state, the mass between Jévar and the River Grande, although it is still considered affected by the regulation of the flow from reservoirs, has become considered Natural mass. Last but not least, the mouth of the River Guadalhorce is also considered a highly modified mass, although in this case due to pressures and impacts on transverse and vertical connectivity.

The Hydrological Plan determines a regime of ecological flows from "La Encantada" Dam (also known as "El Chorro") to Jévar, for whose monitoring the *Luciobarbus sclateri* species is used as a bioindicator. The regime to be achieved in this section is equivalent to 13% of the average annual flow. However, temporarily and for drier periods, a stable regime was adopted with the lowest monthly modules in the series, between 0.35 and 0.30 m^3/s, which represents 50% of HPU - Habitat maximum useful potential calculated, causing a serious problem of downstream resource deficit, which should be solved with different planned actions: correction of saline spills, reuse in agricultural irrigation, desalination of seawater as a support for urban supply, etc. In turn, the ecological flow regime determined in Bajo Guadalhorce from the Aljaima landfill represents 10% of the average annual flow and will continue with the bioindicator species *Pseudochondrostoma willkommii*. It also has a transition regime that represents around 7% of the interannual module, around the lowest monthly values of the seasonal series, between 0.55 and 0.70 m^3/s.

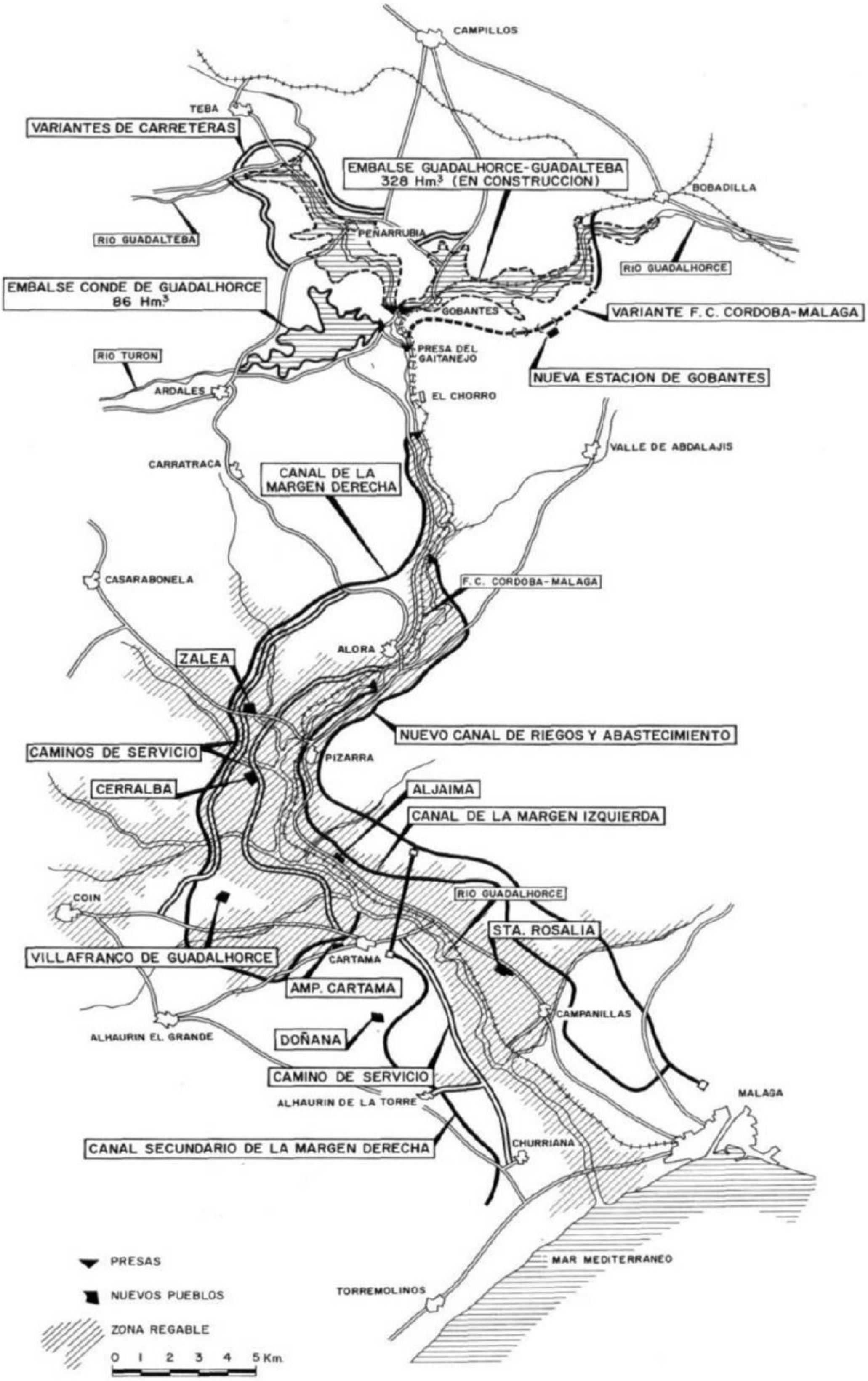


Figure 1.2.6: Works included in the Guadalhorce Plan, Jábega Magazine Nº. 1 (1973) Edition Center of the Diputación de Málaga.

A.1.2.2 Notes on fluvial ecology and values

In the Guadalhorce basin, several Sites of Community Importance are catalogued, including riparian and river habitats: SITE ES6170003 - Los Gaitanes Gorge and SITE ES6170033 – River Guadalhorce, Fahalas and Pereilas (**Figure 1.2.7**).

Figure 1.2.7: Los Gaitanes Gorge. Source: AEMS Ríos con Vida.

To further elaborate this section, we include parts of the report elaborated by Oscar Gavira and AEMS Ríos con Vida for the study case of the River Guadalhorce (Gavira and Garrido, 2019):

"Like any river, the Guadalhorce reflects the management of its territory, so that it suffers all the abuses committed so far: dams, weirs, pollution, hydraulic overexploitation, marine intrusion, deforestation, channelling, invasive alien species, etc. From the headwaters to the mouth, the river is losing naturalness and environmental value, collecting the impacts that are made on the land it crosses".

Structurally, the Guadalhorce basin shows the high complexity of a territory of great extension and is geographically diverse. Three large rivers in its medium-high area, and from three very different directions, the River Turón (southwest), the River Guadalteba (northwest) and the River Guadalhorce (northeast) confluence in a curious X-shape. This is not accidental, but because these three rivers are born on the northern slopes of the Betic Mountains (a mountain range that runs through the Iberian southeast from the Strait of Gibraltar to Alicante), and they have to cross it to flow into the Mediterranean Sea. In this way, these three rivers converge at a single point to cross the mountain in the Gaitanes Gorge, a large canyon that stands out for the height and verticality of its walls. It is in this place where the great dams are located, three for each river and a fourth downstream, after the exit of the Guadalhorce canyon. Another important sub-basin corresponds to that of the River Grande, which joins the Guadalhorce in its lower section. This river is the only one in the basin that is not regulated, so it retains important natural values compared to other similar sections of the main Guadalhorce riverbed.

The great extension of its basin and the geological complexity of the territory cause great diversity of river ecosystems. Despite this, there are some common characteristics: almost all headwaters are born in limestone mountains, which gives all its waters a high hardness. There are also areas with high salinity (gypsum) or heavy metals (peridotites). The three headwaters have a high environmental value, classified as pristine rivers, with an excellent ecological state, because they are born in mountainous areas and, therefore, away from the numerous human impacts. It is not uncommon to find threatened species as the native crayfish (*Austropotamobius pallipes*) along with many endemic and threatened invertebrates species. In these headwaters sections, in general, the riparian forest is well preserved; the domain of willow (*Salix pedicellata* or *Salix eleagnos*) in calcareous areas.

In the middle sections of these rivers, impacts can be noticed. The vegetation is often replaced by communities of invasive exotic species such as eucalyptus (*Eucalyptus camaldulensis*) and cane (*Arundo donax*), especially in sections with a strong agricultural impact. However, in the upper-middle part of the Rivers Turón, Guadalteba and Guadalhorce, on deep clay soils and in areas with less agricultural pressure, the riverside forest shows a rich and diverse community of plant species such as white poplars (*Populus alba*), ash trees (*Fraxinus angustifolia*) and elms (*Ulmus minor*). These middle courses are also home for endangered species of dragonflies such as *Oxygastra curtisii* and *Calopteryx xanthostoma*.

The cyprinids dominate the native fish community: *Luciobarbus sclateri*; *Pseudochondrostoma willkommii* and *Squalius pyrenaicus*, highlighting the presence of *Squalius alburnoides*, a hybrid genetic species consisting only of females that use the male of *S. pyrenaicus* to reproduce and that has in the River Guadalhorce the only Mediterranean population (Doadrio et al, 2011) –maybe by river capture of some tributary of the Guadalquivir basin.

Historical studies carried out suggest that the Guadalhorce basin had the presence of the indigenous trout (Salmo trutta), which is currently considered extinct in the basin. The population of the Guadalhorce would be among the 11 or 12 native trout populations that would have disappeared in the Andalusian region in the last century, 73% of the total (Sáez Gómez, 2010). However, as explained in this report, the environmental DNA study carried out by UNIOVI in the Guadalhorce within the AMBER project, has detected the presence of the species in the headwaters of the basin, so it will be necessary to carry out new investigations that allow to confirm it and know its status.

With the virtual disappearance of trout in the basin, the headwaters currently appear quite weak in fish populations, with the *S. pyrenaicus* chub as the sole representative. However, in the lower-middle courses, the community is enriched with other species, such as *Cobitis paludica*, benthic species, or the eel (*Anguilla anguilla*), relegated to these sections of the rivers due to the construction of large dams. It is noteworthy in the River Grande basin the apparent absence of exotic species of fish is possibly due to the absence of large dams in its channel. However, the basin is not free of invasive alien species such as *Cyprinus carpio* and *Micropterus salmoides*.

Although it is not a fish, the the red swamp crawfish (*Procambarus clarki)i* should be added to this list; a transmitter of afanomycosis. This disease destroys populations of the native crab.

Among the aquatic fauna and specifically among the fish, **Table 1.2.1** compiles the most representative species of the basin.

Table 1.2.1. Native ichthyofauna in the Guadalhorce river basin

Scientific name	Spanish name	Category	Protection	IUCN Proposed
Anguilla anguilla	Anguila	Autoctonous		VU A1acde
Barbus sclateri	Barbo gitano	Autoctonous	Annex V Directive 43/92 CEE	NT
Pseudochondrostoma willkommii	Boga del Guadiana	Autoctonous	Annex II Directive 43/92 CEE	VU A2ce
Squalius pyrenaicus	Cacho	Autoctonous		VU A2ce
Squalius alburnoides	Calandino	Autoctonous		LC

Mediterranean basins have particular characteristics that hinder the development of fish-based bioindicator indices: few native species; little knowledge of their ecological requirements; high number of endemisms with a wide range of tolerance to environmental variations and presence of exotic species (Benejam, Ll. 2008).

The river mouth is where the river shows the most considerable degree of transformation and degradation, accumulating all the impacts of its route. The flow moves through a canalized and partially diverted river, without being able to prevent marine intrusion. The banks have been transformed into breakwaters, and all-natural habitats have disappeared. Between the two delta branches, there is a protected wetland, Special Protection Area (Paraje Natural Desembocadura del Guadalhorce), for its ornithological values due to the presence of artificial ponds (yet the natural processes have been totally annulled) which is the last shelter of migratory birds still left in the very touristic coast of Malaga province.

In the lower part of the river, the flow is overexploited, very contaminated water due to lack of sewage water treatment and the effect of agriculture and livestock. In Malaga, there are two water treatment plants. An additional big water treatment plant was planned near the river mouth in Málaga city. Besides this, several modifications of the river course and riverbed including large channelizations and diversions, and a runway considered a barrier for river species by conservationists were also planned. These plans had created conflicts with environmentalist NGOs and other stakeholders like landowners.

A.1.2.3 Socio-economic conditions

In the Andalusian Mediterranean basins, a total of 1,575hm^3 are extracted annually, of which 155hm^3 are for supply, 21hm^3 for domestic use, 1,150hm^3 for irrigation, 5hm^3 for livestock, 176hm^3 for industrial use, 38hm^3 for hydroelectric use and 21hm^3 for other uses. The consumption data in the System River Basin of the Rivers Guadalhorce and Guadalmedina projected to 2015, attribute 53.7hm^3 to the supply of the resident population; 5.5 a seasonal population supply; 4.9 to other tourist uses; 154.6 to irrigation; 1.6 to livestock; and 10.3 to industry, adding a total consumption of 230.6 hm^3 and a total of 363hm^3 of water distributed for the set of activities. Therefore, the primary use in the Guadalhorce basin is irrigated agriculture, with almost 70% of total water consumption.

The power plants associated with the three large reservoirs of the Guadalhorce concentrate 85% of the total hydroelectric power installed in the Demarcation totalling 463MW.

In the upper zone of the River Guadalhorce the cattle and the agri-food, as well as the tourist and residential uses in the lower zone stand out.

In the supply network of the province of Malaga, almost 74% of the volume used in supply is distributed. Losses or uncontrolled extractions in the supply network account for about 20% of the volume distributed in cities such as Malaga, while in interior areas such as the Guadalhorce Valley the average is around 30%.

A decade ago it was noted that in the province of Malaga, 34% more water was consumed than the Spanish average and the volume of drinking water collected in the province was of the order of $157hm^3$ per year, increasing the average water expenditure up to around at 275 litres per person per day. In the last decade, consumption has been significantly reduced, to around 126 litres per inhabitant and day. Since the start-up of a desalination plant in 2005, the running water that is distributed in the city of Malaga is considered to have excellent quality.

A.1.2.4 Changes in river management plans

The river management plans affecting the lower part of the River Guadalhorce changed within the life of the AMBER project. In 2017, the plan of building a large water treatment plant changed to the construction of one smaller treatment facility to serve the villages of Alhaurín el Grande and Cártama. On the other hand, an alternative, softer, cheaper, project for modifying the river channel was presented in the City Council of Málaga City on March 1, 2019. As with the old plan, its purpose is solving the current problem of flooding of the lower part of the river that affects the delta primarily. The new project comprises several small to moderate intervention in the flood plain and has been prepared by IRTENE Consulting. The original document can be consulted online at https://www.promalaga.es/wp-content/uploads/2019/03/H-461-EI-00-MEMORIA-00-01-B050.pdf (accessed in August 2019). Six interventions are planned and were approved by Málaga City Council: regrowing the left margin of Prado de Jurado, de las Yeguas, Boticario y Pocapringue channels; reconditioning the channel of the main river near Málaga-Fuengirola railway; restoration of the riverbed near the M-21 bridge; reduction of riverbed elevation in several parts of the river channel; regrowing some parts of the main river channel and cleaning up and restoration of several river zones. The plan approval by the Regional Government of Andalusia is still pending. Since modifications of the riverbed can also represent barriers for many species already affected by the four big dams upstream, AMBER is relevant for the new projects too.

As in many other Mediterranean basins, the water management debate in the Guadalhorce basin is developed among those who argue the need to increase the supply of water with the construction of more regulation and storage reservoirs in intermediate valleys, and those who defend other softer alternatives that allow rationalization and reduction of consumption through sustainability and adaptation measures, mainly managing water demand. No significant milestones in this debate occurred in the mid-2000s, with the conflict surrounding the project of a new large dam on the River Grande. At the end of the decade, after a crucial social mobilization at the local and regional level, the project was dismissed, but the debate is still alive and active in society, and it is foreseeable that it will come to light at some point.

Using the AMBER approach to adaptive management, a multidisciplinary set of tools and actions were carried out. Molecular tools were applied to assess biota richness above and below the current dams and in the reservoirs. A trial of participatory approach, based on the results of a social survey on social acceptance of dams was conducted at this demonstration site. AMBER tools were also employed for estimating ecosystem services as well as for the identification and characterization of mesohabitats and evaluating the accuracy of official databases through field validation of the barriers that block the river. It is expected that the application of the AMBER tools will help with the consideration of different points of view and take these into account, especially river connectivity. This will reduce the potential impact of the new modifications planned in the river when they are constructed.

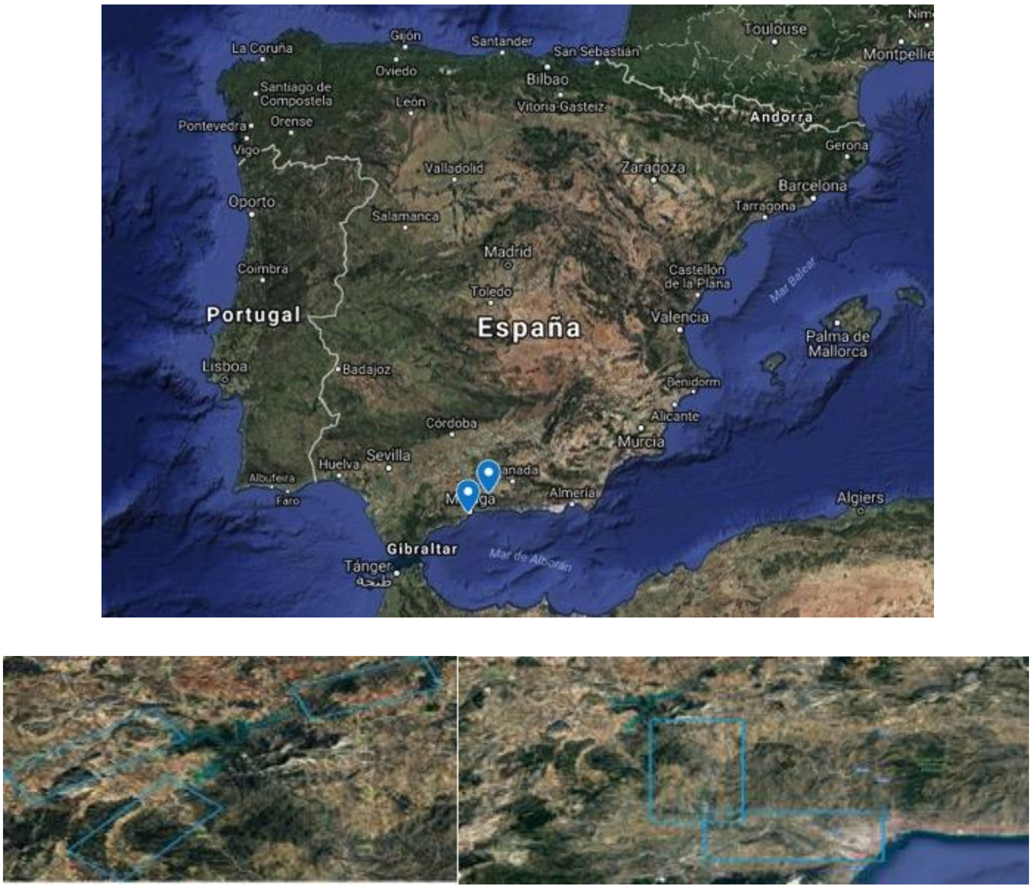


Figure 1.2.8. Map of Spain with the location of the River Guadalhorce head and mouth (above). Below, maps of the areas affected by dams in the upper (left) and lower (right) reaches of the River Guadalhorce.

Figure 1.2.9: Guadalhorce reservoir.

A.1.2.5 How did AMBER contribute to improving River Guadalhorce dam management

Before starting to apply AMBER tools, local stakeholders were identified, and contacts established to initiate networking. The objective was to work together following a participatory approach with stakeholder involvement. The following stakeholders working on different aspects of the River Guadalhorce were contacted: Junta de Andalucia (Regional Government of Andalusia); EU H2020 project SWOS -Satellite- based Wetland Observation System; NGO 'Ecologistas en Accion'; NGO SEO-Birdlife; University of Malaga, Center of Hydrogeology and European Topic Center (Dr Dania Abdul Malak, researcher Christoph Schröder). In the Junta de Andalucia, the following Services and persons were contacted: Subdirección de Explotación, José Manuel Puerto Gisbert; Servicio DPH y Calidad De Aguas de la Delegación Territorial de Medio Ambiente, Oscar Alberto Lorente Castellano; Subdirección General de la Demarcación Hidrográfica del Sur, Fernando Ferragut.

With the help of local stakeholders (amongst others), the following tasks were accomplished: environmental inventory, biological sampling (**Figure 1.2.10**) and social survey. Space, including laboratory use, was provided to UNIOVI researchers within the instances of the University of Malaga, as well as collaboration for field research, in the context of this networking.

Figure 1.2.10. AMBER researcher Dr. Sara Fernandez taking water samples from the River Guadalhorce. The choice of sampling sites was made with the valuable help of local stakeholders. Water turbidity can be appreciated in the photo.

A.1.2.6 AMBER molecular toolkit in Guadalhorce River

The molecular tool applied in this case study was Metabarcoding for the inventory of the community from eDNA. Samples of water were obtained from Two markers (a fragment of the chloroplast RBCL gene and a fragment of the mitochondrial COI gene) were amplified and sequenced using an Illumina platform, then bioinformatically analyzed with QIIME pipeline.

Five points were sampled along the River Guadalhorce (**Figure 1.2.11).** One was upstream, out of the influence of the reservoirs, and the rest were located in running waters between dams and below the lowest dam. The results obtained for the two genes provided evidence of a diversity of plant and animal species that were clearly different upstream and downstream of the dams, associated with the environmental status of the sampling sites. The lack of community connectivity was also evidenced by molecular data.

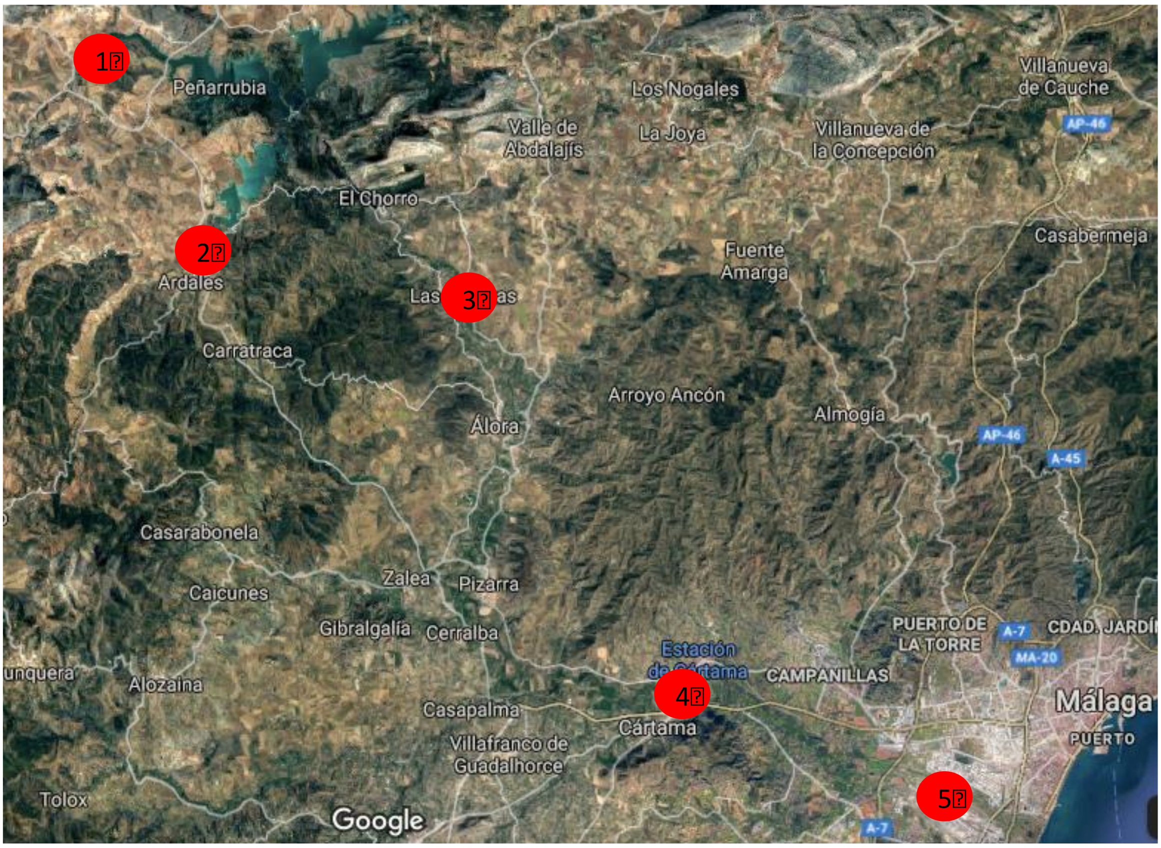


Figure 1.2.11. Sampling points within the River Guadalhorce. Marked in red.

Several nuisance species were found in environmentally disturbed sites only between or downstream of the dams. Some examples are: various harmful algae; the big-ear radix freshwater snail *Radix auricularia* that is a carrier of parasites able to infect humans like trematodes and leeches like *Glossiphonia complanata* (**Figure 1.2.12**). Another animal found in the area affected by dams was the very tolerant river shrimp *Echinogammarus berilloni* (Amphipoda), a species that is expanding to Centeral Europe. DNA of the exotic rainbow trout *Oncorhynchus mykiss* found upstream could be likely attributed to fish farms in the area.

The results are being prepared for publication in a peer-reviewed journal to be presented to the stakeholders and general public inhabiting in the case study area.

A)

B)

Figure 1.2.12. Species potentially harmful detected in the River Guadalhorce waters affected by dams, using AMBER eDNA tools. A: big-ear radix Radix auricularia; B: leech Glossiphonia complanata. Photo sources: Wikimedia Commons open-source (A), APHOTOFAUNA open source by David Fenwick (B).

DNA of native species and bioindicators of good water quality such as the Ephemeroptera *Rhithrogena* sp. was also found (**Figure 1.2.13**). It is important to note that DNA of the genus *Salmo* sp., likely of the native brown trout *Salmo trutta*, was found only upstream. The brown trout is declared protected species in Andalusia territory, and only catch-and-release is permitted to prevent further fishing pressure on the species. It is catalogued as "*In danger of extinction*" in the Red Book of Threatened Vertebrates of Andalusia. Our data indicate that its habitat in the Guadalhorce basin is now restricted to the upper part of the river. Habitat alteration, including water detraction for human uses and construction of dams, is recognized as a main factor of brown trout decline in Andalusia. Between the river dams and downstream, DNA of this species could not be found, despite the molecular tools here employed are highly sensitive. These results would support the establishment of further measures to protect and enhance this species upstream in the River Guadalhorce. This area is not selected in the plan of restoration of the species, where the other five rivers of Andalusia have been chosen, and our data –that were communicated to the Junta de Andalusia- suggest that it could be one more site of choice for brown trout restoration and enhancement actions. The current restoration plan can be found (in Spanish) in the official website of Andalusia regional government at http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=915ac52c2c098510VgnVCM1000001325e50aRCRD&vgnextchannel=cd528c43b07d4

310VgnVCM1000001325e50aRCRD#apartadof09bf91cd5698510VgnVCM2000000624e50a, accessed August 2019.

A)

B)

Figure 1.2.13. Bioindicators of good environmental quality found only upstream dams (A, native salmonid *Salmo trutta*) and all along the Guadalhorce River (B, mayfly *Rhithrogena* sp.). Photo sources: Andalusia Government portal (A), Wikimedia Commons open-source (B).

The NGS analysis of water samples using the RBCL marker allowed the retrieval of 60 operational taxonomic units (putative species) of freshwater phytoplankton. Metabarcoding using RBCL has been recently employed for evaluation of water quality (Rivera et al. 2018), and we followed this approach.

In the results of the River Guadalhorce, the algae diversity was clearly different among sampling points (**Figure 1.2.14**), with an accusated decline in the locations between dams and downstream. Algae tolerant to water pollution, i.e. indicators of bad water quality (for example, Cimarelli et al. 2013) were also more abundant downstream and in areas strongly influenced by dams like Site 2 (**Figure 1.2.11**); especially the rate bad/good quality indicator species was maximum in Site 3, located below the dams. Although Site 5 was in Málaga city, thus expectedly very disturbed, the algae indicators were not the worst, emphasizing the value of this urban wetland whose protection should be maintained at least, or upgraded to being a shelter of migratory birds. As in the case of the River Nalón, the negative effect of dams on water quality could be detected here using AMBER Metabarcoding tools.

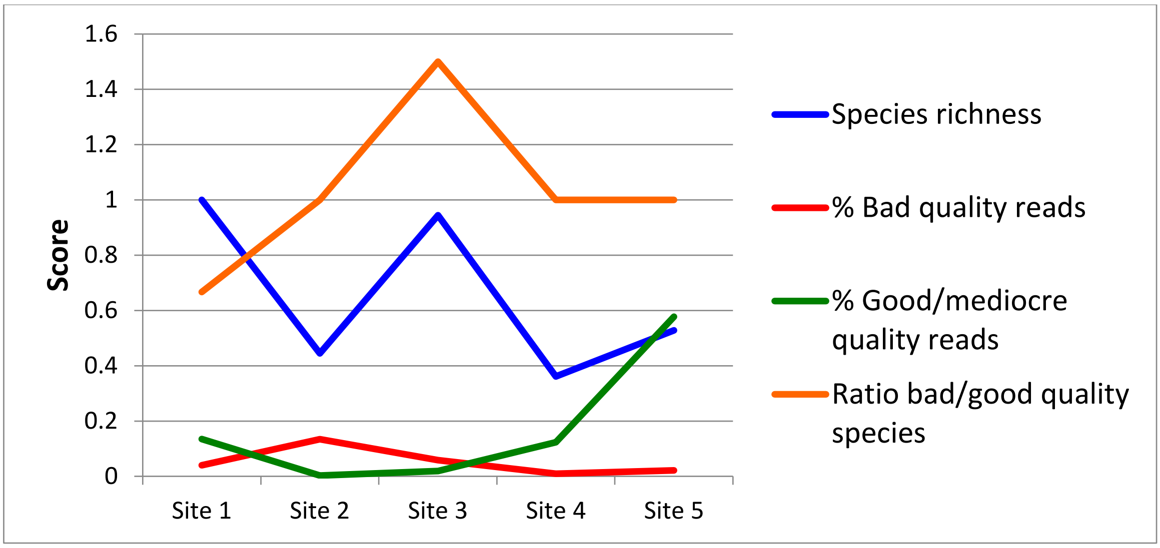


Figure 1.2.14. Diversity of bioindicator algae in the studied sampling sites within the River Guadalhorce. Species richness is relative to the maximum (36 species in Site 1). Reads refer to the number of NGS reads of indicators of bad or good/mediocre water quality.

A.1.2.8 AMBER tool for estimating ecosystem services in the River Guadalhorce

The ecosystem services provided by the River Guadalhorce were estimated using the Ecosystem Services Survey ESS tool developed in AMBER within WP2. The results are summarized in **Table 1.2.2**. It can be seen that many ecosystem services exhibit a positive change both above and below dams in this case study. In particular, the cultural benefits and regulation contain many services with positive changes.

Table 1.2.2. Ecosystem services and disservices provided by the River Guadalhorce dams. In blue, provision; in green, regulation; in brown, cultural.

		Ecosystem Services change	
	Categories of benefits	**Above dams**	**Below dams**
provision (Provisionnutrition, materiaPProls, en	Reared animals and their outputs	0	0
	Wild plants and animals	-1	-1
	Aquaculture	0	0
	Surface water for drinking	1	1
	Groundwater for drinking	0	1
	Materials / biomass from plants, algae and animals	0	0
	Surface water for non-drinking purposes	1	1
	Groundwater for non-drinking purposes	-1	1
	Energy	1	1
regulation	C sequestration/ storage /accumulation by ecosystems	1	0
	Dilution by water	1	1
	Mediation of smell/noise/visual impacts	1	1
	Erosion protection	0	-1
	Flood protection	0	-1
	Hydrological cycle and water flow maintenance	1	1
	Drought prevention	1	1
	Soil formation - decomposition and fixing processes	0	0
	Micro and regional climate regulation	1	1
	Chemical condition of freshwaters	0	1
	Maintaining nursery populations and habitats	0	0
	Experiential use of plants, animals and landscapes in different environmental settings	0	0
	Physical use of landscapes in different environmental settings	1	1
	Scientific	1	1
	Educational	1	1
	Heritage, cultural	1	1
	Entertainment	1	1
	Aesthetic	1	1
	Symbolic	1	1
	Sacred and/or religious	0	0

The catalogue of services scored higher in this estimation include drinking water and energy supply, entertainment and leisure activities (kayaking, bath), as well as historical sites and cultural patrimony. Examples are the Caminito del Rey (Prize Biosphere to Sustainable Tourism, Cultural Patrimony EU Prize Europa Nostra) in the upper zone and archaeological sites in lower reaches.

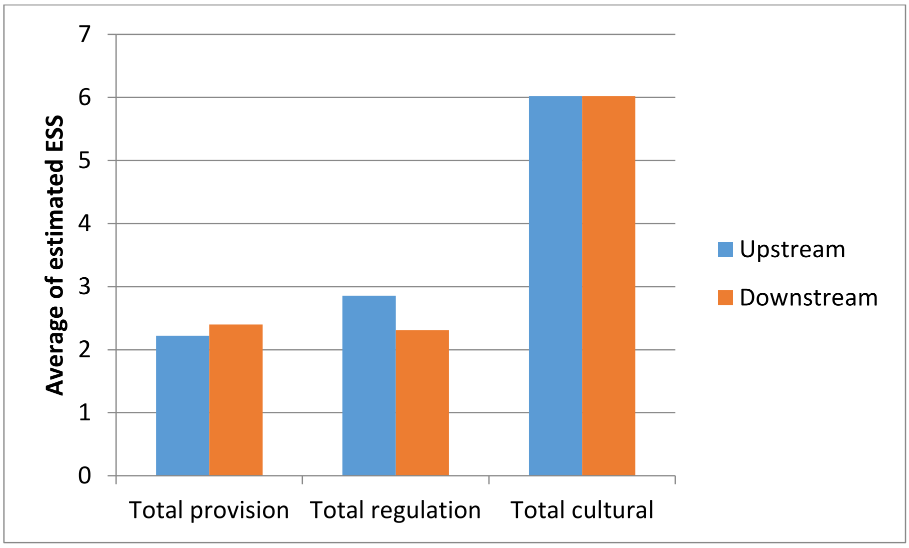


Figure 1.2.15. Average estimated values of provision, regulation and cultural services provided upstream and downstream by River Guadalhorce dams.

A.1.2.9 Quantification of costs and benefits of dams in Guadalhorce River.

The AMBER tool questionnaire designed for the "Social survey on attitudes toward dams and reservoirs" (D3.5) has been employed in full in this case study. Local residents in the case study zone were contacted directly by the researchers near the sampling points (**Figure 1.2.16**) and in Málaga city. The researcher wore neutral clothes for not influencing the respondent's opinion and just explained briefly the project objectives.

A total of N = 319 interviews were conducted. The results are prepared for publication in a peer-reviewed journal.

Figure 1.2.16. AMBER researcher Elena Arboleya, MSc, interviewing residents in the upper zone of the River Guadalhorce**.**

We will next show the answers to question Q3, which is the willingness to pay more taxes for different actions on rivers and estimates the public valuation of the River Guadalhorce dams and reservoirs. In this case study, the only proposed action that was not economically supported by the majority of respondents was the demolition of dams (**Figure 1.2.17).** For this action, 31% of respondents would not increase their taxes at all, and less than one half would give more than a 0.5% increase. In contrast, improving river connectivity and constructing new dams and reservoirs were options supported in the region. More than 70% of respondents would increase their taxes by more than 0.5% for them. This is highly coherent with the use of dams and reservoirs for water supply and the positive ecosystem services provided by them, also for cultural and regulation issues in this case study. It is coherent with the popularity of fishing in the reservoirs, since increased connectivity would increase the number of species if migratory fish are allowed to reach the reservoirs located in the upper river reaches.

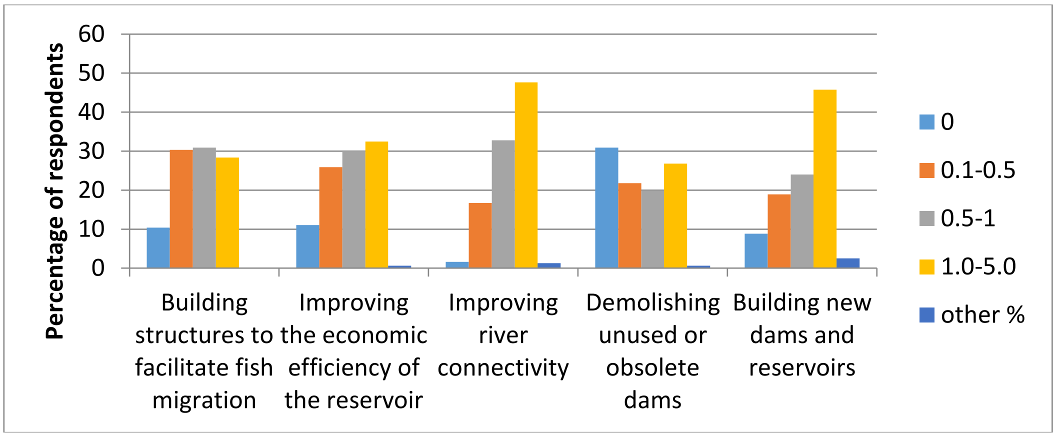


Figure 1.2.17. Proportion of respondents willing to increase their taxes by a percentage for actions to improve River Guadalhorce features.

Regarding the dam cost and benefits in the case study (**Figure 1.2.18**), survey results showed that in general, the respondents perceived more benefits than costs in the River Guadalhorce dams. In the question about the dam acceptance, five options were given: They should be eliminated, I would prefer them out of the area where I am living, Should be modified for having a less ecological impact, Should be maintained as they are today, More dams and reservoirs are needed to provide more services. The proportion of respondents choosing these options were 0.3%, 3.8%, 38.5%, 12.6% and 44.8% respectively. This demonstrates a majority of participants accepting and supporting dams in the River Guadalhorce , as high as 57.4%, while the level of rejection was 4.1% of participants.

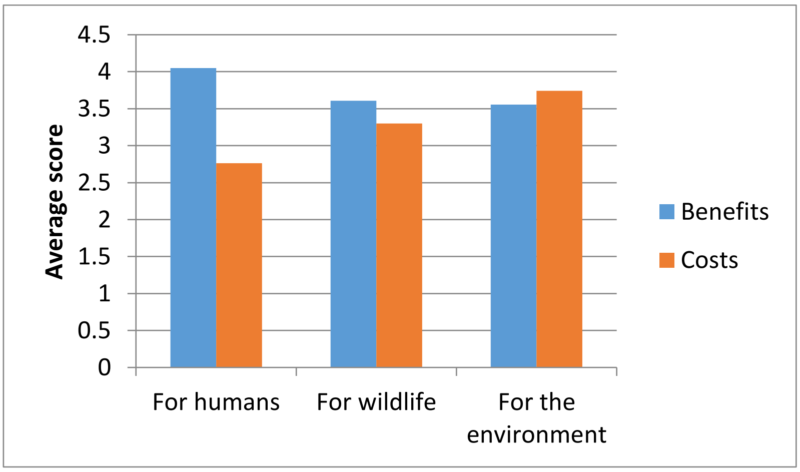


Figure 1.2.18. Dam costs and benefits perceived by respondents in the Guadalhorce River.

A.1.2.10 Field validation of databases

The field validation work report corresponds to the AMBER task T1.2.2: In situ field validation of barrier data in selected representative watersheds. The fieldwork in Spain was allocated during the AGM meeting in Milan to be performed in Spain by the two Spanish partners as following: field validation of one river to be carried out by Universidad de Oviedo (UNIOVI hereafter) and four rivers by AEMS– Rios con Vida (AEMS hereafter). The selection of basins, rivers and location of field validation sections corresponded to each partner; results compiled in one single report, elaborated by AEMS.

Team and Schedule: The first stage of fieldwork was performed after summer 2017. The field validation of the the River Guadalhorce required four days in the last week of September 2017. It took an average of 6 hours per river for three people working team.

Selection of rivers and general characteristics: For the field validation action, the selection of rivers not only had to follow homogenizing criteria but represent the wide Spanish variability yet be accessible and passable to perform the field validation.

One of the criteria used for the selection of the rivers was it should belong to the Case Study basin. For that reason, both the Rivers Nalón and Guadalhorce were included in this task. However, the selection of the sections required a first analysis of the basin district. Following, an in-depth analysis of the different areas, in order to locate the four rivers in a way that represents variability required for the study (in type of river, altitude, slope, sinuosity and land use –**Table 1.2.3** compiles the information for both sections of all five rivers validated). Finally, the databases available (national and regional) were compared to ortophotographs to pinpoint the possible transversal obstacles on the field.

Table 1.2.3. Summary information about selected rivers in order to justify and validate field site selection. River sections: 1, upstream; 2, downstream. River type: ST, single-thread; MT, multi-thread. Landuse (Corine Land Cover 2012): 1, Artificial surfaces; 2, Agricultural areas; 3, Forest and seminatural areas. Measurement units: Altitude: m; Slope: m.m-1; Sinuosity: sinuosity coefficient.

Name	Section	Alberche	Guadajoz	Guadalhorce	Nalón	Tirón
Altitude	1	1349	228	113	283	809
	2	1230	214	75	221	691
Slope	1	0,019	0,002	0,004	0,007	0,012
	2	0,005	0,001	0,004	0,005	0,012
River type	1	MT	ST	MT	ST	ST
	2	ST	ST	MT	ST	MT
Sinuosity	1	1,39	1,59	1,53	1,02	1,07
	2	1,13	1,66	1,52	1,02	1,03
Landuse	1	3	2	2	1	3
	2	3	2	3	1	3

This river is located in a river mouth area above 100m a.s.l.. It represents soft slopes, multi-thread pattern in both sections, and high sinuosity (**Figure 1.2.19 to 21**). The selected 20km of the river is located in the proximity of Álora municipality, yet it is surrounded by forestry areas (section 2) and agricultural areas (section 1).

Figure 1.2.19: The River Guadalhorce . Location of the river basin within Spain.

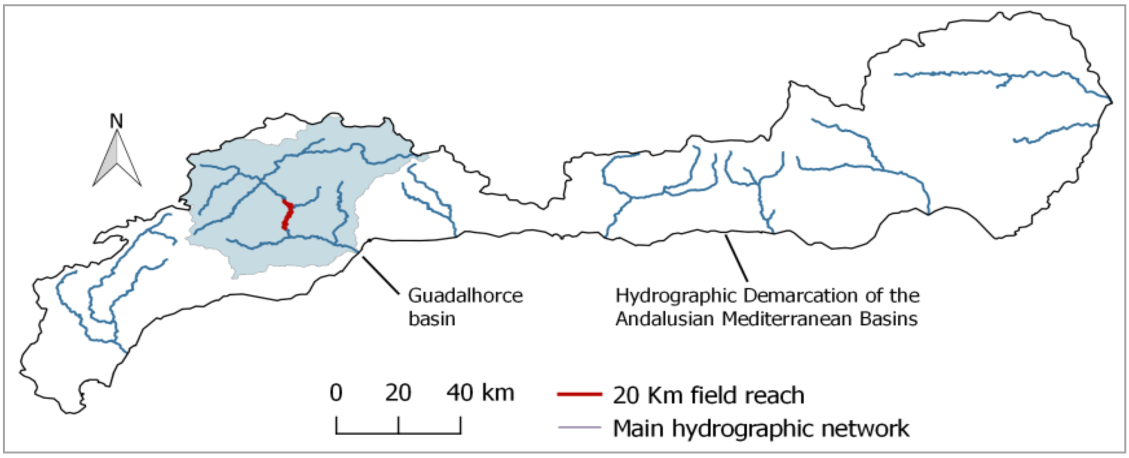


Figure 1.2.20: Location of the 20 km river reach selected for field validation, location of Guadalhorce basin within the hydrographic demarcation of the Andalusian Mediterranean basins.

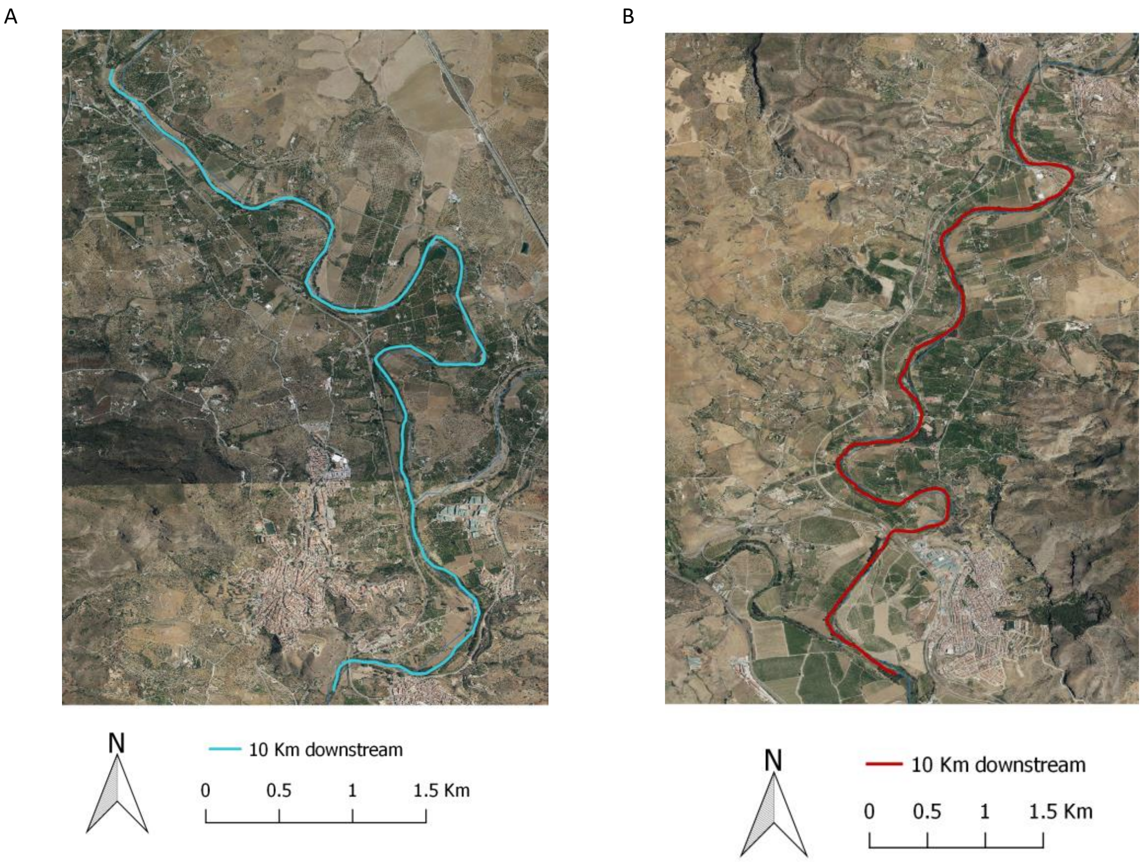


Figure 1.2.21: A and B, overview of the upstream and downstream river sections, respectively.

A.1.2.11 Results of the fieldwork Guadalhorce River

Along the River Guadalhorce, the field team found six obstacles: three fords, one dam, one weir and one gauging station (**Table 1.2.4** contains main data of the barriers, represented on **Figure 1.2.22, Figure 1.2.24** compiles pictures of barriers found), all in use and registered in the national database. However, more obstacles are in this database, which it was not possible to identify during the field validation. Regarding the height, the obstacles are distributed in all height classes smaller than 5 meters. These obstacles have three main uses: gauging, water derivation and crossing, dominating the crossing structures.

Regarding the passability of these obstacles, fords are considered not passable. From the perspective of fish migrations, no structure has a fish passage device at the River Guadalhorce. When looking at the barrier uses and purposes, most of the barriers at this river are in use. However, the River Guadalhorce registered one obstacle of which use was not possible to define.

Table 1.2.4. Obstacles encountered in field validation work in Guadalhorce River.

	Type	Height	Use	Width	Notes/Description
Gh01	Dam	2 - 5 m	Yes	Yes	Dam of sluices. Water derivation. Irrigation
Gh02	Ford	<0,5 m	Yes	Yes	Ford. Crossing for vehicles.
Gh03	Weir	0,5 - 1 m	Yes	Yes	Derivation channel, with open sluices. Water derivation
Gh04	Gauging station	1 - 2 m	Yes	No	Bridge with weir and gauging station. Bed stabilization.
Gh05	Ford	<0,5 m	Yes	Yes	Crossing of vehicles
Gh06	Ford	<0,5 m	Yes	Yes	Ford in use with culverts. Crossing of vehicles.

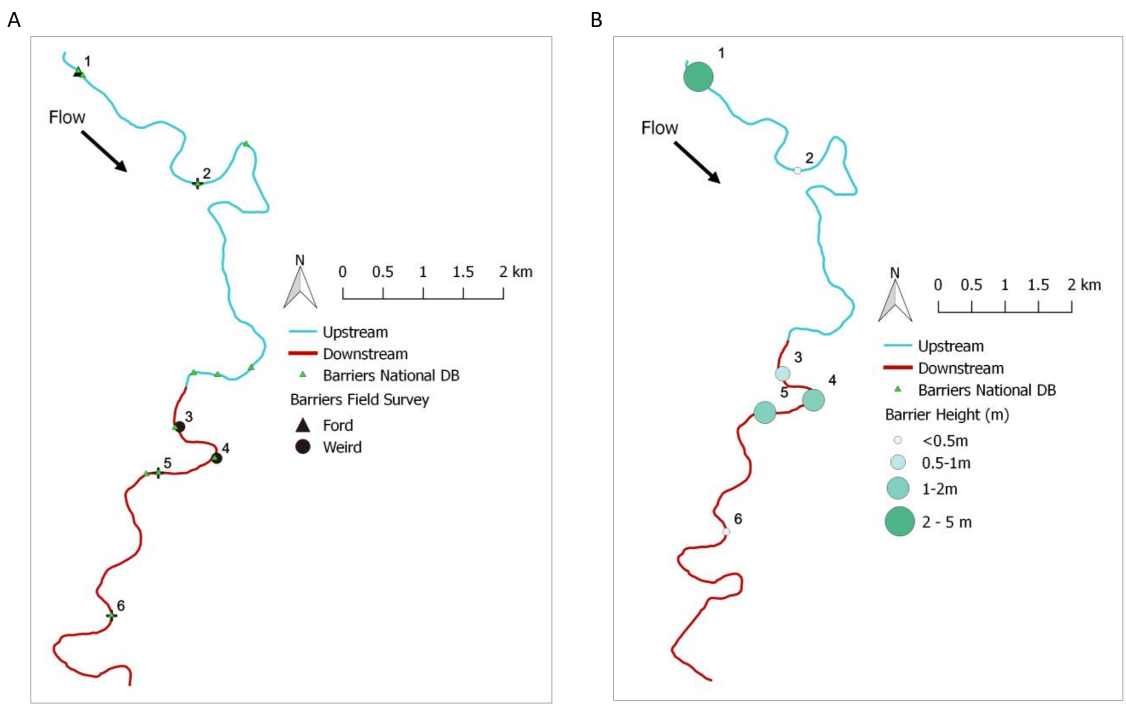


Figure 1.2.22: Location of the river barriers for the Guadalhorce river along the 20 km river reach. A, barrier types and comparison with the regional database. B, barrier height.

A.1.2.12 Comparison to official databases

In all the rivers and stretches studied in the field validation, more barriers have been found than those considered in the regional or national databases. The density of barriers in the regional databases is high in most cases, although it also varies vary significantly between the different river basins studied, in some cases also depending on the availability of information. In the case of the River Guadalhorce, for example, the inventory so far only reaches the middle and lower reaches of the river.

In Spain, there are regional and national databases. The Guadalhorce basin, totally embedded in the Hydrographic Demarcation of the Andalusian Mediterranean basins, is managed by the regional administration; therefore, the database corresponds to a regional level.

It is important to emphasize that there is a lack of homogeneity between different databases that limits the analysis in this sense. For example, the data represented in **Figure 1.2.23** mainly referrs to the information provided by the “Study of improvement of eel flow in river beds” a study focused on the eel, but not strictly on the barriers in the broader perspective.

When comparing the barrier density between field survey results and the national database, it emerges that the national database is underestimating barrier presence.

We must bear in mind that many of the transversal barriers inventoried in some of the Spanish basins, in this case especially those collected in the regional inventory in the River Guadalhorce, correspond with structures that suppose morphological alterations but not obstacles for fish connectivity, like bridges of footbridges or railways.

In the River Guadalhorce, 43 obstacles were identified in a regional inventory, while, within the sampling section, a total of 13 structures were defined as obstacles from the hydromorphological point of view. In the regional inventory, 13 obstacles were considered along the River Guadalhorce section defined for the field validation, In the field visit, a total of 5 barriers to the passage of fish in the study section were located in the 20km selected.

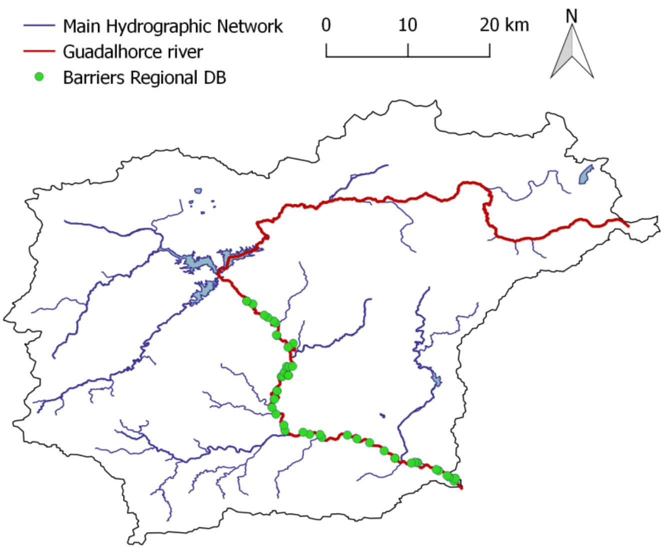


Figure 1.2.23: Obstacles registered in a Regional Database for the Guadalhorce basin.

The low visibility of the river conditioned the selection of the validation section as well as the track of the barriers. The low visibility is caused by the diverse plant colonization of the banks -mainly by an exotic species such as *Arundo donax*. The low visibility, along with the embedded and high depth of the channel at many points, caused difficulties during the field work, limiting the access to the channel.

Table 1.2.5: Comparisons of barrier number and density (n/km) between the field survey and the national database. NF, number of barriers after the fieldwork; NNR, number of barriers in the national or regional database; DF, density of barriers after the fieldwork; DN, density of barriers in the national or regional database. DF and DN whole basin on average; Total Length in km.

	NF	NNR	DF	NN whole basin	DN whole basin	Total length
Alberche	8	4	0,40	50	0,43	117,00
Guadajoz	6	4	0,30	85	0,40	215,00
Guadalhorce	6	6	0,30	43	0,16	262,40
Nalón	62	3	3,10	16	0,11	140,80
Tirón	18	5	0,90	12	0,18	64,95
TOTAL	**100**	**22**	**1,00**	**206**	**0,26**	**800,15**

Out of the five basins where the field validation was carried out in Spain, the Guadalhorce basin has the most extended fluvial length. It is also the only basin where the number of barriers found in the fieldwork match the inventories. It is also observed that the density of barriers found in the field validation is above the average density of barriers that inventories present in the entire basin. This may indicate, on the one hand, that perhaps one of the most accessible sections has been sampled, and on the other, that in the fieldwork it was not possible to locate and register all the existing barriers in it.

Gh01

Gh02

Gh03

Gh04

Gh05

Figure 1.2.24: Pictures of barriers on the River Guadalhorce.

A.1.2.13 Meso Habitats

In cooperation to WP2, performed the fieldwork to compile the data related to the different meso-habitats of a section of the River Guadalhorce. The AMBER partner Stanisław Sakowicz Inland Fisheries Institute (SSIFI) performed an analysis of the data collected.

The rapid stream habitat mapping from high-resolution drone platforms was also formulated, yet was not possible to apply as the entire Guadalhorce basin is included in a controlled airspace area (**Figure 1.2.25**), and required special permissions for the drone pilot as well as very complicated paperwork (impossible to finish in the time set for this task). However, the regional government; Cartography division of the Territorial Service of Information (Departamento de Cartografía del Servicio de

Información Territorial, Junta de Andalucía) provided high resolution (10cm resolution) orthophotos from 2012, that cover the section needed.

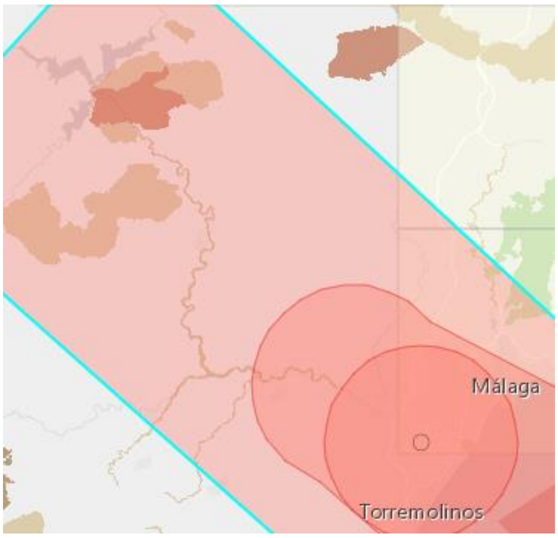


Figure 1.2.25: controlled airspace area that covers the upper part of the River Guadalhorce and large dams (https://www.enaire.es/servicios/drones)

The data for the MesoHABSIM simulations were gathered through intensive field surveys conducted over a section free of barriers, downstream of "La Encantada" dam. The section selected is located approximately 2,3km downstream of "La Encantada" dam, also known as "El Chorro". **Figure 1.2.26** shows the location of the section surveyed in relation to the infrastructures present in the area; the dam and the power plant installed in this reservoir.

Figure 1.2.26: Location of the surveyed section for mMesoHABSIM.

The selection of the section to survey was performed by the AMBER partners SSIFI (The Stanisław Sakowicz Inland Fisheries Institute) and ERCE (European Regional Centre for Ecohydrology Polish Academy of Sciences), who provided guidance throughout the process of surveying, compilation of information and logistics, as well as training for the AEMS team during the first survey in July 2019 (**Figure 1.2.27, 1.2.28**).

The length surveyed is related to the average width of the river. In this case, the team covered approximately 700-800m.

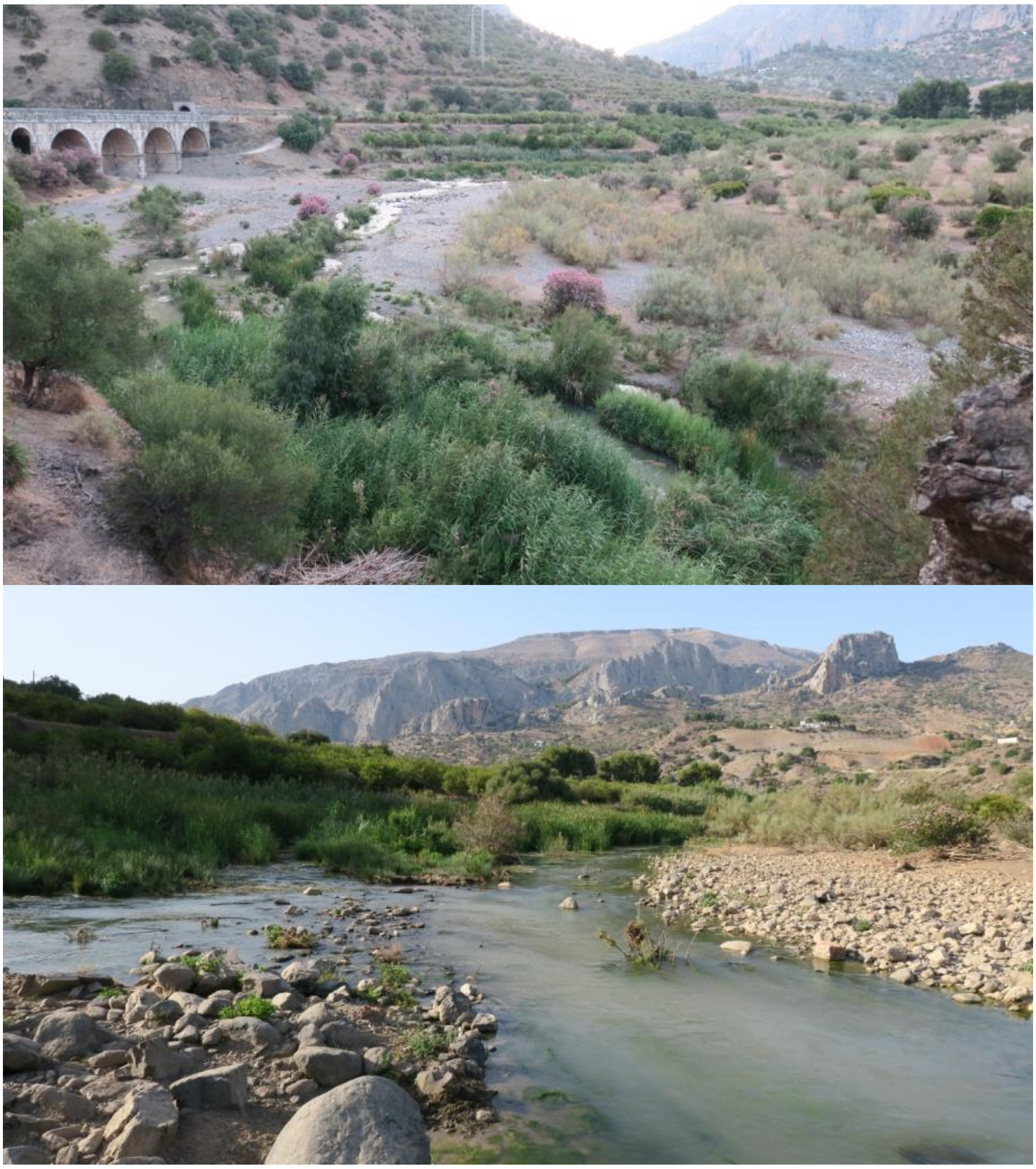


Figure 1.2.27: Section for mMesoHABSIM survey starting point.

Figure 1.2.28: Data collection for hydro-points at the River Guadalhorce by Zbigniew Kaczkowski (ERCE) and César Rodriguez (AEMS). July 2019.

Each survey required 2 to 3 days of fieldwork, depending on the conditions. The area was visited to control the flow conditions a total of three times, in July, August and October of 2019. This resulted in two surveys at different flow conditions. It is essential to have in mind that the River Guadalhorce is a regulated river from the very top. For this reason, the flow regime is constant (approximately 0,400m^3/s) and has minimal fluctuation. However, during the second visit to the area, the company that manages the dam was performing improvement works and left a sluice partially open which resulted in a flow of 0,663m^3/s. In turn, the flow during the third visit to the area had returned to the usual level of 0,391m^3/s.

During the stream habitat mapping, the team delimited the different units or mesohabitats found and described hydraulics of every unit with at least 7 points (hydro-points) and annotated the data related to channel dimensions, slope gradient, water depth, velocity, vegetation, and grain sizes for both the dry and submerged beds. In **Figure 1.2.29**, the identified hydromorphologic units - are displayed for the August survey. Following, **Figure 1.2.6** shows the type of units, the total number of each unit per survey and the total number of hydro-points per survey. Finally, **Figure 1.2.30** shows an example of several units and the distribution of hydro-points.

Figure 1.2.29: mesohabitats at the River Guadalhorce – August survey.

Table 1.2.6: Type of units, the total number of each unit and the total number of hydro-points per survey.

Type of unit	July Survey	%	August survey	%	Variation July-august
BACKWATER	3	6,0 %	2	4,1 %	-1
FASTRUN	2	4,0 %	1	2,0 %	-1
GLIDE	4	8,0 %	7	14,3 %	3
PLUNGEPOOL	1	2,0 %	0	0,0 %	-1
POOL	8	16,0 %	9	18,4 %	1
RAPIDS	4	8,0 %	4	8,2 %	0
RIFFLE	1	2,0 %	1	2,0 %	0
RUFFLE	5	10,0 %	4	8,2 %	-1
RUN	13	26,0 %	12	24,5 %	-1
SHALLOWMARGIN	1	2,0 %	2	4,1 %	1
SIDEARM	8	16,0 %	7	14,3 %	-1
nº units	**50**		**49**		**-1**
nº hydro-point in total	**364**		**359**		
Nº points/unit	**7,28**		**7,33**		

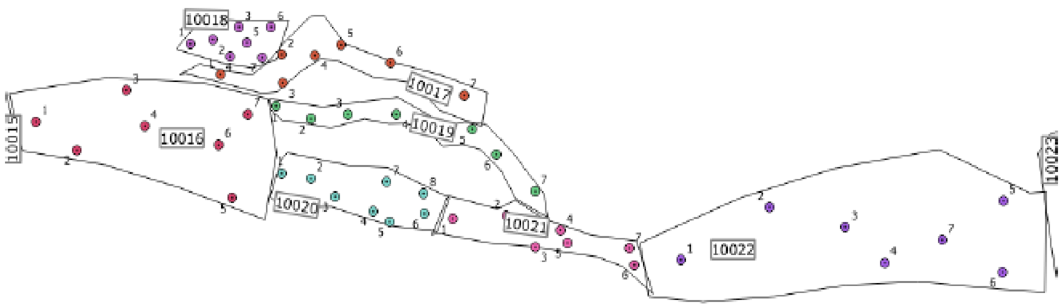


Figure 1.2.30: hydropoints collected during the surveys for different units.

All these data are complemented for the analysis with long-term flow time series, obtained from nearby gauging stations (see **Figure 1.2.31**, map of the gauging stations in the Guadalhorce basin). In the basin, there are a total of nine circulating flow measurement stations, four located in the three headwaters (Turón, Guadalteba, Guadalhorce), three along the Guadalhorce axis and two others in the main tributaries (Grande and Campanillas). Data from the existing gauging stations in the Guadalhorce basin are available from the Hidrosur information service, except for station No. 34, located between the large reservoirs in the upper part of the basin and Álora, which it was necessary to request from the managers of the river basin.

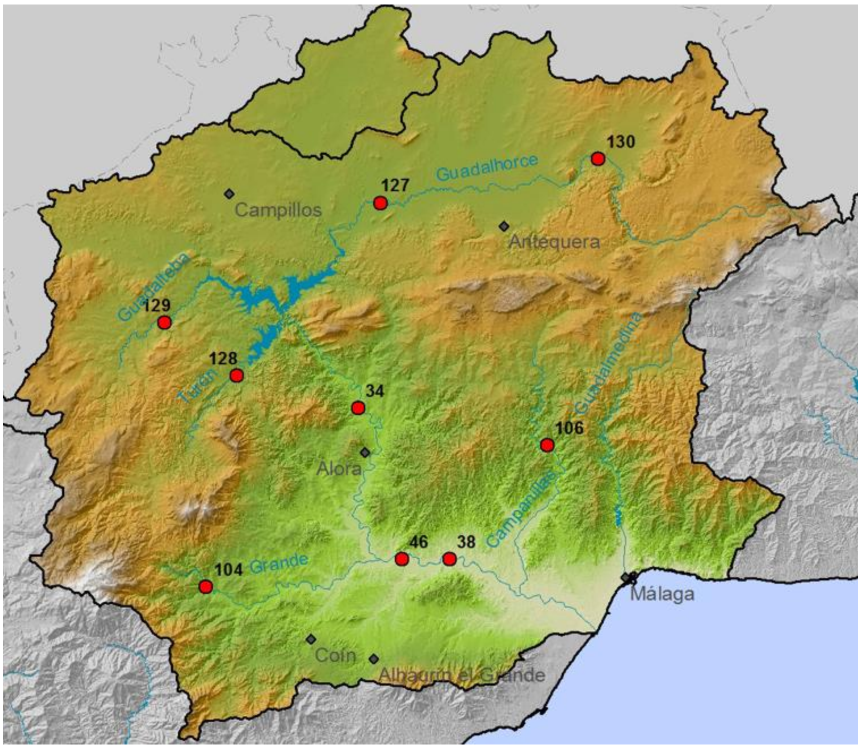


Figure 1.2.31: Gauging stations Guadalhorce Basin. For more information see: http://www.redhidrosurmedioambiente.es/saih/mapa/tiempo/real/subsistema/i4i5/aforos)

In the section where the MesoHABSIM survey was carried out, the flow is regulated by the large reservoirs located above. There is information related to data of inflows to the reservoir from the stations 126,127 and 128, as well as of the stations located in the waters downstream the reservoir, both in the main course - stations 38 and 46. There is data available as well from the main tributaries to the lower zone from the stations 104 and 106.

Figure 1.2.32: Gauging station nº 34 Guadalhorce Basin.

Figure 1.2.33: Gauging station nº 46 Guadalhorce Basin.

The hydrological data series offered by these stations are partial and incomplete. Some of them offer data from the 1970s, but most of the data corresponds to recent periods, and in addition, these periods are different from one another. Furthermore, the surface flow data measured points out that gauging stations are highly influenced by various and very important factors: first of all, the large regulation dams that store and regulate the flow provided by the three main headwaters; the diversion channel on the right bank that starts from the El Chorro dam and reaches to practically the lower part of the river; and finally, the catchment of the Paredones weir that drives along the left bank to the city of Malaga.

Station 34, located in the Paredones weir, presents data that does not match the flow patterns measured in the rest of the gauging stations. In turn, the data seem to correspond to the flow derived in this intake better than to the flow that circulates through the river. For this reason, the data corresponding to this gauging station were not considered, despite being the closest to the MesoHABSIM sampling section (**Figure 1.2.34**).

Furthermore, it seems likely the data from gauge 46 better reflects flow circumstances in the downstream river section and takes into account the irrigation withdrawals occuring downstream of the dam. Hence, focusing potential environmental flow management on this location as a compliance controll for environmental flow management would protect the aquatic fauna in the entire section from the dam to gauge 46. To reflect the concurent flow condtion in the section and still be able to refer to gauge 46, we standardised the the flows observed during the survey using area transfer method with a gauge 46 watershed area of 1860 km^2. For easier interpretation, the flow was also recalculated to liters per second providing specific flow values of 0.26 liters per second per square kilometer (lskm) and 0.42 lskm for survey 1 and 2 respectively.

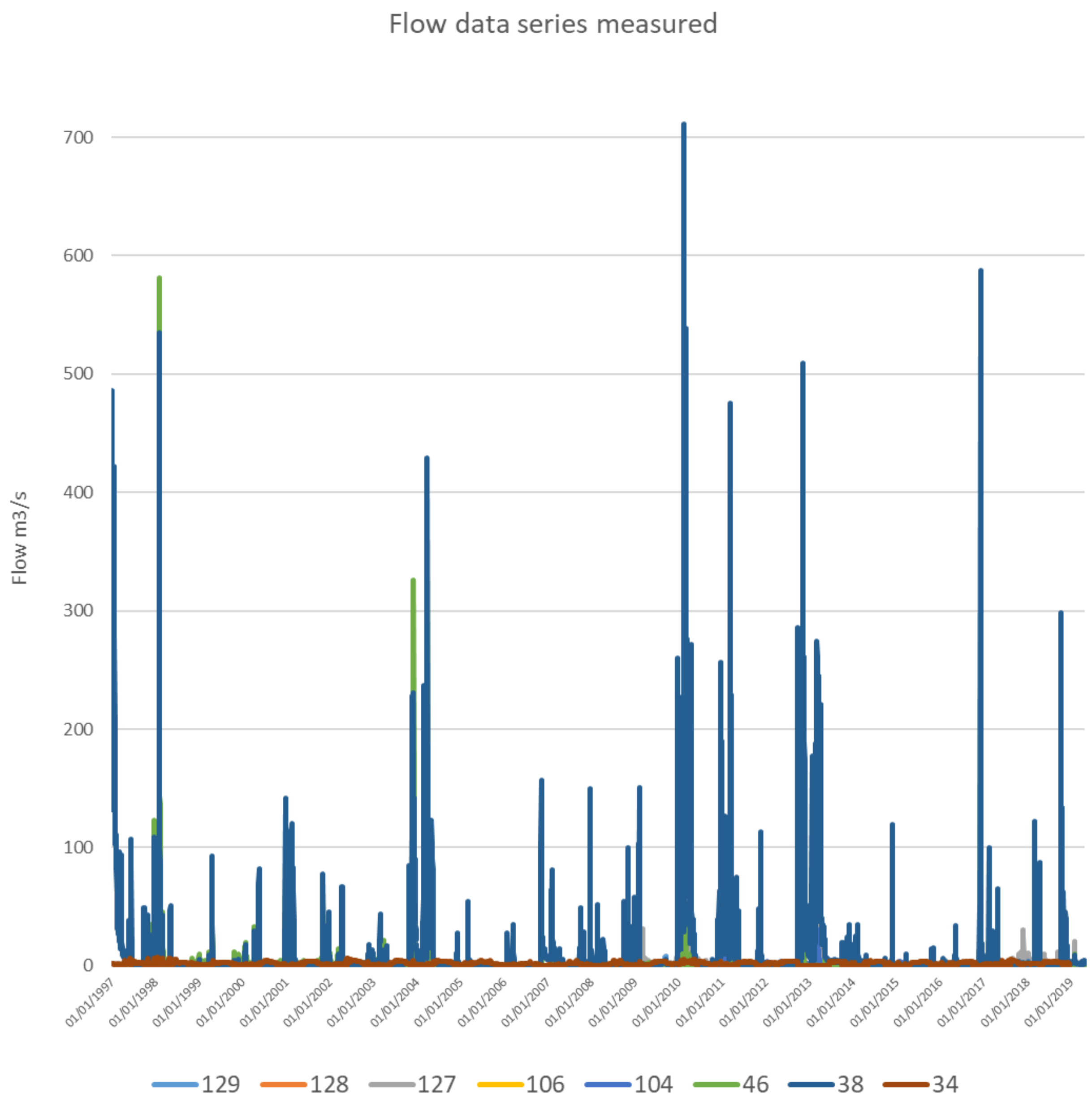


Figure 1.2.34: Series of average daily flows measured at all gauging stations installed in the basin.

Considering this data, it was possible to calculate and contrast the drainage basin upstream of the survey section by using different tools. This area is displayed in the following map (**Figure 1.2.35**).

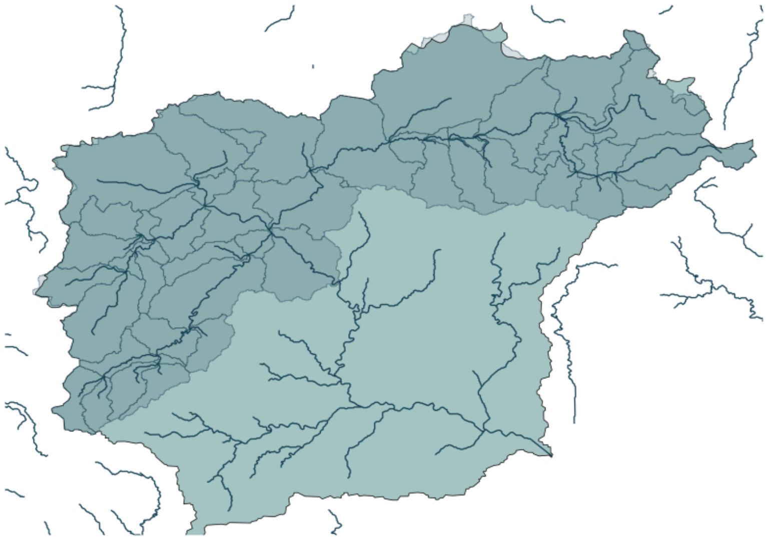


Figure 1.2.35: Guadalhorce basin. In dark blue highlighted the drainage basin upstream of the sampling point.

Expected fish community of the River Guadalhorce

According to the Hydrological Plan of the Andalusian Mediterranean basins, the section of the Guadalhorce between the El Chorro dam and Jévar -where the MesoHABSIM sampling station is registered - belongs to the ecotype "Low altitude Mediterranean mineralized rivers (107)", one of the eight habitat types of community interest defined in continental lotic ecosystems. The specific ecological characteristics of these habitats would correspond to what the WFD calls "Specific Reference Conditions" for each type. The nine characteristic fish taxa are defined for this river ecotype: Anguilla anguilla (Linnaeus, 1758); Aphanius iberus (Valenciennes in Cuvier & Valenciennes, 1846); Atherina boyeri (Risso, 1810); Barbus sclateri (Günther, 1868); Chondrostoma willkommii (Steindachner, 1866); Malaria cobitis (de Buen, 1929); Salaria fluviatilis (Asso, 1801); Squalius alburnoides (Steindachner, 1866); Squalius pyrenaicus (Günther, 1868); six of which are in the Guadalhorce basin (Toro et al, 2009).

Expected fish community habitat distribution for the River Guadalhorce in the study area was estimated from Fish Community Macrohabitat Types (FCMacHT) map created in the AMBER project (Parasiewicz et al., in prep). It corresponded with the FCMacHT of Mediterranean Rivers. It entails four habitat use guilds of which Limnophylic phytophylic Moderate Tolerant species dominate the community (41%), followed by the Generalist (20%). Rheophylic Benthic sand and gravel species (14%) and Rheophilic water column sand gravel (10%) are rheophylic component of the community. Further are Bentic (8%) and Limnophylic lithophylic moderate tolerant (7%) species.

Using the habitat suitability critera demonstrated in the Vistula Case study we calculated habitat suitability for both measured habitat distribution for reach guild. Since only two flow values could be surveyed, we assumed that the habitat is equal 0 at no flows and such created a third survey point for building rating curves (**Figure 1.2.27**). **Figure 1.2.25** and **Figure 1.2.26** below represent calculated habitat suitability for both measured habitat distribution for each guild.

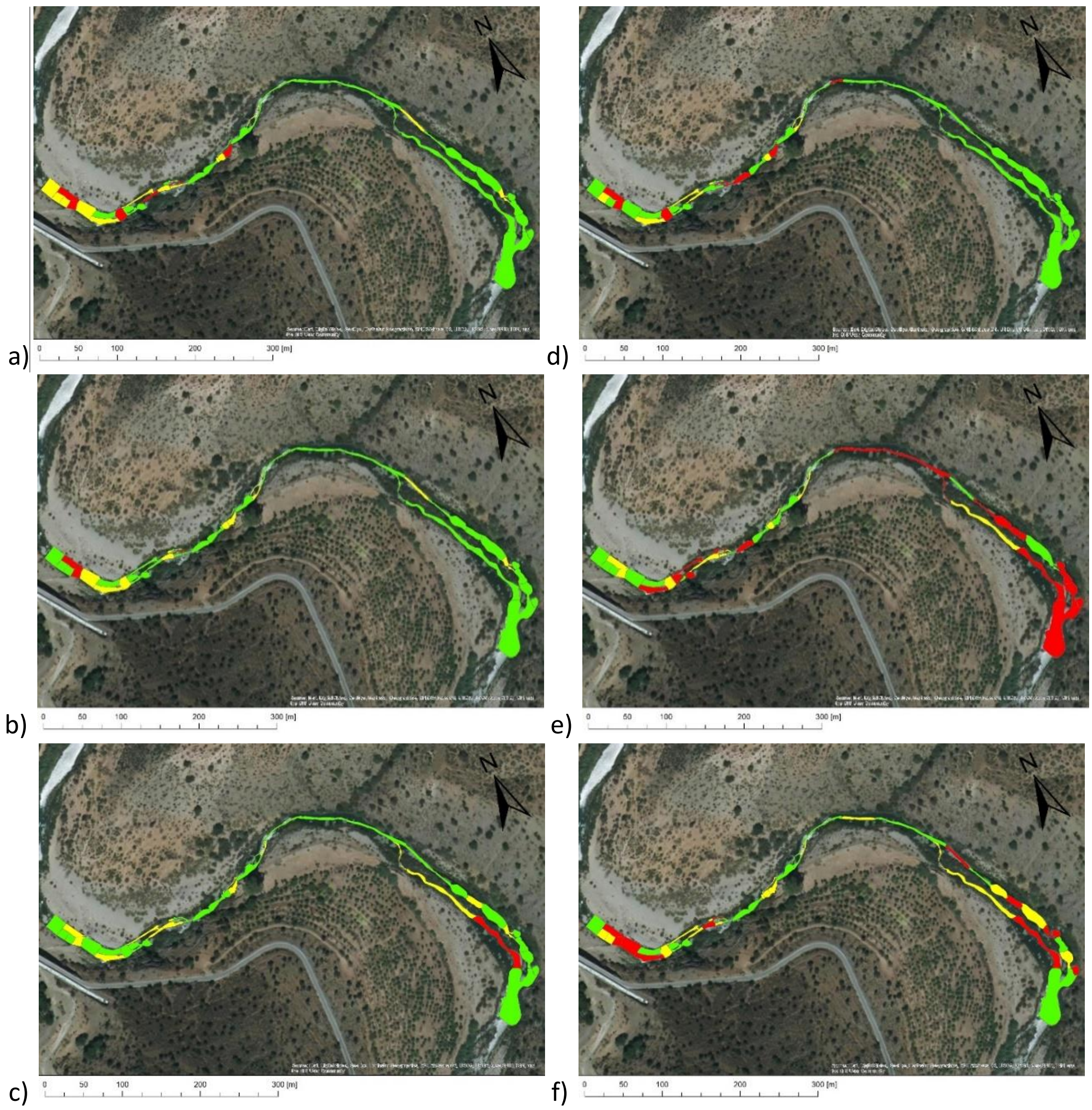


Figure 1.2.25: River Guadalhorce, July 2019, Q= 0,390 m^3/s: a) Benthic moderate tolerant, b) Generalist tolerant, c) Limnophilic litophilic moderate tolerant, d) Limnophilic phytophilic moderate tolerant, e) Rheophilic benthic sand gravel, f) Rheophilic water column sand gravel. (Habitats: green – optimal, yellow – suitable, red – unsuitable).

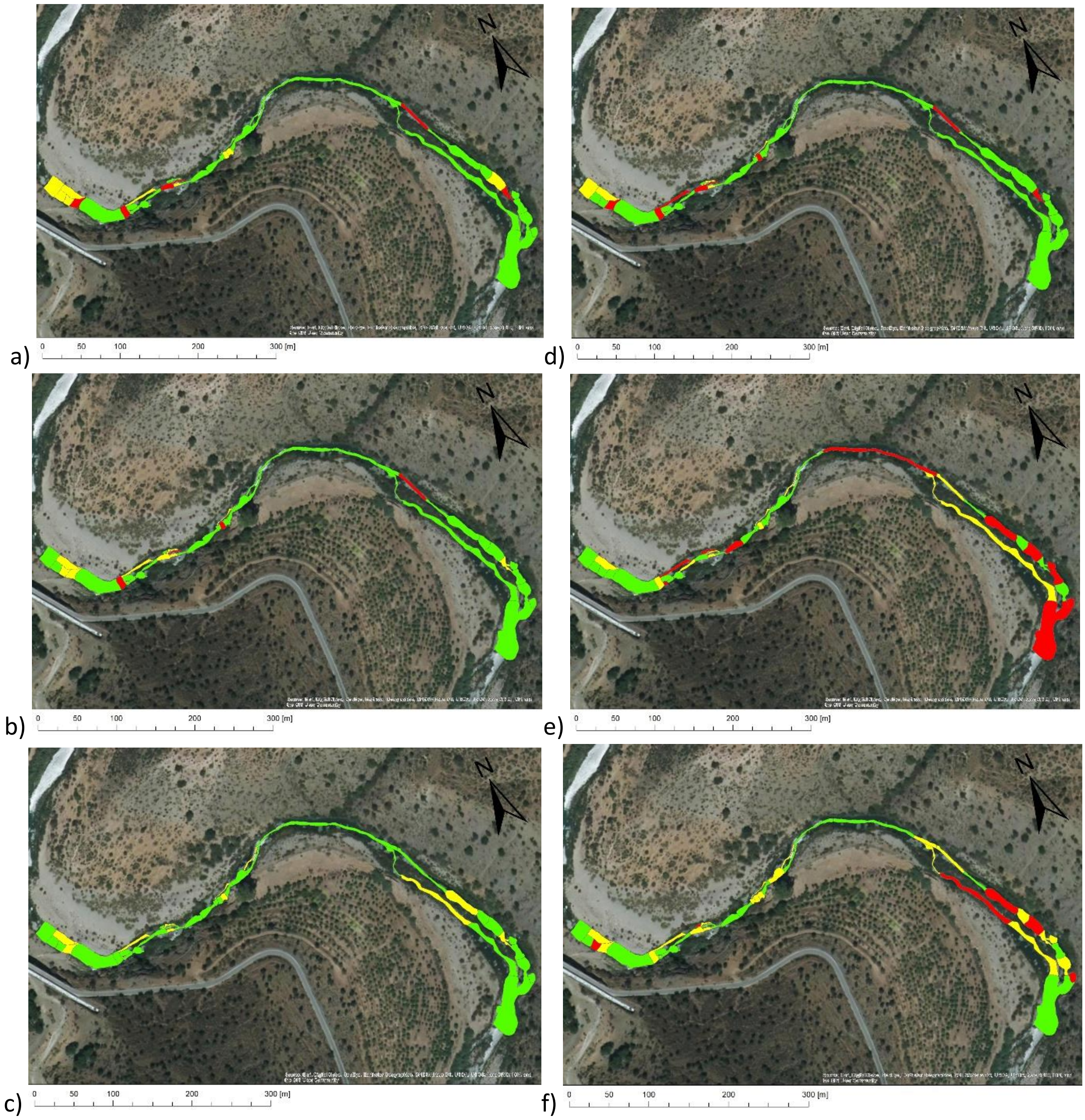


Figure 1.2.26: River Guadalhorce, August 2019, Q= 0,663 m^3/s: a) Benthic moderate tolerant, b) Generalist tolerant, c) Limnophilic litophilic moderate tolerant, d) Limnophilic phytophilic moderate tolerant, e) Rheophilic benthic sand gravel, f) Rheophilic water column sand gravel. (habitats: green – optimal, yellow – suitable, red – unsuitable).

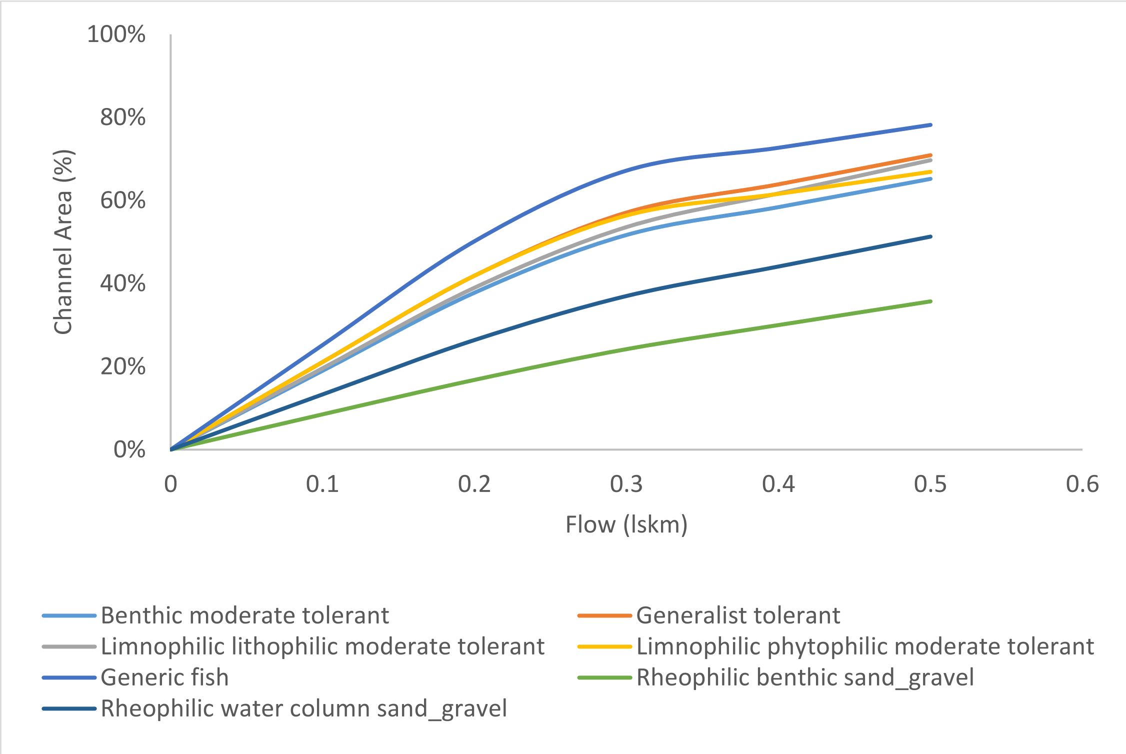


Figure 1.2.27: Rating curves for habitat use guilds.

According to the model, the suitable habitat is increasing until about 0.3 lskm for all guilds where the curve flattens out. For the rheophylic species, which have the least habitat, the slope of the curves changes only minimally. The greatest decline is for Limnophylic phytophylic species guild. The distribution of observed habitat has been compared the distribution of expected habitat according to FCMacHT. **Figure1.2.28** demonstrates that the habitat for this most dominanting guild is strongly underrepresented and for Benthic moderate tolerant overrepresented. Other guilds occur in proportions close to those expected. Nevertheless, the overall affinity of the observed and expected habitat distribution is between 75% and 76%, which is a high similarity (**Figure 1.2.28**).

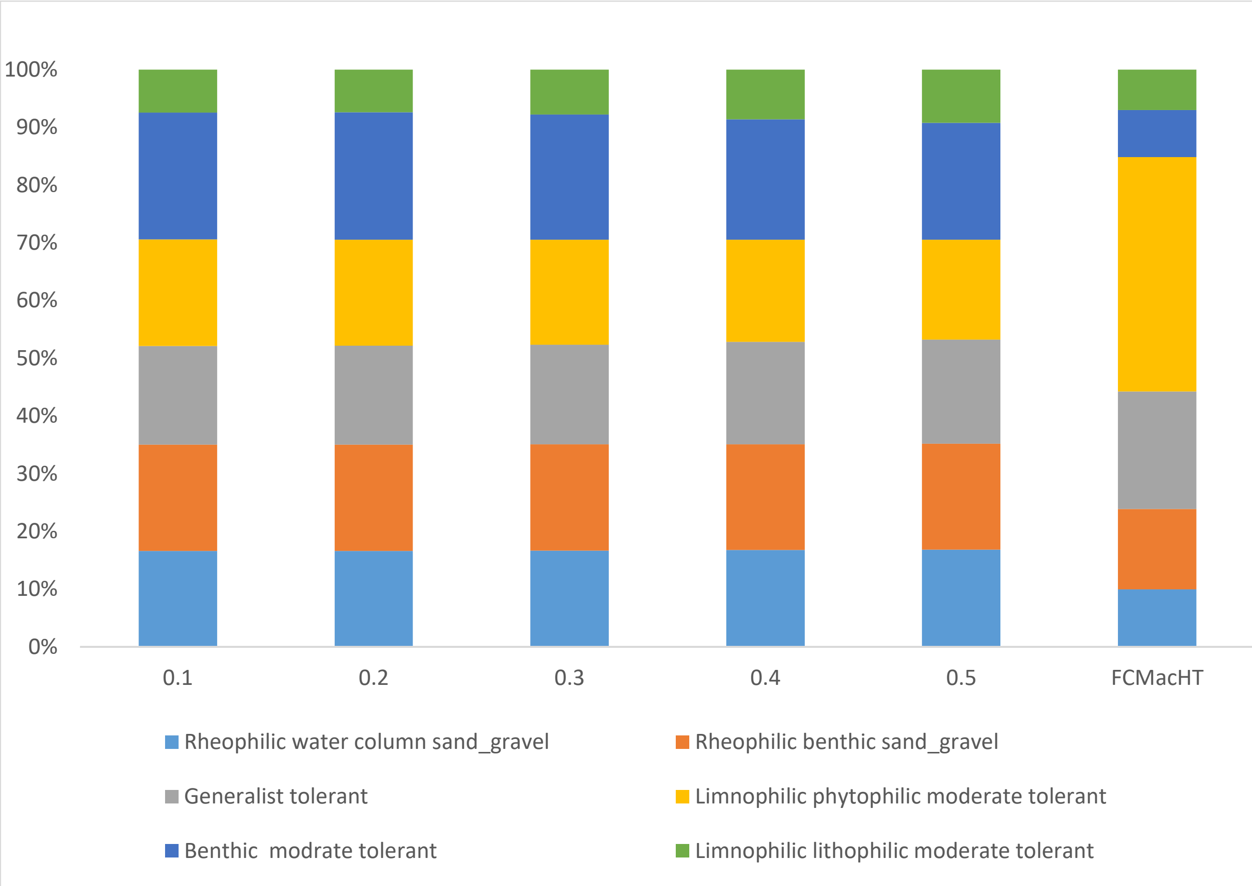


Figure 1.2.28: Structure for habitat use guilds compared with FCMacHT.

The community rating curve in **Figure 1.2.27** also demonstrates a high level of affinity increasing with flows as well as overall habitat area availability. Unfortunatley the curve is not too well fitted, and below 0.26 lskm demonstrates linear decline, which may be an artefact of the lack of data at lower flows. In reality, the critical point of the curve may be at lower flows and the initial incline steeper. On the other hand, the assumption of 0 habitat are at 0 flow is valid only for longer drought periods, where the river completely dries (**Figure 1.2.29**).

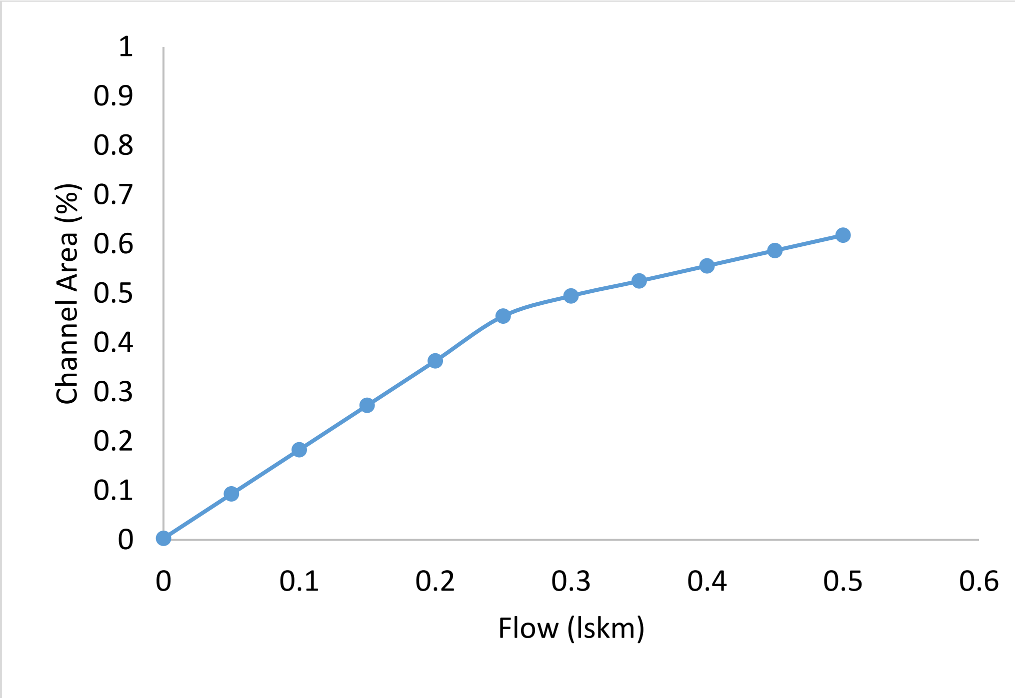


Figure 1.2.29: Community rating curve.

The rating curve was used to calculate habitat time series for multiple scenarios. To compute reference habitat model reference conditions, we used the flow time series calculated with climate change models combination used in the River Vistula case study (for further explanation see chapter A2.3.6 Materials and Methods, Habitat time series analysis). To take into account potential impact of water withdrawals in the watershed, the flows were modelled for the area upstream of the reservoirs. This was to reduce the impact of potential water withdrawals included in the model as well as of flattening of the rating curve. Habitat time series were analysed with UCUT technique and the result is presented below (**Figure 1.2.30**).

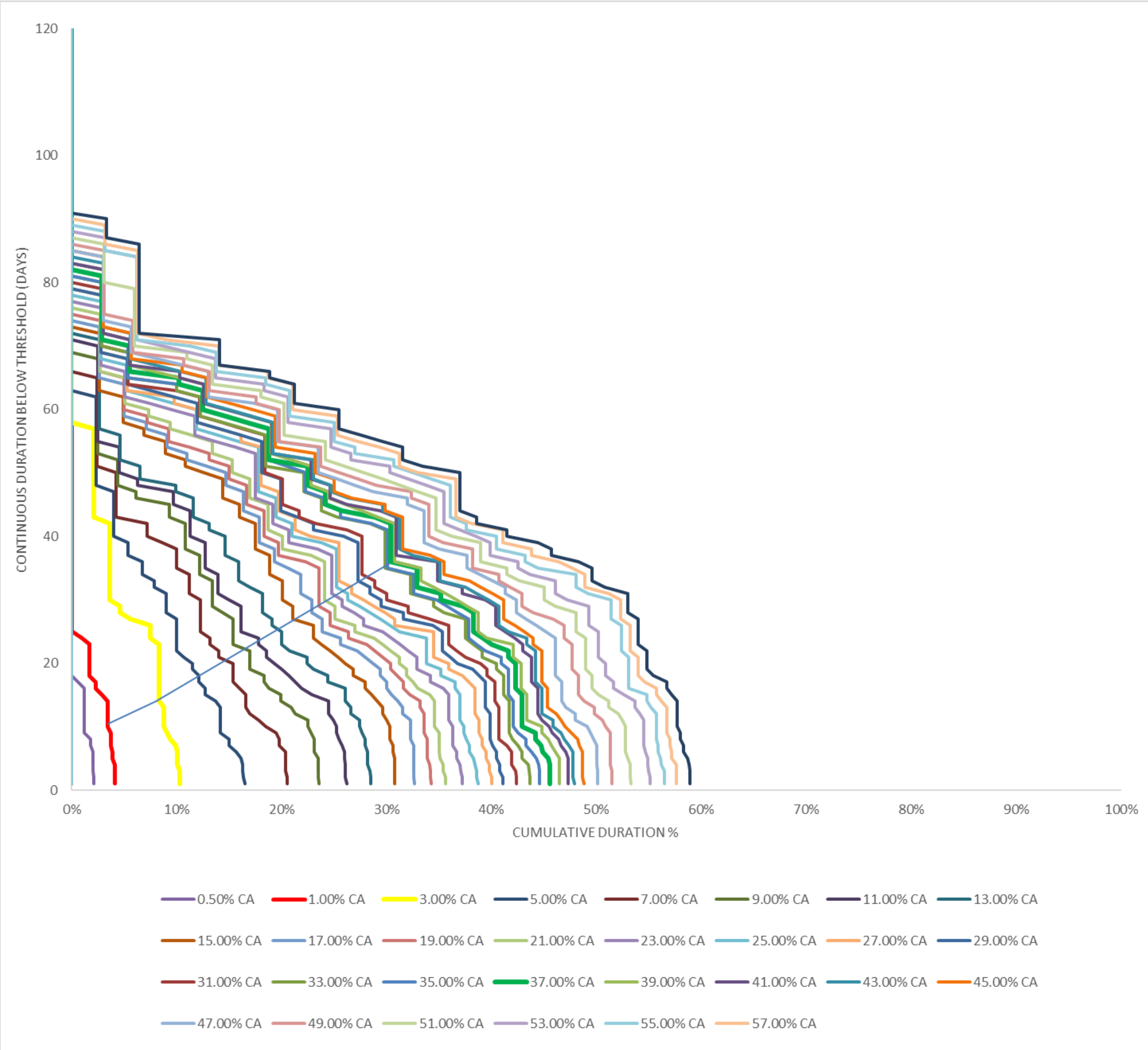


Figure 1.2.30: UCUTs for reference conditions. The blue broken line connects the persistent duration thresholds.

From the UCUT diagram for reference conditions, three habitat thresholds are selected rare, critical and common with 1%,3% and 37% of channel area as suitable habitat respectively. The threshold to peristent duration days is annotated on **Figure 1.2.30**. Catastrophic durations and flows corresponding with the thresholds are presented in **Table 1.2.6**.

Table 1.2.6: represents flow management criteria for the River Guadalhorce at location of gauge 46. Elaborated by SSIFI.

River	Guadalhorce
Rearing and growth	VI-VIII
Gaging station	46
watershed area (km2)	1860
Common habitat (%CA)	**37**
Allowable duration under (days)	35
Catastrophic duration (days)	65
Habitat base flow (lskm)	0.247
Habitat base flow (m^3s-1)	0.459
Critical habitat	**3**
Allowable duration under (days)	14
Catastrophic duration (days)	39
Trigger flow (lskm)	0.016
Trigger flow (m^3s-1)	0.030
Rare habitat (%CA)	**1**
Allowable duration under (days)	11
Catastrophic duration (days)	17
Subsistence flow (lskm)	0.0046
Subsistence flow (m^3s-1)	0.009
Abs. Minimum (lskm)	**0.00**

Scenarios

The results in **Table 1.2.6** are applied for comparing the impact on fish habitat in varioius scenarios. Scenario 1 represents past conditions is uses the observations recorded at gauge 46, over 38km downstream of the reservoirs between the River Grande discharge and the final stretch of the river. Scenario 2 uses the same data but applies criteria developped in **Table 1.2.6** to simulate releasing water from reservoir when allowable duration is exceeded. In such a situation, the flow is increased to the level of the next threshold (for example, from subsistence to trigger) for a duration of two days. For the schematic example see **Figure 1.2.31**. Scenario 3 simulates minimum flow policy where flows are never lower than 300 l/s. Scenario 4 is a climate change scenario for reference conditions based on the upstream (Archidona gauge 130) location and scenario 5 is a climate change scenario using historical flow time series from gauge 46. Scenarios 6 and 7 are combinations of scenarios 2 and 3 with scenario 4 (i.e. introducing climate change).

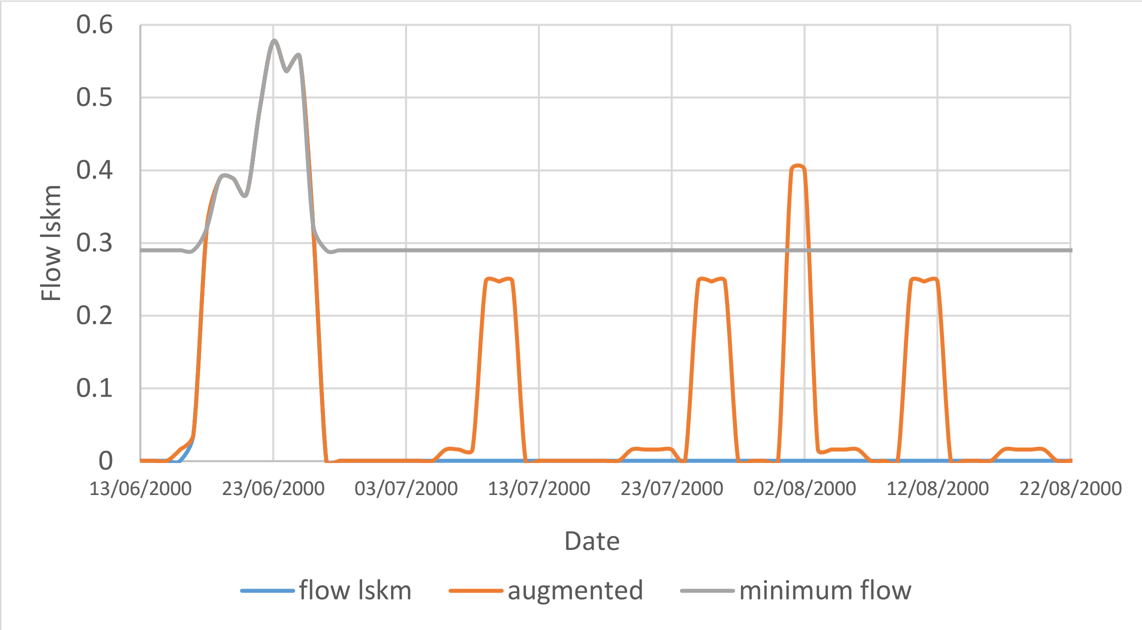


Figure 1.2.31: Simulation of flow scenario 2 and 3 on the example of summer 2000.

To create these two scenarios, the proportion of habitat stress days occurring on gauge 46 was increased by number of stress days occurring at the reference flows (i.e. scenario 4). For scenario 6 (minimum flow of 300 l/s), only the change of the common level threshold was raised by the habitat stress days occurring at the climate change scenario for the reference.

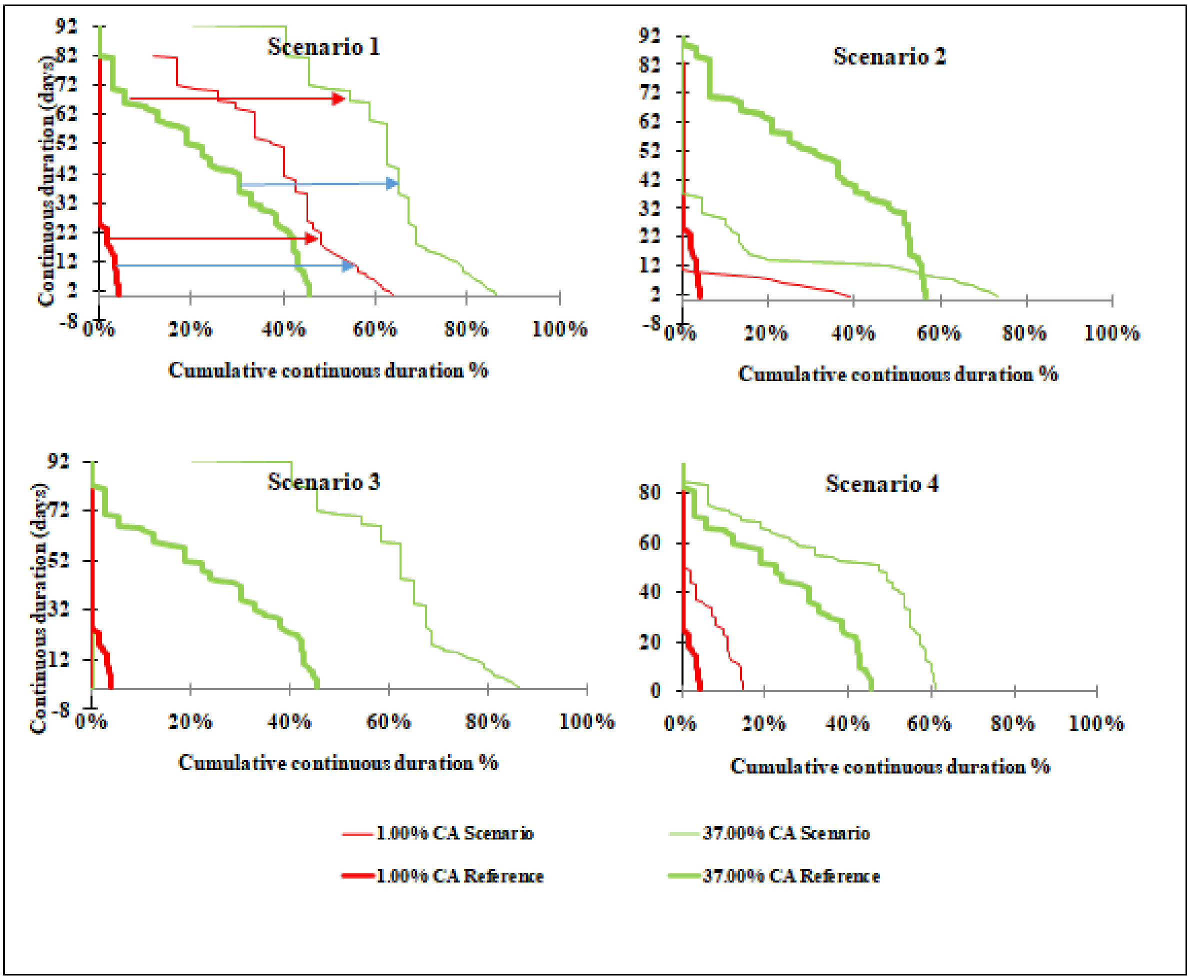


Figure 1.2.32: Comparing UCUT curves for rare and common habitat thresholds for 4 scenarios.

Figure 1.2.32 demonstrates the UCUT curves for rare and common habitat thresholds for each of the tested scenarios. The shift of corresponding curves to the right indicates an increase of frequency of events when habitat is lower than the threshold. The blue arrows in the Scenario 1 diagram indicate where the increase of stress days is measured (lowest persistent duration).

The red lines represent an increase of stress days at a catastrophic duration. The sum of averages of these values is used as a metric for scenario comparison at an RAA diagram (**Table 1.2.7**). As visible on these figures, for scenario 1 there is sharp increase in frequency of habitat stress days for the rare conditions and for common level. Compared to the current situation in scenario 2, the augmentation sharply lowers the number of events of persistent and catastrophic durations at the cost of higher frequency of short lasting events. In scenario 3, introducing minimum flow removes stress days for rare conditions, but for common thresholds, frequencies remain as in scenario 1. At scenario 4, increases in stress days are observed, but mostly for catastrophic durations.

Table 1.2.7: Average increase in the number of stress days for each scenario at both levels of disturbance.

Simulated scenario	description	persistent	catastrophic	sum
Scenario 1	present conditions	820%	1314%	2134%
Scenario 2	present conditions dynamic augmentation	3%	0%	3%
Scenario 3	present conditions + minimum flows of 300l/s	120%	246%	367%
Scenario 4	climate change reference	290%	358%	647%
Scenario 5	climate change+ present conditions	1110%	1672%	2782%
Scenario 6	climate change + dynamic augmentation	3%	0%	3%
Scenario 7	climate change + minimum flow	66%	192%	258%

To compare all the above scenarios demonstrates an RAA diagram for the River Guadalhorce (**Figure 1.2.33**). It is clear that current flow management creates substantial stress to aquatic fauna, which will be further exacerbated by climate change. However, since habitat structure does not deviate strongly from expected conditions, this problem could be alleviated by an appropriate flow release strategy.

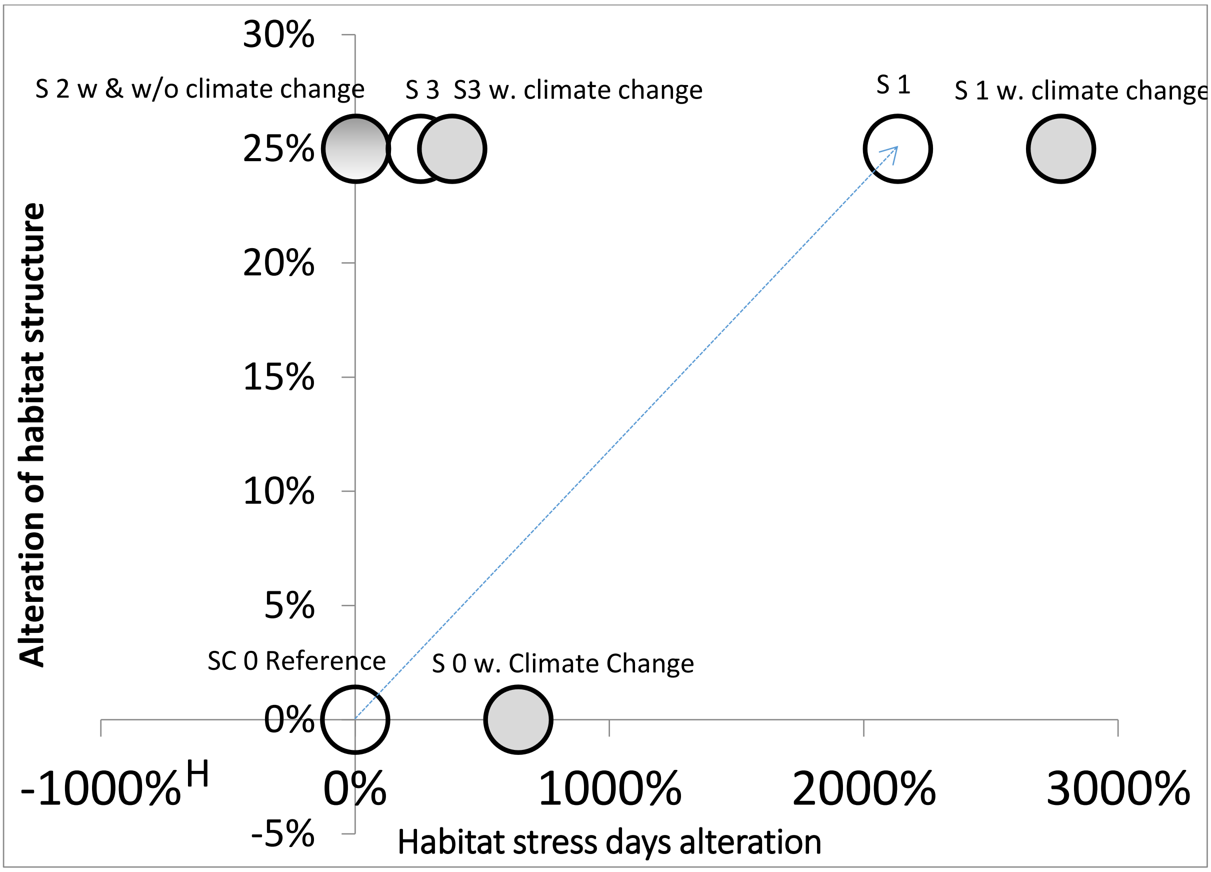


Figure 1.2.33: 7 point RAA diagram for analyzed scenarios including climate change estimates. The stress days values represent the sum of average stress days increase for each scenario.

Currently, the flows in the river downstream of the El Chorro Dam are erratic and large parts of the river are diverted dry during the summer season. Introducing an ecological flow strategy that refers not only to dam releases, but requires specific flow in the river at it entire length, would be the most appropriate management. Out of the two presented environmental flow strategies, the dynamic flow augmentation as presented in Scenario 2 accomplishes best results with lower augmentation cost. This is because the flow augmentation needs to be offered only when flows are lower than selected duration thresholds.

The results presented here demonstrate a relatively easy adaptive management strategy, which needs to be verified with more solid databases. This will also allow for better fine tuning of the proposed augmentation approach.

A.1.2.14 Symposium on fluvial connectivity in Andalucia Mediterranean Basins. Conclusions on the case study

On September 3 2019, AEMS organized the workshop on River Connectivity in Mediterranean Basins in Malaga with the collaboration of the University of Malaga (UTC-UMA), the municipality of Málaga, and the regional government of Andalucía. The meeting brought together different experts in planning management, conservation, and restoration of inland aquatic ecosystems to research centres and projects as well as members of the AMBER consortium and other stakeholders at a regional and local level.

The in-depth program focused on the River Guadalhorce as a practical example, with a focus on ecological status, environmental issues and management, conservation and restoration initiatives, and plans in the Mediterranean river basins.

The symposium included a guided morning tour, with stops at different points of interest along the Guadalhorce basin from its head to the mouth, as well as an afternoon workshop. The workshop was held at "La Térmica" of Málaga, and the topics discussed included ecological state, environmental problems and management, conservation and restoration initiatives, and plans in the Mediterranean river basins.

The symposium had the direct participation of the technicians responsible for the Guadalhorce management system. They accompanied the group to the visit of the Guadalteba Dam, where the group learned about the dam infrastructure and the main aspects of the basin and its natural environment. Moreover, the group could discuss the problems present in the basin with different stakeholders, from management technicians and managers to organizations for the defence of the natural environment and environmental associations. Finally, managers and participants of other projects related to water management shared their experience and results with the attendants.

The participation of representatives of the Network of the New Culture of Water in Andalusia highlights the latent social conflict over the use of water in the Guadalhorce basin. Salvador Sánchez (Platform in Defense of the River Grande and the Jara Environmental Association) informed the participants about the social conflict that arose in the early 2000s as a result of the project for construction of a dam on the River Grande (Coín, Málaga) to divert water supply to the capital (**Figure 1.2.34**). The project was considered to have a severe environmental impact on the River Grande ecosystem (currently not regulated by large dams). It would imply the alteration of the natural flow regime, the drastic decrease in water circulating through the channels, the physical-chemical alteration of the water quality and the morphology of the channel and the river bed, reduction of the flood plain, with significant alteration of river habitats and biological communities, etc. and various socio-economic impacts associated with the deterioration or loss of infrastructure or artefacts of the traditional hydraulic heritage, the degradation of landscapes and the loss of knowledge, traditions and practices associated with the natural river.

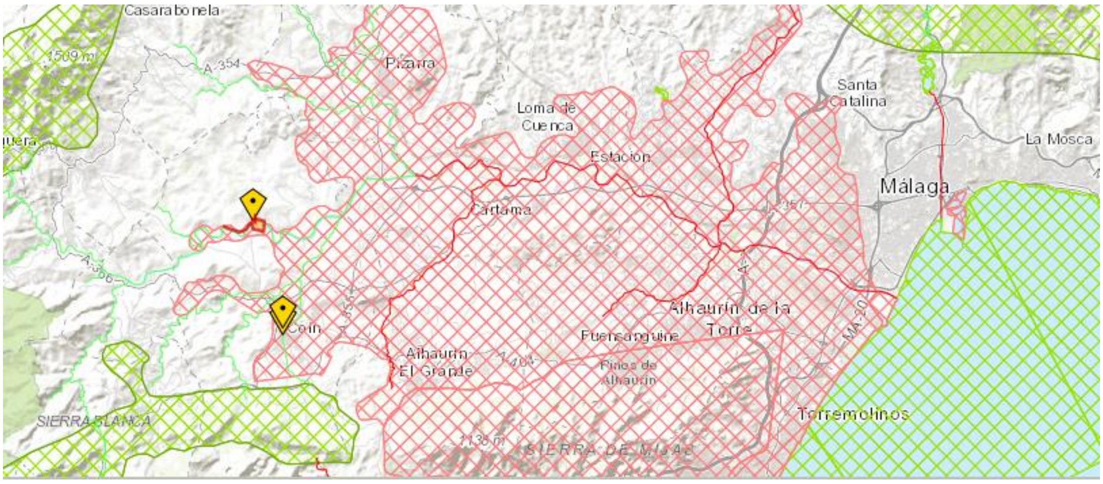


Figure 1.2.34: Location of projected barriers and associated infrastructures in the Grande River. Collaborative map of water conflicts in Andalusia. For more information see: https://redandaluzaagua.org/mapa/reports/view/13

The project was promoted by the state and autonomous administrations. In the affected populations, Guaro, Coín, Pizarra and Cártama, there was a majority reaction against it, led by local and citizen entities. There were massive social mobilizations, dissemination in the media and social networks, information and awareness campaigns, citizen meetings and encounters. All these escalated into increasing social tension and resulted in fines and arrests. Among the forms of mobilization, independent studies and reports were prepared, letters, official petitions and complaints were sent to the authorities involved, there were artistic and recreational actions, occupation of public spaces or buildings, protests and street demonstrations and traffic cuts and strikes. The alternatives proposed by civil society and/or the social organizations involved mainly focused on the management and control of water demands through different systems.

The response of the administrations to this conflict was finally the moratorium or temporary suspension of the project. However, currently, there are still sectors that ask it to be raised again.

The symposium provided an arena to discuss the different situations that could be faced in the future, taking into account the importance and additional interest in the study of Mediterranean basins in the current climate change horizon.

Figure 1.2.35: Program of the Symposium..

Figure 1.2.36: First visit during the symposium to Guadalteba Dam, where the staff provided an in-depth explanation of the characteristics of the basin and the water management system.

The results obtained in this case study were presented in a public workshop held in September 2019 in Malaga, before the annual AMBER meeting. Attendants represented the main sectors involved in river management and use. Local stakeholders that have networked and collaborated with AMBER researchers helped in the organization of the workshop (**Figure 1.2.37**– Christoph Schröder, collaborator for the study case presents SWOS work within the Guadalhorce basin).

Figure 1.2.37: Christoph Schröder, collaborator for the study case, presents SWOS work within the Guadalhorce basin at La Térmica, Málaga (Spain).

The Symposium included interventions on government plans that constitute the institutional framework where adaptive management should be developed; Rocío Navas, from the Office of Hydrological Planning - Environment and Water Agency of the Andalusian Government - spoke of the Hydrological Plans as an instrument for the achievement of the Environmental Goals of water bodies Hydrographic Demarcation. The current Spanish legislation is recognizing the dimension of the river fragmentation problem through establishing the restoration of fluvial ecological continuity as an essential objective. To do so requires government agencies to promote the longitudinal and lateral continuity of the river courses, making them compatible with current uses and existing infrastructures, the installation and maintenance of devices ensuring the passage of native ichthyofauna, the elimination of abandoned Hydraulic Public infrastructures without fulfilling any function linked to water use, and taking into account the possible conditions for the transport of sediments in the granting of new transversal works.

The morphological alteration and ecological fragmentation due to transversal barriers are still not clear and contemplated explicitly among the direct causes of non-compliance with the environmental objectives of achieving the good condition of the water bodies of the Demarcation. However, the hydrological alteration caused by the regulation of the flow regime from the dams is recognized as a significant pressure (**Figure 1.2.3a**).

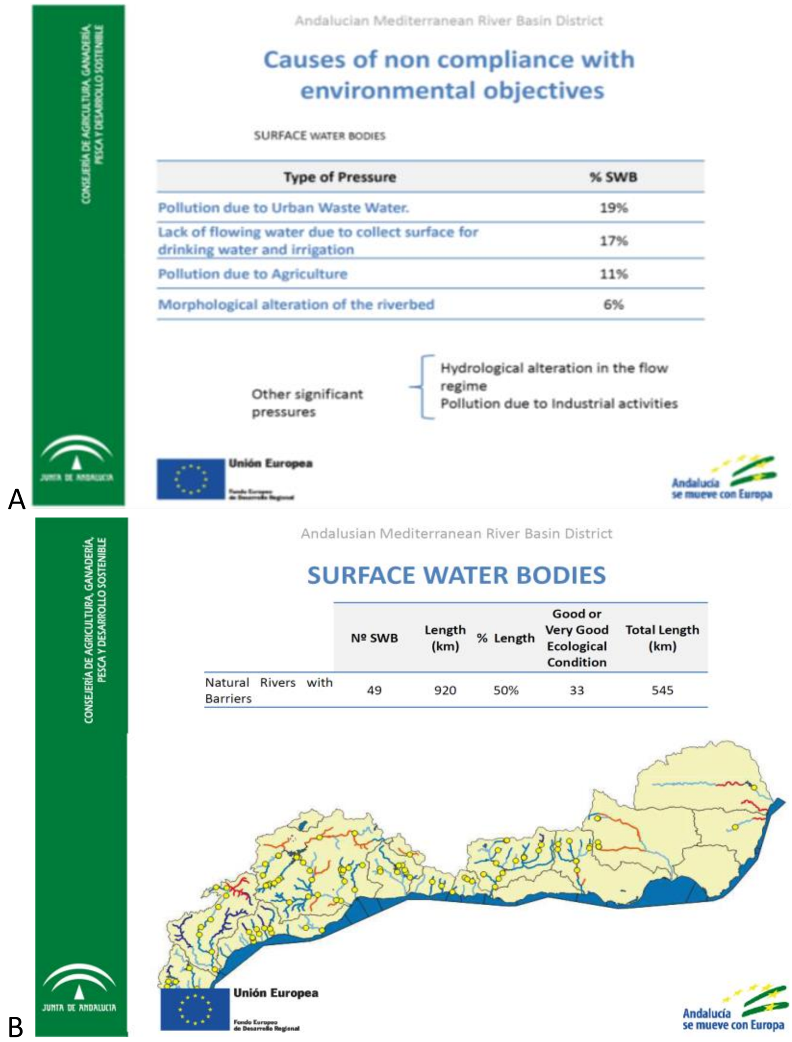


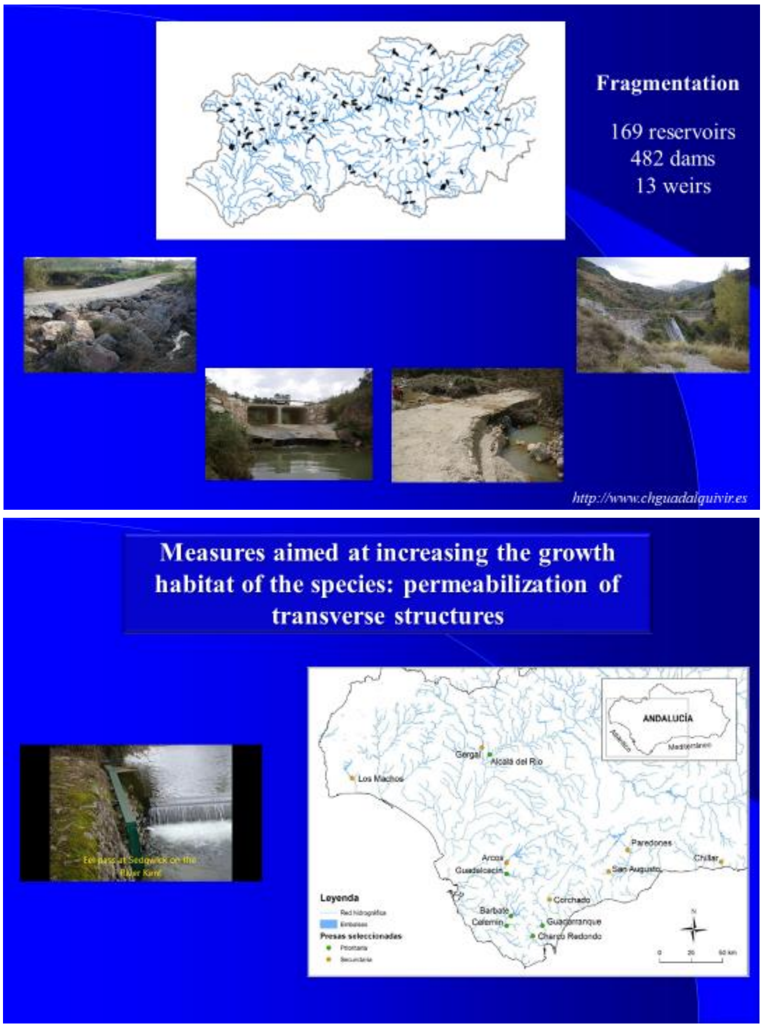
Figure 1.2.38 A,B: A- Causes of non-compliance with the environmental objectives of hydrological planning in the Mediterranean basins. B- Natural rivers with barriers and ecological status of the Demarcation's water bodies.

Out of the rivers with barriers in this Demarcation, 49 bodies of water are defined, which represent a fluvial length of 920km. These water bodies represent 50% of the total of this river length. Of these 49 water bodies, 33 are considered to be in good condition, which represent a fluvial length of 545km. (**Figure 1.2.38**). The transverse alterations due to the presence of barriers are considered one of the most critical anthropic pressures in the entire Demarcation. Except for the headwaters, which donot have significant pressures registered, the water bodies of the basin share an extensive list of pressures that in many cases are associated with the multitude of existing and in-use barriers (for hydroelectric energy production, irrigation or supply –especially from the city of Malaga and its surroundings), as well as some in disuse.

Other pressures are the extraction and contamination of the water by point sources - urban wastewater discharges - or also diffuse - irrigation returns - that occur on the axis of the Guadalhorce and the main tributaries. These pressures increase from the high area towards the mouth. The alteration of the habitat by regulation and extraction of water interacts with contamination by nutrients or chemicals, intrusion and salt contamination, especially in the middle and lower areas of the basin. In turn, these habitat alterations also contribute to some other relevant pressures such as the acclimatization of non-native species of flora and fauna.

In any case, the next hydrological plan should include in the Programmes of Measures, as one of the environmental objectives, the recovery of longitudinal ecological connectivity in the surface water bodies of the Demarcation as well as actions intended for it.

Carlos Fernández Delgado –University of Córdoba- spoke about the Recovery Plan of the European Eel in Andalusia, undertaken by the regional government as a result of Regulation EC 1100/2007. Indeed, one of the main problems of migratory fish and specifically of eel in these basins is fragmentation by transverse barriers and loss of growth habitat. Apart from the Mediterranean basins, the scope of this plan includes the Guadalquivir basin, where 169 reservoirs, 482 dams and 13 weirs have been inventoried, in addition to many other barriers associated with tubes or frames under roads, fords, etc. The plan evaluated the frangibility of the inventoried obstacles for the eel by identifying some critical barriers whose permeabilization is considered a priority.



A

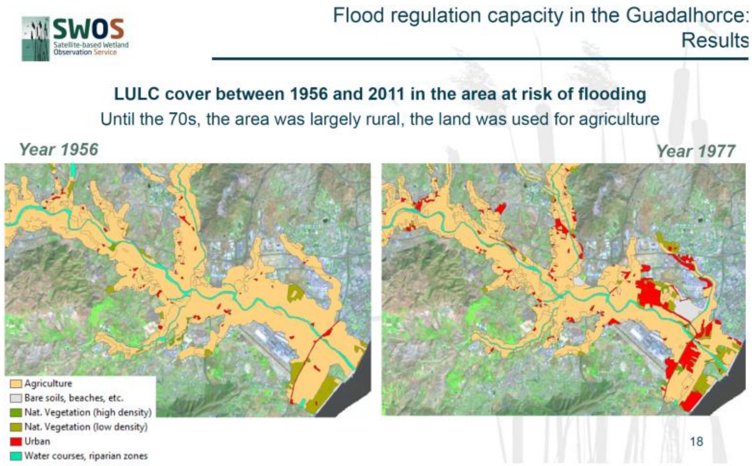
B

Figure 1.2.39A,B: A- fragmentation and barriers in the Guadalquivir basin. B- Measures aimed at increasing the growth habitat of the species: permeabilization of transverse structures.

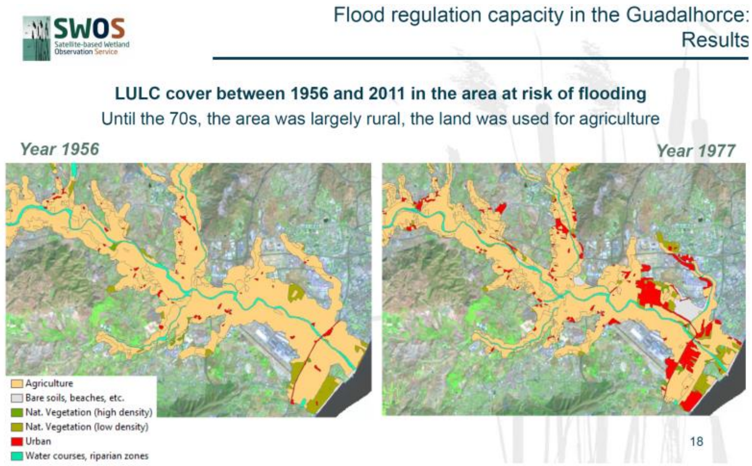
For the recovery of the habitat of growth of the eel in this river, it is necessary the permeabilization of the barrier “Paredones dam”. This dam, located in the middle section of the river, it is used for the collection of flows that supply Malaga city and its surroundings.

Christoph Schröder (University of Malaga) focused on the relationship between surface waters and wetlands. He presented the results of the SWOS project, dedicated to mapping these ecosystems and studying their ability to regulate flooding in the Guadalhorce basin. The main objective of the project is to support flood protection measures with a spatially explicit indicator of flood regulation capacity for the river basin. Based on the functional retention capacity of the ecosystem, in this case of wetlands, the production of the flood regulation service it provides and the benefit thereof are calculated.

The advance of knowledge and experience shows that a strong regulation of large reservoirs does not reduce the risk of flooding in the long term (for low recurrence events). On the other hand, this regulation causes false security, which contributes to the exponential growth of land occupation in flood areas. In the end, this implies an increase in exposure to the risk of flooding, especially in the area of the mouth, with the consequent increase in demand for the regulatory service.



A



B

Figure 1.2.40 A,B: The SWOS map of land use and coverage between 1956 and 2011 in the surroundings of the lower Guadalhorce shows that until the 1970s the area was mostly rural, with mainly agricultural land use, and how in the following decades the urban agglomeration of Malaga and the nearby populations are gradually occupying the area at risk of flooding.

From CEHIUMA, José Manuel Nieto López presented some of the projects underway in the area of the mouth of the River Guadalhorce. These projects are aimed at restoring wetlands and the recovery of associated ecosystem services such as reception and tertiary treatment of the effluents treated in the sewage treatment plant.

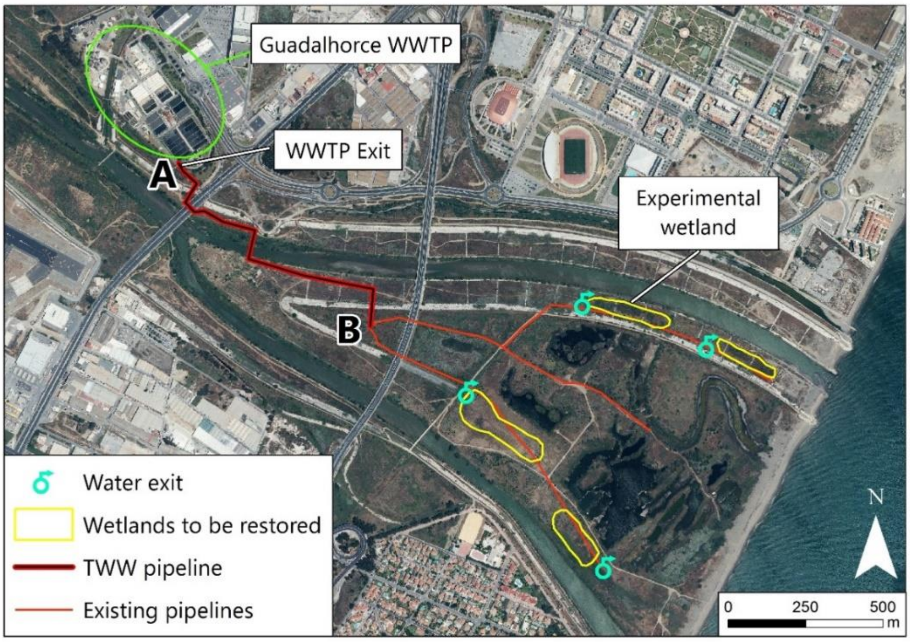


Figure 1.2.41: Application area of the wetland recovery project in the area of the mouth of the Guadalhorce.

The interventions of Eduardo Dopico from the University of Oviedo inaugurated the program section on the case study of the River Guadalhorce in the framework of the AMBER project. Eduardo focused on summarizing the work carried out on the field through the application of the AMBER tools such as the environmental DNA and reservoir perception survey.

AEMS - the organizing entity of the event- concluded the Symposium, with the intervention of Sara Garrido, who described the work carried out by this organization within the case study. This intervention focused on the field validation of the inventories of barriers. With the collaboration of IRS and ERCE teams from Poland presented as well the fieldwork and some results of the application of the MesoHABSIMAMBER tool.

Finally, as a spokesperson for the Symposium, Sara summarized the three main problems detected concerning the ecological connectivity of the Guadalhorce basin and proposed possible actions for adaptive management.

In summary, three main problems about river connectivity in Guadalhorce basin could be highlighted:

I. Structural alteration by regulation from the large reservoirs: The Guadalhorce is a particular case of a fully regulated river with four dams. The uses of these barriers are (in priority of use): supply, irrigation and hydroelectric. According to hydrological planning, there is a resource deficit. The establishment of an environmental flow regime is complicated and conflictive.
II. Presence of other transverse barriers downstream: These are smaller structures for water extraction, pass of vehicles, etc.
III. Transversal / vertical connectivity in the mouth area: We find the original layout and the contours of flooding altered by channelling, waterproofing of the channel and banks. Relationship between the three axes of river connectivity (longitudinal, transverse and vertical).

In turn, the AMBER proposal for possible adaptive measures are:

I. Structural alteration by regulation from the large reservoirs: Reduction of consumption and derivation of water, environmental flow regime. Demand management.
II. Presence of other transverse barriers downstream: Elimination of barriers not in use, permeabilization of barriers in use, improvement of environmental flows downstream of extractions.
III. Transversal/vertical connectivity in the mouth area: Renaturalization of riverbanks, rehabilitation of natural flood zones, buffers.

The set of interventions highlighted the need to improve river connectivity in all its three axes, vertical, transversal or lateral and longitudinal. This connectivity in its three dimensions must be considered in a comprehensive river management strategy that would allow progress to be made in achieving a good ecological status. The strategy should consider the need to recover associated ecosystems, such as wetlands and coastal waters. As a result of this integration, the resilience of the entire system would increase, and the risk of extreme events would be reduced. This is a crucial factor in terms of droughts and floods, which in this area of the Mediterranean will acquire more and more virulence with global climate change.

The exposed projects and their conclusions are very relevant to question the persistent demand for the construction of new reservoirs among users of the water resource and in public opinion. Despite the advances made in knowledge and legal instruments and in light of the experience with floods, in numerous political and user forums in Spain, regulating the flow of water from large dams, in general, is still considered to be the only solution possible for flood control. However, from the perspective of comprehensive and adaptive management of river basins, it is very evident that these long-term strategies do not give the expected results and not only do they not prevent floods, but instead contribute to increase the risk that entails. In Spain, especially in the basins with the most significant scarcity and water irregularity, there is still a large gap between the persistent demands of the sectors that use water and the flood zones - with the political speeches that reflect them - and the latest regulatory advances in flood planning and management in light of decades of experience and knowledge.

A.1.2.15 Actors and AMBER experts collaborative work on the study case.

The symposium held in Malaga in September 2019 brought together experts in river management (some, members of the AMBER project) with agents involved in the case study. During the day, the experts received complete information about the case study and had the opportunity to contact the different agents who explained their perspectives on the case. As part of the collaboration between the AMBER project teams, experts were asked to contribute to the case from their perspective and in their specific field. The experts who contribute to this section are Carlos García de Leániz (Swansea University), Jim Kerr (University of Southampton), Lucio Marcello (University of the Highlands and Islands), Zbigniew Kaczkowski (European Regional Center for Ecohydrology, Academy of Sciences of Poland) and Arjan Berkhuysen (World Foundation for Fish Migration).

All experts agree that the implementation of a real long-term integrated water management strategy is necessary, while identifying possible changes in the short and medium-term. If skills are scattered, the ecological function is in jeopardy. Some ideas related to this were suggested, considering ecological service as one of the critical aspects to integrate into water management policy:

1. Integrate different pressures through various scales in the basin. Not only identify the demands and pressures on the water bodies but define and prioritize environmental objectives and indicated measures to address them.
2. Identify key target areas.
3. Vary flow regimes to test what flows ecosystem services can maintain (empirically)
4.. Map ecosystem services and run simulations (what-if scenarios)
5.. Make projections with different climate change scenarios.
6.. Calculate fragmentation metrics
7.. Evaluate the costs and benefits of each dam
8.. Prioritize areas/scopes for restoration and test the potential benefits for society
9. Consider a "water tax" as part of a water audit scheme for Malaga.

In this sense, the experts highlighted the need for a direct contribution to advise on the water management plan instead of just collecting data and facts, since that in itself does not constitute adaptive management, as well as identifying more exhaustive evaluations of the seed, past (and current trends) by analyzing historical dam management changes, to track evolution so far and possible future directions.

It was clear that a key part of the basin's artificial nature is the need to supply irrigation water. In this sense, the suggestions are diverse. Perhaps the effort should focus on switching crops to less thirsty varieties. Hopefully, this would reduce the demand for irrigation and thus allow more scope for better adaptive management of the rivers in the basin. A reduction in demand may mean that one of the larger dams could be phased out, which would provide a more natural hydraulic regime and increase the available habitat for key species (i.e., improve connectivity). This restored river could be used as a focus for future restoration efforts and, ultimately, offset the negative effects on the remaining two highly fragmented rivers.

Considering the saline nature of one of the headwaters, other proposals are related to developing saline crops, adapting to the existing environmental situation, instead of adapting the environment to the existing freshwater needs of current crops, since crops tolerant to the saline solution can take up to 30g per litre.

Finally, the participation and integration of actors and citizens was also highlighted as a key point for adaptive management of barriers, both when it comes to alternative proposals for water irrigation, reuse of water or water policies for agree on a schedule and parameters or requirements, or concerning recreational function areas in the estuary that allow for more natural floodplains compatible with the social use of the area.

A1.2.16 Possible AMBER projection for future Guadalhorce River dam management

The application of the respectful and environmentally responsible AMBER strategies for river management, under the slogan *Let It Flow*, is especially important in the lower reach of the River Guadalhorce. The Guadalhorce wetland, situated in this place, is a Special Protection Area (SPA) for migratory birds and it is essential to highlight its dune vegetation. It contains species that are almost extinct from other littoral places of the region, as *Medicago marina*, *Polygonum maritimum*, *Otanthus* *maritimus*, *Pancratium maritimum*. On the other hand, invasive species are present in this part of the river. Within this group of biological nuisances we can find, for example, *Galenia secunda*, *Ricinus communis*, *Pittosporum* sp., *Oxalis pes-capraa*, *Eucalyptus camaldulensis*, *Arundo donax*. Besides that, this place has a variety of native birds, reptiles and amphibians. For all these reasons AMBER should have a continuity there.

The results obtained applying AMBER tools show that the local population is generally favourable to the presence of dams and reservoirs and that these provide valuable ecosystem services in this region. The importance of river connectivity has been highlighted. The differences between better conserved upstream sites and the sites affected by dams that contain more species potentially harmful for humans were presented and discussed. The construction of passages for aquatic organisms to pass the dams and reconnect populations along the River Guadalhorce has been proposed for further discussions. The idea of networking with citizens of other regions affected by dams, for example, the Upper River Nalón, has been proposed for extending AMBER benefits beyond the project life.

AMBER researchers have contributed in this case study to spread the message of AMBER using an interdisciplinary approach that combines environmental analysis, biological study including eDNA and other measures, and a social approach based on participatory management – in this case producing objective data about the real impact on biotic connectivity and the social acceptance of dams, and sharing data and outreach of AMBER results with local stakeholders and public. Hopefully, the results of this case study will help to give more value to aquatic ecosystems and river connectivity in dry European landscapes such as Mediterranean basins.

This contribution may be more significant in a region such as the Andalusian Mediterranean basins, where water is scarce and irregular, where, with current legislation and socio-economic developments and on the horizon of accelerated climate change, the adaptive approach should prevail over old strategies to continuously increase the supply of water through large and expensive hydraulic infrastructures.

A2. BARRIER MITIGATION

A2.1 CASE STUDY 3: Poutès Dam, River Allier

The ability to produce electricity has altered the ecological situation extensively in the Allier river system, especially with the advances in engineering which have slowly allowed the construction of larger dams. Tens of thousands of large dams have been built in almost all major rivers in the world (Grill et al. 2019) in an impressively short period of time. This very rapid development of hydropower plants on all large and small rivers has had major consequences including, among other things, the disappearance and decline of many populations of migratory fish. A prime example of this ecological, cultural and economical disaster is the situation of the Atlantic salmon population on the River Rhine which went from approximately 1 million individuals to near zero following the installation of artificial barriers during the 19th century.

A2.1.1 Atlantic salmon

Atlantic salmon (Salmo salar) is a famous anadromous species, with both juveniles (smolts) and adults undertaking long migrations between freshwater and marine habitats. Unfortunately, the species has undergone a general decline. Recruitment of the European stock has been divided almost three-fold (from 8 to 3 million) since the early 1970s (Friedland et al. 2009). River fragmentation is frequently reported as the main cause of this decline (Lucas and Baras 2001, Thorstad et al. 2008, Limburg and Waldman 2009).

When migrating to marine habitats, smolts can encounter hydroelectric facilities and thus suffer direct or delayed mortality when passing through the turbines (Pracheil et al. 2016, Thorstad et al. 2017). Moreover, dams can also cause migratory delay that can elevate the energy cost of migration, expose fish to predation and reduce passage success (Marschall et al. 2011, Gauld et al. 2013, Nyqvist et al. 2017a). Additionally, decreased migration speed can decrease smolt survival when migration timing and optimum environmental conditions in rivers, estuaries and the coastal environment are out of phase (McCormick et al. 1998, Thorstad et al. 2012). In the context of climate change, the need to restore longitudinal connectivity is all the more crucial (Jonsson and Jonsson 2009, Isaak et al. 2015). Shifts in the phenological periods of migrations are already being observed (Jonsson and Jonsson 2014, Otero et al. 2014), and delayed migration may adversely affect the long-term survival of the salmonid population (Crozier and Hutchings 2014, Morita 2018).

Remedial measures for both upstream and downstream migration, such as fishways, have been implemented for a long time, and their rate of construction has increased in recent decades (Silva et al. 2018). More specifically, solutions exist for downstream migration of smolts, but have only been implemented more recently (Larinier and Travade 2002): for example, stopping fish at the intake rack before guiding them toward a surface bypass (Larinier and Travade 2002, Nyqvist et al. 2018). Recent tests on fine-spaced low-sloping racks showed good effectiveness (Tomanova et al. 2017, Nyqvist et al. 2018, Tomanova et al. 2018). Other solutions using behavioral systems to guide fish have been tested, but no clear solution easily applicable to various locations has been determined (Williams et al. 2012).

Implementation of passage solutions in large installations is complex and expensive (Larinier and Travade 2002). This is why other active solutions, such as trap and transport or turbine modulation/shutdown during migration peaks, are sometimes considered to mitigate the impact of dams (Thorstad et al. 2012, Stich et al. 2015, Teichert et al. manuscript submitted for publication). Mitigation measures need a precise forecast of migration timing, on the basis of calendar dates or using environmental records, in order to limit the impact on hydropower generation (Teichert et al. manuscript submitted for publication). Smolts typically migrate to the ocean in spring. “Smoltification” is controlled by photoperiod and temperature, with migration onset triggered by temperature and sometimes by discharge (McCormick et al. 1998, Thorstad et al. 2012, Nyqvist et al. 2017b), especially when river flow peaks occur at the beginning of the migration season (Whalen et al. 1999, Otero et al. 2014, Teichert et al. manuscript submitted for publication).

A2.1.2 The Poutès dam

Poutès dam is located in the upper River Allier (France), the main tributary of the River Loire. This river is of great importance for Atlantic salmon, as it includes the most functional spawning zones of the Loire River basin (Baisez et al. 2011), especially in the area of the Poutès dam. The dam was built in 1941 and constituted a total barrier to migration until 1986. Fish passage solutions for upstream (in

1986) and downstream migration (in 1987) were then implemented and progressively improved from 1986 to the early 2000s. However, a number of problems remained: migratory delay for upstream and downstream migration and difficulty in using the fishways.

When the Poutès-Monistrol hydropower complex was relicensed in 2011, and after several years of concerted discussions between the French authorities, the hydropower company EDF, local representatives and environmental protection associations, it was decided to reconfigure the Poutès dam. Objectives were set to maintain hydropower production while meeting ecological connectivity requirements (for sediment and fish). These objectives were supported by an ambitious scientific program to monitor the ecological benefit of the reconfiguration. As a first step, this scientific program helped to assess the impact of the Poutès dam on smolt migration before reconfiguration. This impact was quantified (Tétard et al. 2016a, Tétard et al. 2019), showing passage efficiency of 66% and significant median reservoir of 9.3 days (less than 23.6 days for 75% of smolts).

The beginning of construction, which was to start in 2016, was postponed to summer 2019, and temporary measures during smolt migration were proposed as early as 2017, pending the beginning of the reconfiguration.

These proposed measures were discussed with stakeholders and aimed to improve passage efficiency while minimizing residence time in the reservoir. To decrease migratory delay in the reservoir, it was proposed to lower its level by 5.5m so as to decrease its length by 70% (3.5 to 1km). As the original bypass entrance was nonfunctional at this level, a new bypass design was proposed to allow smolt migration toward the bypass stretch. To increase passage efficiency, it was proposed to modulate turbine operations for 20 nights, by setting a minimum bypass discharge ratio in a predetermined range of river flow to prevent smolts entering the turbines. To assess the efficacy of these proposed measures, a 2-year telemetry experiment was conducted as part of the European Union's Horizon 2020 AMBER project. These temporary measures were discussed and adapted with the stakeholders, through a structured iterative process of "learning by doing". Consequently, the temporary measures were improved after the 1st year of experimentation. The objective of the present study is to give a comprehensive assessment of successive measures taken to improve smolt migration at the Poutès dam. As measures were chronologically decided thanks to acoustic telemetry results, the report will present 2017 and 2018 results successively before discussing more global implications for smolt migration in the final section.

A2.1.3 Material and Methods

Study area

The River Loire (**Figure 2.1.1**) is 1,012km long and has a drainage area of 117,000km². It is the longest river system in Europe in which spawning migration of Atlantic salmon still occurs (Cuinat 1988). The River Allier , its main tributary (**Figure 2.1.1**), represents the main migration axis, with high-quality habitats for salmon reproduction (Baisez et al. 2011). The Poutès dam is located 861km from the estuary (**Figure 2.1.1**), in a crucial zone for the salmon population: areas upstream of Poutès represent about 60% of the potential juvenile production of the Allier River (Minster and Bomassi 1999).

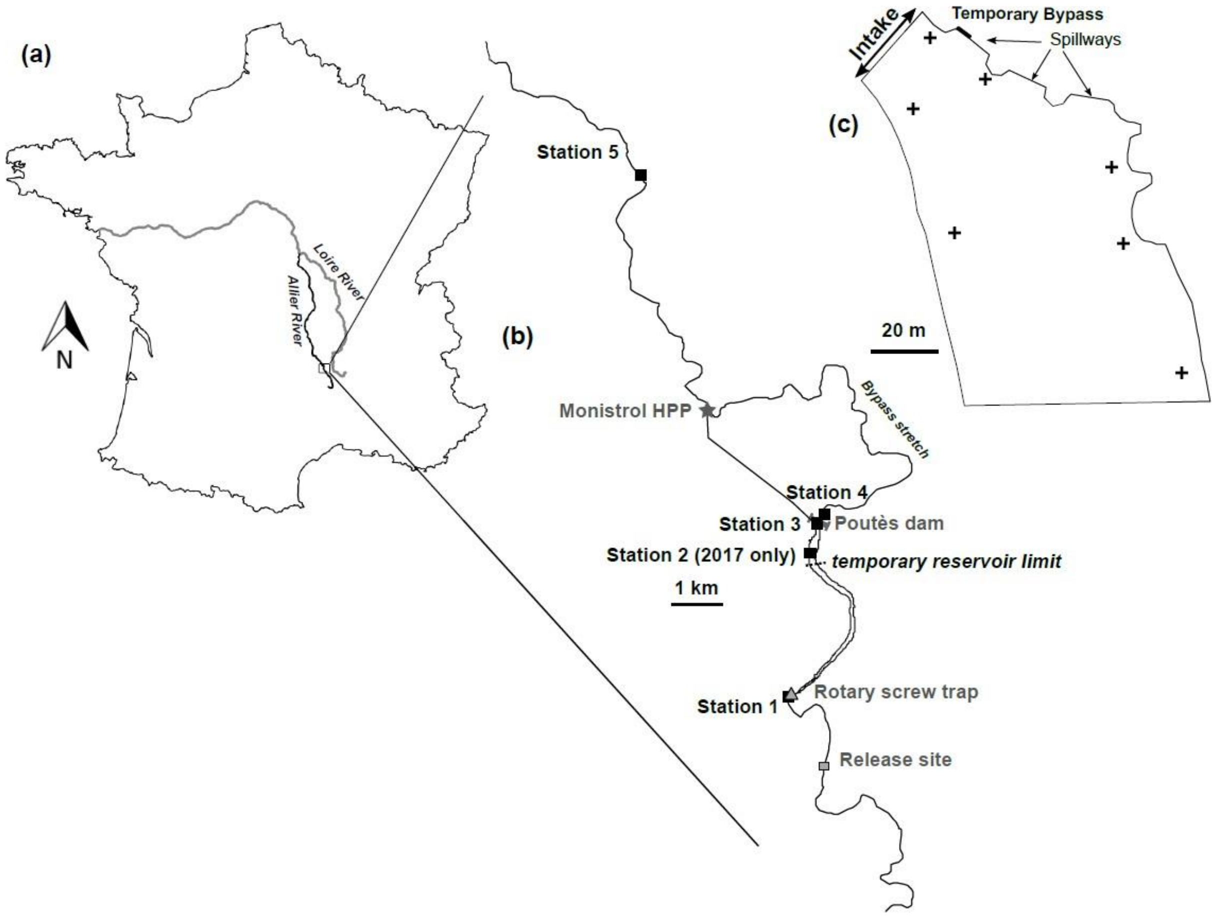


Figure 2.1.1: Study area (a, b) and Poutès "dam zone" (c). The crosses indicate hydrophone locations in 2017.

The dam is 18m high and 85m wide and bypasses a 10km river stretch of the River Allier from Poutès to Monistrol d'Allier, creating in normal operation a reservoir of 2.4Mm^3 that extends over 3.5km (mean water residence time, 1.67 days). Three spillways, each 14m long, discharge floodwater. The mean annual discharge of the River Allier in Monistrol d'Allier is 16.6m^{3}s^{-1}. The maximum diverted flow to the Monistrol d'Allier powerhouse is 28m^{3}s^{-1}. The powerhouse is equipped with three Francis turbines (#1/2: 16m^{3}s^{-1}; #3: 3m^{3}s^{-1}). The legal minimum flow in the bypass stretch downstream of the dam is 4 to 5m^{3}s^{-1}, depending on the season (Tétard et al. 2019).

Figure 2.1.2: Aerial view of the Poutès dam (top), side view of the bypass entrance (bottom left) and front view of the intake and bypass entrance (bottom right) (Tétard et al. 2019).

The rack (24m wide, 5.7m high) is located on the left bank, between 7 and 13m below the surface (in normal operating conditions) (**Figure 2.1.2**). A surface bypass, operating from March to June, is located at the downstream end of the rack. The entrance to the bypass consists of a weir, designed to provide progressive acceleration of flow from the entrance towards the weir crest that controls discharge (0.5m s^{-1} m^{-1}), in order to minimize smolts' reluctance to pass through (length, 2.4m; progressive width reduction from 3.6m at the entrance to 2.3m; and progressive depth reduction from 1.1m at the entrance to 0.6m). It is mounted on a gate automatically regulated according to water level, to ensure a continuous flow of $2m^3s^{-1}$, representing 7.1 % of the maximum turbined flow. The bypass is lit by a 50W mercury vapor lamp positioned 3 m above the entrance and creating a halo of light of approximately 3m diameter (Tétard et al. 2019). For upstream migration, a fish lift is raised every 2 hours throughout the year. Both fish passage solutions (bypass and lift) are video- monitored in normal operating conditions by the LOGRAMI association (Tétard et al. 2019).

A2.1.4 Adaptive management for smolt migration in spring 2017

Temporary operating measures in 2017 consisted in:

- Lowering the reservoir level from March 1st to 644.7 NGF (lowering of 5.5m from the normal water level of 650.2 NGF). This measure decreased reservoir volume by 85% (238,706m^3, down from 1,716,116m^3) and length by 70% (1,000m, down from about 3,500m) (**Figure 2.1.1**).

- Creating a functional bypass system, the current being unusable at this level: the left bank spillway (width, 14m) was used to set up a temporary bypass entrance (**Figure 2.1.3**). An extension, made of metal uprights and wooden parts of about 1m, was created to partly obstruct the weir crest, thus obtaining a hydraulic head ≥70cm over the weir crest. Unlike in normal operating conditions, the temporary bypass is not lit.
- Softening the bypass (concrete wall of the dam) downstream of the entrance to prevent abrasion injury.
- Modulation of turbine operation, beginning at night (7pm – 7am, local time), either when smolts were caught in the Alleyras rotary screw trap located upstream of the Poutès reservoir (**Figure 2.2.1**) or when river flow exceeded a threshold of 20 m3.s-1. This measure was continued for 20 nights:
    - Turbines could be switched on when river flow reached ≥9m^3s^{-1} (8m^3s^{-1} in the bypass and 1m^3s^{-1} in the intake). Up to 11m^3s^{-1} (included), between 73% and 89% of river flow was discharged by the spillways.
    - For river flows ≥12m^3s^{-1} but ≤40m^3s^{-1}, a ratio of at least two-thirds of flow was discharged by the bypass, the rest being discharged through the intake.
    - From river flow ≥40m^3s^{-1}, the Monistrol power plant could again turbine its maximum capacity (28m^3s^{-1}).

Figure 2.1.3: Top-left, picture of upstream limit of the temporary Poutès reservoir. Top-right, top view of temporary bypass. Bottom, upstream view of intake, usual (non-functional) and temporary bypass entrances.

A2.1.5 Adaptive management for smolt migration in spring 2018

The same temporary operating measures as in 2017 were renewed in 2018:

- reservoir level lowered on March 1st.
- use of the temporary bypass.
- 20 nights of measures concerning turbine operation between 7pm and 7am (local time).

However, considering the 2017 results of the telemetry study, it was decided to entirely stop the turbine operations instead of merely modulating them.

A2.1.6 Telemetry study

To study the behavior of smolts throughout the study area (**Figure 2.1.1**), and especially their approach to the Poutès dam and passages through the bypass, 23 and 16 WHS4000 hydrophones (Lotek Wireless Inc. ®) were used in 2017 and 2018, respectively. The telemetry array had to be scaled down in 2018 due to installation issues (reservoir and Allier River entirely frozen over).

Five and 4 stations were equipped with hydrophones in 2017 and 2018, respectively. From upstream to downstream (**Figure 2.1.1**):

- Station 1 (kp = 3km from release site): 4 hydrophones. Located in Alleyras. This station detected smolts in the free-flowing River Allier, (about 1.5 km from upstream normal limit of the Poutès reservoir).
- Station 2 (kp = 6.9km): 4 hydrophones. This station was not equipped with hydrophones in 2018. In the area of the upstream temporary limit of the Poutès reservoir (about 700 m upstream of the Poutès dam).
- Station 3 (kp = 7.6km): 7 hydrophones in 2017 and 4 in 2018. Hydrophones in the dam zone were installed to track fish movement up to approximately 80 m upstream of the dam (**Figure 2.1.1**).
- Station 4 (kp = 7.9km): 4 hydrophones. Located 300 m downstream of the Poutès dam, in the bypass stretch. This station confirmed bypass passages.
- Station 5 (kp = 21.6km): 4 hydrophones. Located in the free-flowing River Allier, 4 km downstream of the confluence between the bypass stretch and the tailrace of Monistrol d'Allier powerhouse.

The hydrophones were mounted on 1m PVC tubes anchored on 25kg concrete bases and attached to the bank by ropes. Precise GPS location (precision to within 0.3m) of the hydrophones was retrieved with a differential GPS (Leica®). Position was calculated using UMAP V1.3.1 (Lotek Wireless Inc. ®). Position data were post- processed using a DOP (Dilution of Precision, UMAP parameter) of 0.3 (Tétard et al. 2019). A preliminary survey was conducted in 2017 to assess location probability (i.e., proportion of tag transmissions that resulted in a calculated position) and positioning error (i.e., Euclidian distance between calculated and actual positions of the tag) (Roy et al. 2014). A first test was conducted with a tag at a fixed position (**Figure 2.1.4**) for 15 h 35 min. Mean location probability was 93.3% and median positioning error 1.7m. Then, two trajectories were conducted (**Figure 2.1.4**), with differential GPS, on a boat. Mean location probabilities were low: 12.5 and 15.5% for the first and second trajectory, respectively. Median positioning error was 0.7 m (mean = 2.2m) but only 16 positions were calculated. Excessive boat speed was certainly the cause of the low trajectory location probabilities: a posteriori estimates of boat speed with GPS trajectories ranged between 0.8 and 1m.s-1, which may have been faster than smolt movements in the reservoir.

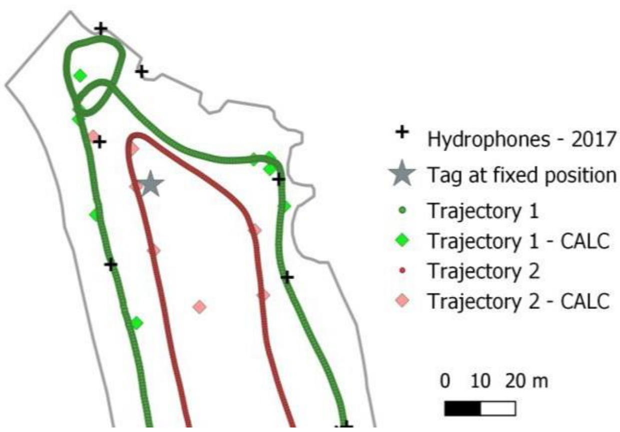


Figure 2.1.4: Preliminary survey: assessment of location probability and positioning error.

Fish catching and tagging
Like in the previous studies conducted in Poutès from 2014 (Tétard et al. 2016a, Tétard et al. 2019), two rotary screw traps were used to catch wild migrating fish. The first was positioned in Alleyras about 1.5km upstream of the normal Poutès reservoir, and was used to monitor natural smolt migration dynamics and to assess the impact of the Poutès dam and its reservoir on smolt migration from 2013 to 2015 (Tétard et al. 2019). In 2017 and 2018, the monitoring period had to be shortened and the trap was not checked at weekends in 2018 (the Alleyras trap was used only to collect smolts and not to monitor migration). Based on mark-recapture calibration studies, mean trapping efficiency was estimated at 6.5% (CNSS 2013, 2014).

The other trap was located in Chanteuges, next to the CNSS fish farm, about 28.5km downstream of the Poutès dam. This trap has been used since 2009 to monitor smolt in the upper River Allier (CNSS 2013, 2014). Its mean trapping efficiency was estimated at 5% (Imbert et al. 2013). The two rotary screw traps can operate until river flow reaches a maximum of around 30m3.s-1 and 50m3.s-1, for Alleyras and Chanteuges, respectively (CNSS 2013, 2014).

As the majority of spawning areas are located downstream of Poutès, the trap at Chanteuges collects more fish yearly. This trap could be used in addition to the Alleyras trap, which was preferred as far as possible so as not to need to transport fish over a long distance (about 30km) to the release site. Finally, the possibility of collecting and tagging fish from the CNSS fish farm was kept open, in case of hydrological conditions (floods) that prevented capturing fish from the two rotary screw traps.

In 2017, the Alleyras trap was put in operation from February 27 to April 10, and the Chanteuges trap from February 28 to May 31. In 2018, traps were operated from March 3rd to April 12th and from March 1st to May 13th at Alleyras and Chanteuges, respectively. Traps were checked every morning during the study period.

Before tagging, fish were anaesthetized in phenoxyethanol solution at 0.3ml.l-1, then measured (total length), weighed and tagged. Acoustic tags were carefully inserted into the body cavity via a lateral incision. Closure used surgical glue. JSAT L-AMT-1.421 tags (10.5x5.2 mm wide; Lotek Wireless Inc. ®) were used, weighing 0.32 g in air. Transmitters were programmed to emit a unique individually recognizable coded acoustic signal every 5 seconds, resulting in a battery life of approximately 40 days. Weights in air amounted to less than 2% of fish body weight, as recommended by Winter (1996). After recovering from the anesthesia, fish were released 3km upstream of the reservoir.

Data analysis
In order to pass a dam, fish must traverse the forebay and locate a passage route (Nyqvist et al. 2017a). However, locating a passage route does not mean that the fish will in fact pass the dam, and passage failures are regularly observed with upstream and downstream fishways (Williams et al. 2012, Nyqvist et al. 2017a). At the Poutès dam, repeated attempts (defined as presence in the dam detection zone) before passing (or not) were observed under normal management of the reservoir in 2015. Moreover, a majority of smolts were disoriented and went back to the upstream end of the reservoir (Tétard et al. 2016a). Attempts in the dam zone and potential back-and-forth movements in the temporary reservoir were computed (back-and-forth movements could only be computed in 2017 when station 2 was operational). To distinguish between different "dam attempts", a time threshold of 30 min between two consecutive detections was used (Tétard et al. 2019).

Successful passages were confirmed by detection in the bypass stretch downstream of the dam. However, some smolts which used the bypass were missed in the bypass stretch during high flow periods. 2D trajectories in the forebay were used, when possible, to adjust passage rates. In the case of a precise trajectory leading to spillways or bypass, the passage route was considered to be the bypass stretch. Otherwise, the passage route was unknown and could possibly be the intake. Consequently, calculated passage efficiencies are conservative as an unknown passage route is considered as a turbine route.

The time of the fish's last position in the forebay before passage was used to assign the time of passage and corresponding period of the day. To define periods of passage, times of twilight according to the angle between the center of the sun and the horizon were considered (when the geometric center of the sun reaches -6° and -18° below the horizon, for civil and astronomical twilights, respectively) were counted.

Transfer rates between stations, defined as the proportions of individual fish detected in a given station with respect to those detected in the previous station, were examined. Transfer rates were adjusted when possible, as missed detections occurred during high flow periods. Adjustment was performed by adding single fish detected in downstream stations that must have passed the previous ones. In the case of station 5, as smolts detected in this station could come either from the bypass stretch or from the power plant, the transfer rate was calculated by considering fish detected in station 5 that had been detected in station 4. Thus, the calculated transfer rate was reduced by the fact that smolts missed in station 4 but detected in station 5 were not included in the calculation.

To assess potential migratory delay, residence time in the reservoir was calculated as the time between 1st detection in the temporary reservoir (station 2) and last detection before passage (or not). At high reservoir level, the upstream limit of the reservoir was not equipped with hydrophones (**Figure 2.1.1**). Reservoir entry time was estimated by adding median travel time between station 1 and the reservoir at high level, which was determined in 2015, to the last detection in Station 1. Thus, residence time was the time between the last detection in [Station 1 + 2.4h] and the last detection in the reservoir (Station 3). In 2018, Station 2 was not equipped with hydrophones. Reservoir entry time at low level was estimated using travel time between station 1 and station 2 as calculated in 2017. At high level, the estimation used the same method as in 2017 (see above).

All results were interpreted according to reservoir level and river flow. As some smolts were tagged and released later in the study period and some delayed their migration, passages, transfer rates and residence times were calculated in relation to reservoir level during smolt passage. The low reservoir level period ended on April 7th at 8 pm UTC (Universal Time Coordinated) and on April 9th at 11pm UTC in 2017 and 2018, respectively. For river flow, it was decided to set a threshold at 30 m3.s-1, which is approximately twice the mean inter-annual flow. This threshold allowed: 1) results to be examined when detection efficiency was high and 2) the impact of river flow on residence time and transfer rates between stations to be minimized. High river flow necessarily increases smolt migration speed.

To explore spatial behavior of smolts in the dam zone, detection density maps were created. The UD (utilization distribution) was also calculated with the kernel method according to reservoir level (Silverman 1986, Calenge 2011). Finally, considering all passages at low reservoir level, a Generalized Linear Model (GLM) with binomial distribution was adjusted to explain passage routes (bypass = 1, or turbines = 0) according to environmental variables (river flow, turbined flow, spilled flow, spill ratio [spilled flow/river flow]). Inter-correlated variables were not included simultaneously in models to avoid multi-collinearity. A model selection procedure was conducted with the Akaike criterion (AIC) to determine the most parsimonious model. All statistical tests were performed using R software (R

Development Core Team 2018) and the MASS, maptools, sp, raster, adehabitatHR and rgdal packages. Conventional procedures to test for statistical assumptions were performed.

A2.1.7 eDNA metabarcoding to detect fragmentation in freshwater communities

We investigated whether eDNA can recover reliable information about communities of fish, invertebrates and primary producers (cyanobacteria, algae and vascular plants) that may contribute to an assessment of stream connectivity. To this aim, twenty sites distributed along an altitudinal gradient of approximately 1000m along the main stream of the Allier river (Loire basin, central France) were sampled at relatively constant increments in altitude of 50m, covering over 400km of stream (**Figure 2.1.**). Thirty-two barriers had been previously recorded for this length of river, including ramps/bed sills, culverts, weirs and dams are distributed along the main-stream sampling range, rising to a cumulative barrier height of ~67.76m at the highest altitudinal site sampled (**Figure 2.1.5**).

Water samples for eDNA analyses were collected from the surface layer at a sampling depth of 20cm using 1L Sterile bags (Whirl-Pak® stand -up Sample Bag) by holding it into the stream in a well-mixed portion of the flow. 3 replicates of ~1 L water samples were collected in each sampling point and kept refrigerated till the moment of filtration. Samples were filtered through 25mm sterile 0.22µm pore size polythersulfone hydrophilic membranes (Millipore Express PLUS) using encapsulated filtration device consisting of a polycarbonate filter holder (⌀25 mm, Cole-Parmer) and a disposable sterile 50ml syringe. DNA was extracted from each filter using DNeasy PowerLyzer PowerSoil® DNA Isolation Kit (Qiagen GmbH, Hilden, Germany) following manufacturer's instructions.

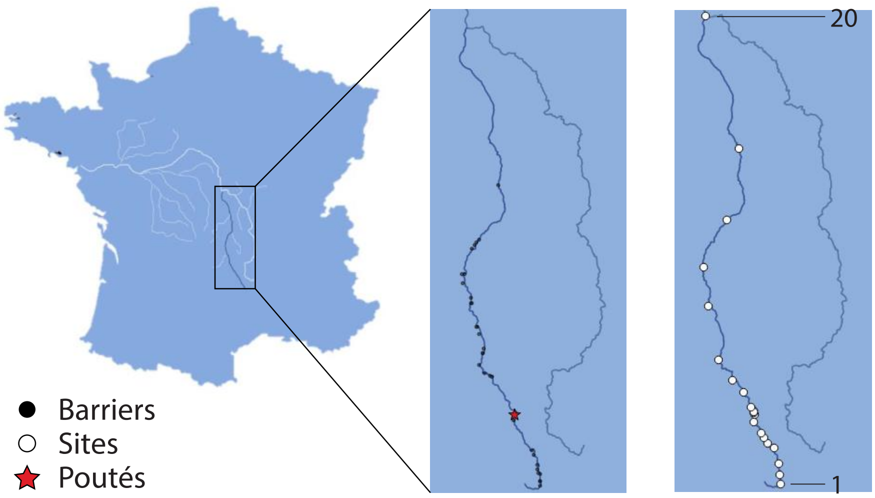


Figure 2.1.5: Sampling sites and locations of barriers along the Allier tributary.

Metabarcoding libraries were constructed following a standard Illumina protocol using locus specific PCR primers in the first round of PCR and a second round PCR attaching dual indices and Illumina sequencing adapters using Nextera XT index kit. Primers targeting fragments of mitochondrial and plasmid loci were used to enrich taxonomically informative organelle DNA for fish, macroinvertebrates and plants (Riaz et al., 2011; Clark et al., 2014; Elbrecht et al., 2016; Sherwood and Presting 2007). Paired end sequencing (2x300 bp) was carried out on an Illumina MiSeq platform (Illumina, San Diego, CA, USA) using the Paired- MiSeq Reagent Kit V3 (600 cycle) (Illumina, San Diego, CA, USA) following the manufacturer's instructions at the Institute of Life Sciences, School of Medicine, Swansea, Wales, UK. The resulting DNA sequence reads were processed with a custom bioinformatic pipeline and analyses performed on a species matrix that had been transformed to presence/absence.

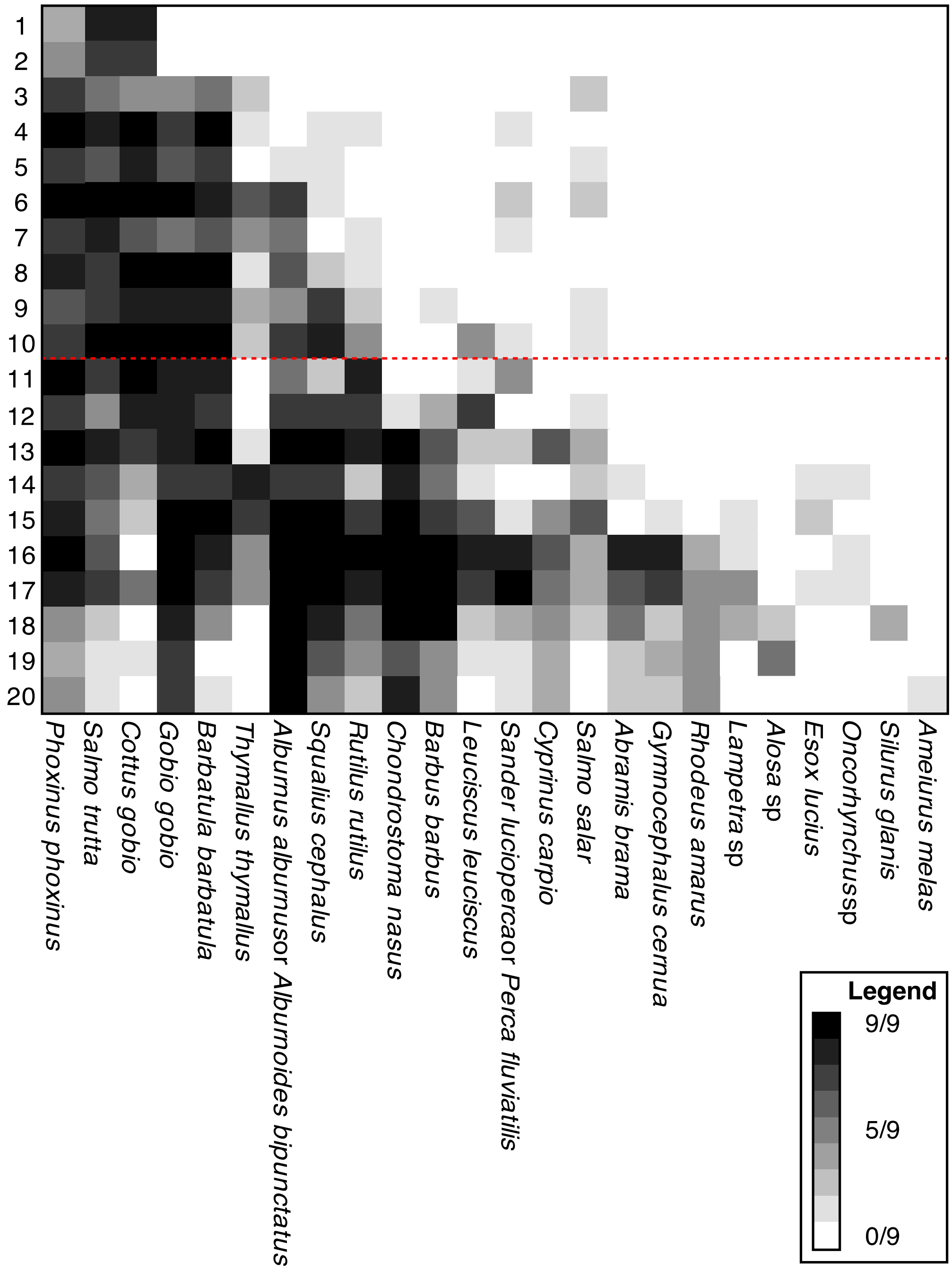


Figure 2.1.6: Fish presence along altitudinal gradient. Heatmap showing if a species of fish (column) was detected at a particular site (column). Site 20 is furthest downstream, and the red dashed line demarcates the position of the Poutés dam. Darkest squares indicate that a species was detected from eDNA in all sample replicates and white indicates non-detection.

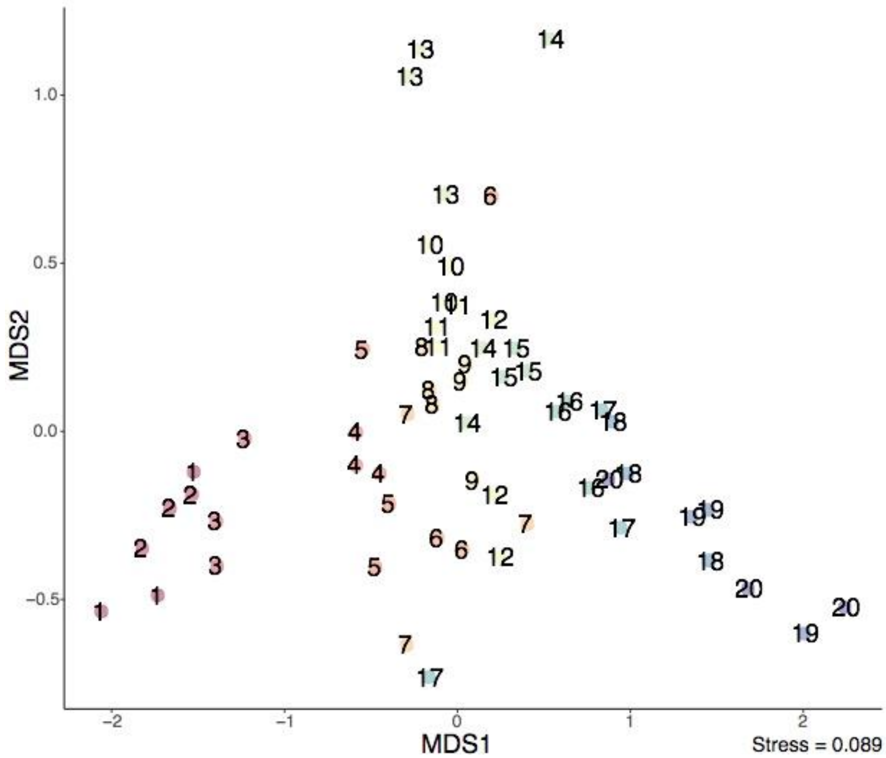


Figure 2.1.7: MDS plot of Jaccard distances between primary production communities sampled across sites. Each number dot represents a site numbered from 1 (upstream) to 20 (downstream). The closeness of points indicates how closely the plant community samples resemble each other along the two axis that explain the most variance in the dataset. Upstream and downstream samples are clearly differentiated by MDS1, the axis that explains the most variance, but samples from the water impounded by the Poutés dam (9 and 10) and immediately below are only distinct if a second dimension, MDS2, is considered.

A2.1.8 Results

2017 Results
Environmental conditions – turbine operations and captures
In accordance with the 2017 temporary operating measures, the reservoir level reservoir was lowered to 644.7m NGF (French vertical datum) on March 1. Modulation of turbine operations began on March 4, when river flow reached 20m3.s-1 (**Figure 2.1.8**). It continued to March 16 and was then stopped until the 24 to keep “modulation nights” quota (8 “modulation nights” left) for more upcoming “stimulating days”, in accordance with the monitoring committee decisions (public services and EDF).

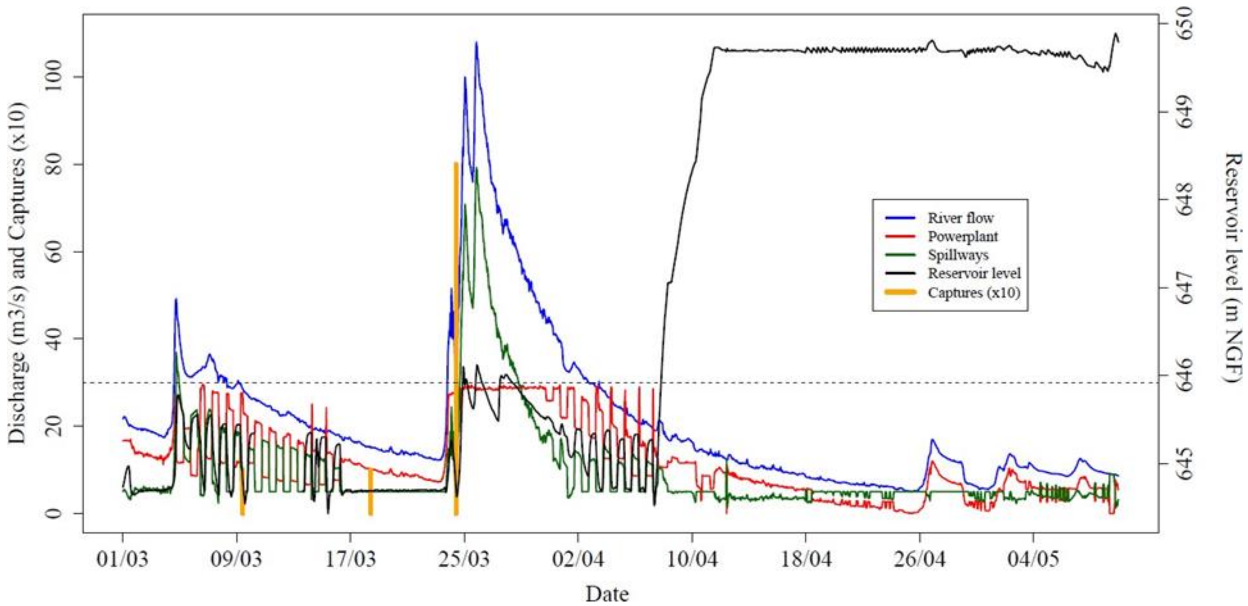


Figure 2.1.8: Changes in hourly river flow (blue), turbine discharge (red), spillway discharge (green), reservoir level (black) and captures at the Alleyras trap (x10) during the study period. The horizontal dashed line indicates the approximate discharge limit for the Alleyras rotary screw trap operation.

On March 24, a significant flood quickly raised the river flow above 20m3.s-1. Hourly river flow reached 108m3.s-1 on March 25at 10pm. The intake was therefore at full capacity of 28m3.s-1 from March 24 8am to March 30 at 6pm. From this date, turbine operation modulation was continued for 8 nights until April 7. The reservoir level began to rise on April 7 at 2pm (water level over 645 m NGF) and reached normal level on April 11. Turbine operation modulation was therefore conducted over 20 nights in total: 12 nights from March 4 to 16 and 8 nights from March 30 to April 7. A total of 54 smolts were tagged and released between March 9 and April 12 2017 (**Table 2.1.1**). Only 10 wild smolts could be trapped and tagged in 3 tagging sessions (March 9, 18 and 24).

The flood occuring from March 24 to April 2 had important implications for the study. Temperature was favorable for smolt migration in the preceding days (between 6.5° and 9°C) and 8 wild smolts were caught in the night of March 24-25 when the river flow rose from 20 to 50m3.s-1. This suggested the beginning of an important migration episode, considering the low migration activity since the beginning of the migration season.However, the rotary screw trap at Alleyras quickly came to be outside of its river flow operating range, preventing monitoring of this highly likely downstream migration episode.

Table 2.1.1: Tagging sessions in 2017

Release date	Number	Origin	Reservoir level	Total Length	Weight
03/09/2017	1	Wild	Low		
03/18/2017	1	Wild	Low	152 ± 30.5 mm	31.8 ± 19.6 g
03/24/2017	8	Wild	Low		
04/02/2017	24	Fish farm	Low	164 ± 9.7 mm	40.4 ± 7.4 g
04/12/2017	20	Fish farm	High		

Considering these stimulating environmental conditions occuring in a favorable period and the fact that spawner returns were low during the previous years, indicating a low smolt, it was decided to tag hatchery smolts from the Chanteuges fish farm in order to track fish before the end of the temporary operating measures (on April 2, 5 “modulation nights” left). A first group of 24 fish was tagged and released on April 2 at low reservoir level, and a final group of 20 smolts on April 12 at high reservoir level. There was no statistical difference between wild and hatchery smolts, either in mean total length (Mann-Whitney, $p = 0.09$) or in mean weight (t-test, $p = 0.2$).

Migration dynamics

The dynamic of tagged’ smolt movements is presented in **Figure 2.1.6.** Cumulative percentages of detected smolts in each station are shown, excepted for station 3, for which real passages are shown (last detection in station 3 for smolts detected (or assumed to have passed according to 2D) downstream in station 4 or station 5), as a smolt could possibly be detected at the dam without passing it (Tétard et al. 2016a, Tétard et al. 2019). Thus, passage dynamics could be characterized as via the intake, the bypass (high reservoir level), the temporary bypass (low reservoir level) or the spillways.

It should be noted that cumulative percentages were calculated considering the total number of smolts detected in each station during the whole study period. Results must be interpreted with caution because, when smolts were missed in a particular station and detected at the next, the cumulative percentage increased for the latter only. Changes in river flow and temperature are also shown. The vertical dashed line corresponds to April 7, 2017, the date on which the reservoir level was raised.

During the whole study period, passage dynamics in station 1 and 2 were very similar, indicating that smolts did not seem to stop between these two stations upstream of the temporary reservoir. Interestingly, after the reservoir level was raised on April 7, smolts still did not stop, whereas station 2 was located 2.8km downstream of the upstream reservoir limit at high level.

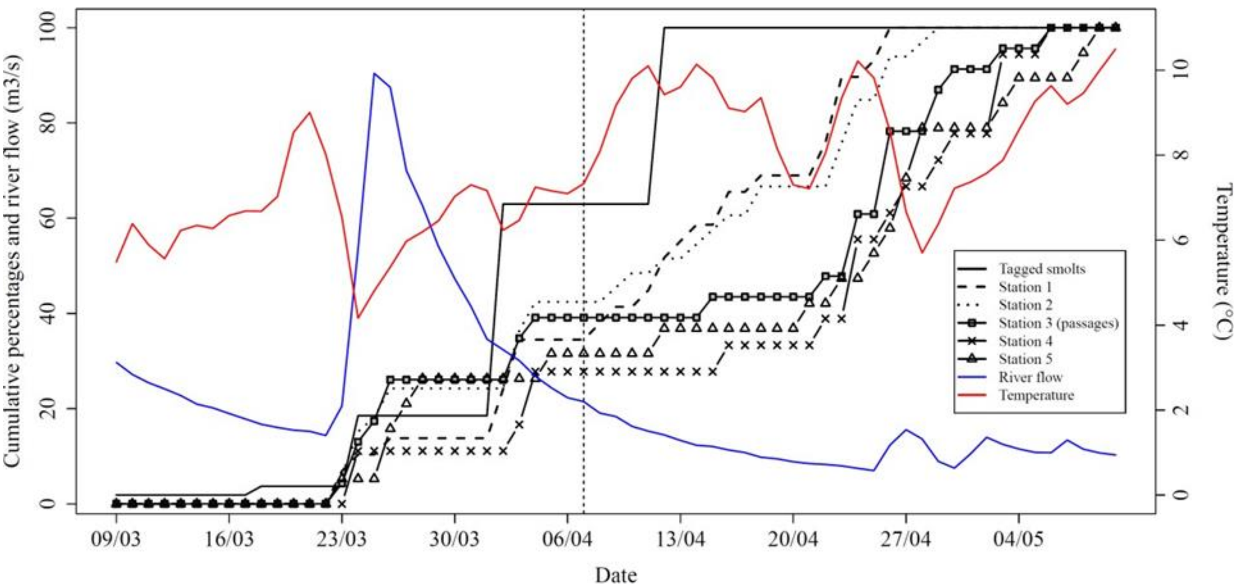


Figure 2.1.9: Cumulative percentages of tagged smolts (dark solid line), detected in Station 1 (thick dashed line), detected in Station 2 (fine dashed line), passing the Poutès dam (squares), detected in Station 4 (crosses) and detected in Station 5 (triangles). River flow (blue) and temperature (red). The vertical dashed line indicates the day at which the reservoir level was raised.

Passage dynamics at Poutès differs between the two phases (before and after the raising of the reservoir level on April 7). Before April 7, passages (station 3) follow followed detections in station 2 (upstream of the temporary reservoir). The impact of the flood is visible, as detections in stations 1 and 4 were synchronous with detections in station 2 and with passages but were lower (missed detections). After raising the reservoir level, the passages in station 3 and detections in stations 4 and 5 had different dynamics from detections in stations 1 and 2. From April 7 to April 18, cumulated detections in stations 1 and 2 greatly increased, from 35% to 69%, but passages and cumulative detection in stations 4 and 5 increased by only a few percent. This shows that smolts continued to enter the Poutès reservoir but did not manage to exit it. Thereafter, passages at Poutès and detections in stations 4 and 5 showed logically showed similar changes. Lastly, it should be noted that the main migration episode (from April 22 to the end of the study) may have been initiated by an increase in temperature (from 7.2°C on April 21 to 10.2°C on April 24) and/or a slight increase in river flow.

Transfer rates and passage hours

Transfer rates between stations are presented in **Table 2.1.2**. Overall, only 63% of smolts were detected (34/54). Transfer rates from station 1 to the Poutès dam were very high (97% to station 2 and 97 % between stations 2 and 3). However, only 63 % of smolts detected at the dam were transferred to station 4. Finally, the transfer rate to station 5 (adjusted by considering only fish that were detected in station 4) was 70%.

Table 2.1.2: Transfer rates between stations: global and sub-selections according to reservoir level or river flow when smolts entered the Poutès reservoir (detection in station 2). Number and transfer rates in brackets for station 5 were calculated according to the sub-selection of smolts detected in station 4 (detections in station 5 included fish that did not pass station 4 but passed though the turbines).

	Release site	Station 1	Station 2	Station 3	Station 4	Station 5
Global						
Nb (raw)	54	29	33	32	18	19
Nb (adjusted)	54	34	33	32	20	19 (14)
Transfer (%)	/	**63%**	**97%**	**97%**	**63%**	**/ (70%)**
Reservoir at low level (Before 7th April 2017 8pm)						
Nb adjusted	34	14	14	14	7	7(4)
Transfer (%)	/	/	**100%**	**100%**	**50%**	**/ (57%)**
Reservoir at low level and river flow less than 30 $m^3.s^{-1}$						
Nb adjusted	/	6	6	6 (5*)	3	2 (2)
Transfer (%)	/	/	**100%**	**100%**	**50% (60%*)**	**/ (67%)**
Reservoir level > 646.1 NGF (after 7th April 2017 8pm)						
Nb adjusted	/	20	19	18	13	12 (11)
Transfer (%)	/	/	**95%**	**100%**	**72%**	**/ (85%)**

*One smolt was detected in station 3 but did not approach the dam.

For smolts entering the Poutès reservoir when its level was low (smolts detected in station 2 before April 7 at 8), only 14 smolts were detected but all were transferred to station 3. Passage efficiency to the bypass stretch was 50%. River flow was very high for several days (March 24 to April 2), limiting detection efficiency. However, whether the dataset is limited to a period when river flow was lower than 30m3.s-1 (6 smolts), which is twice the mean annual flow, or not, passage efficiency was still 50% (or 60% one fish that did not approach the dam is discounted). Finally, the transfer rate to station 5 was 57% (67% out of the "high flow period").

After the reservoir was raised, 20 smolts were detected in station 1. Transfer to the dam was still very high (95% from station 1 to station 2 and 100% from station 2 to station 3). During this period, passage efficiency increased, to 72% (13/18). However, this difference in passage efficiency between low and high reservoir level was not statistically significant ($\chi 2 = 0.85$, $p = 0.36$). Finally, transfer to station 5 also increased, to 85% (11/13), but again the difference was not significant ($\chi 2 = 0.66$, $p = 0.42$). Whatever the route used by smolts (spillway, bypass, intake or unknown), passages times at Poutès (N=30 passages) were compiled and are presented in Figure 2.1.10. All passage times are UTC. Overall, passages were mainly "twilight and nocturnal": 93% (N=28) occurred between 6pm and 4am, 83% (N=25) of which between 7pm and 2am. For passages occurring at low reservoir level (N=13), 92% occured between 6pm and 4am. Only 1 passage occurred at 10h34. At higher reservoir level, the pattern was similar with 94% of passages occuring between 7pm and 3am.

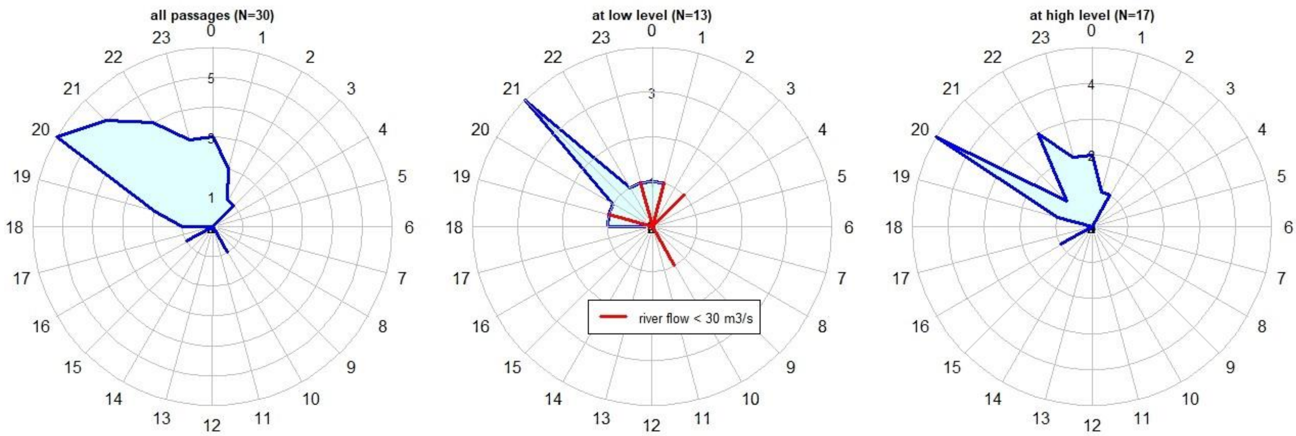


Figure 2.1.10: Radial plots of passages times (UTC) at Poutès according to reservoir level.

Using twilight time specifically, distribution of passages according to time of day can is shown in **Table 2.1.3**: it did not differ according to whether the reservoir was at low or high level ($\chi 2 = 0.32$, $p = 0.85$).

Table 2.1.3: Passages according to period of the day.

	Day		Twilight		Night	
	nb	%	nb	%	nb	%
At low level	1	8%	2	15%	10	77%
At low level (river flow <30 $m^3.s^{-1}$)	1	20%	1	20%	3	60%
At high level	1	6%	4	23%	12	71%

Residence time and behavior in the reservoir

Median residence time at low reservoir level with river flow ≥30m3.s-1 was 50.8 min (mean = 99 min; range, 32.8 min to 7.6 h); 3rd quartile, 62.8 min) (**Figure 2.1.11**). Median residence time at low reservoir level with river flow <30 m3.s-1 was 3.6 h (mean = 5.8 d; range, 52.5 min to 31.5 d; 3rd quartile, 2.1 days). It should be noted that one smolt spent more than one month in the reservoir; omitting this individual, median residence time was 1.6 h (mean, 15 h). At high reservoir level, median residence time was 4 days (mean = 7.5 d; range, 16.8 h to 20 d; 3rd quartile, 12.5 d).

A log-normal linear model confirmed that the effect of reservoir level on residence time was significant (ANOVA, $F = 27.9$, $p < 0.001$). The model coefficients were all significant indicating that residence time was significantly higher at low reservoir level when river discharge was <30m3.s-1 (t-test, $p < 0.05$) and higher at high reservoir level (t-test, $p < 0.001$), both compared to residence time at low reservoir level with river flow ≥30m3.s-1.

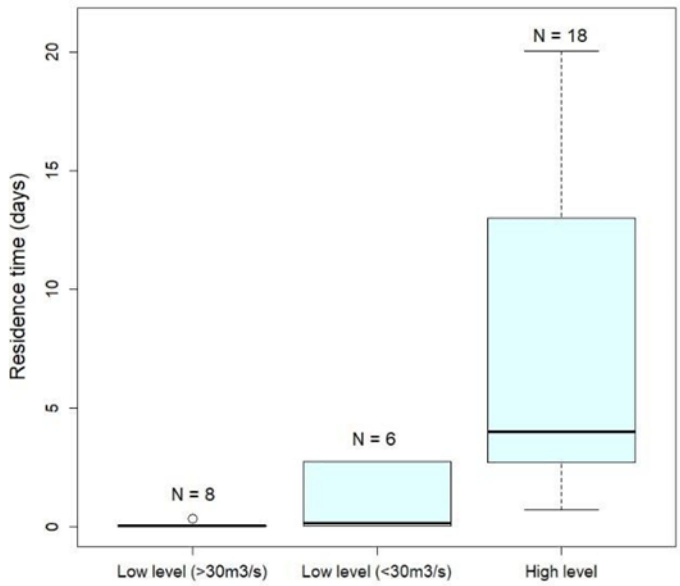


Figure 2.1.11: Residence time according to reservoir level and river flow during smolt entry. For visual purposes, one outlier (low level [< 30 m3.s-1], residence time = 31.5 d) is not represented

At low reservoir level, 93% of smolts (13/14) passed the dam at the first attempt. The last smolt passed after 20 attempts at the dam (**Figure 2.1.12**). At high reservoir level, the median number of attempts per smolt was 3.5 (mean = 5.4; range, 1-16). 90% of smolts made fewer than 11.1 attempts. The difference in attempt number between low and high levels was significant (Mann- Whitney, W = 50.5, $p < 0.01$).

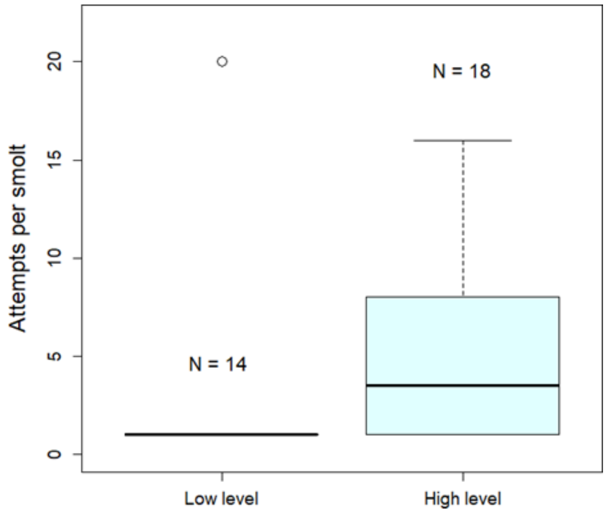


Figure 2.1.12: Number of attempts per smolt according to reservoir level.

Spatial representation of position density (**Figure 2.1.13**, pixel size 2 x 2.7m) indicated that the dam area was well covered. Maximum detection density was in the north-west corner of hydrophone array. Despite the DOP filter, a few positions were positioned outside reservoir boundary.

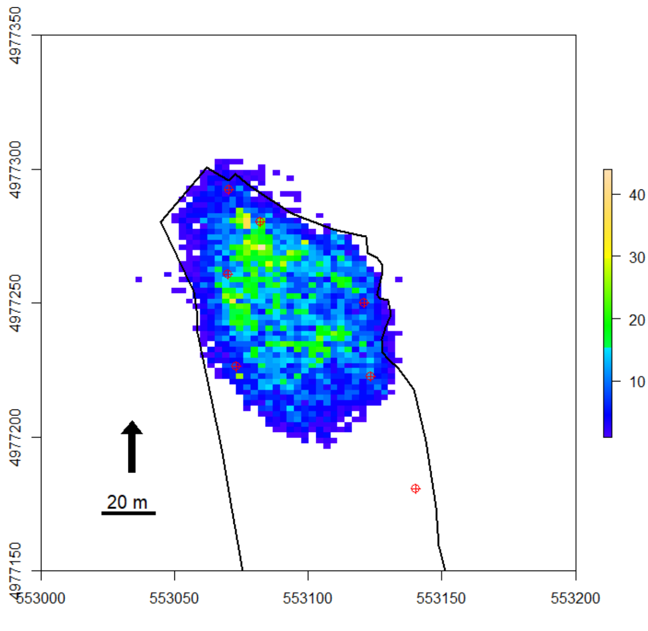


Figure 2.1.13: Spatial representation of position density (pixel size = 2 x 2.7m).

UD maps according to reservoir level are presented in **Figure 2.1.14**. At low reservoir level, the probability distribution of smolt relocation was quite concentrated, forming a "channel" directed toward the bypass. Maximum probability density was in a zone just upstream of the bypass, at approximately 11 to 29 meters from the bypass entrance, indicating an accumulation of relocations in this area. At high reservoir level, smolt relocation was distributed over the whole dam area.

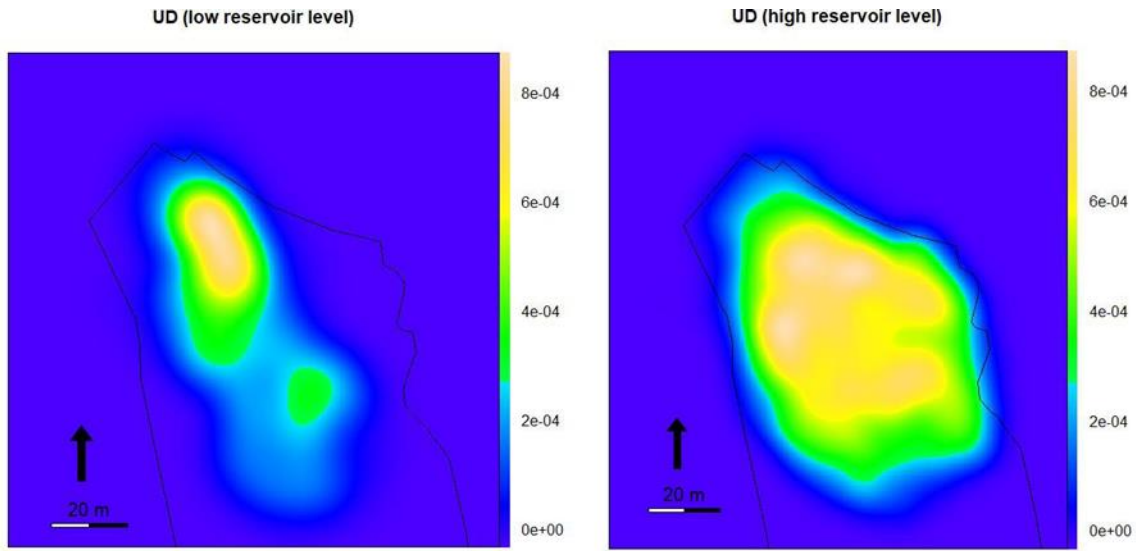


Figure 2.1.14: Probability density of smolt relocation (UD) according to reservoir level.

2017 Results

Environmental conditions – turbine operations and captures

In accordance with the temporary operating measures, the reservoir level was lowered to 644.7 m NGF on March 1 Firstly, it is important to note that the duration of turbine shutdown changed during the temporary operating measures period, lasting 2 hours less (from 7pm to 5am local time) until March 20 and then prolonged to the planned time slot of 7pm to 7am (local time).

First smolts (N=8) were caught in the rotary trap at Alleyras on March 8 and triggered the first night of turbine shutdown at 6pm (UTC). 25 smolts from the Chanteuges trap were tagged and released at 6:30pm (**Table 2.1.4**).

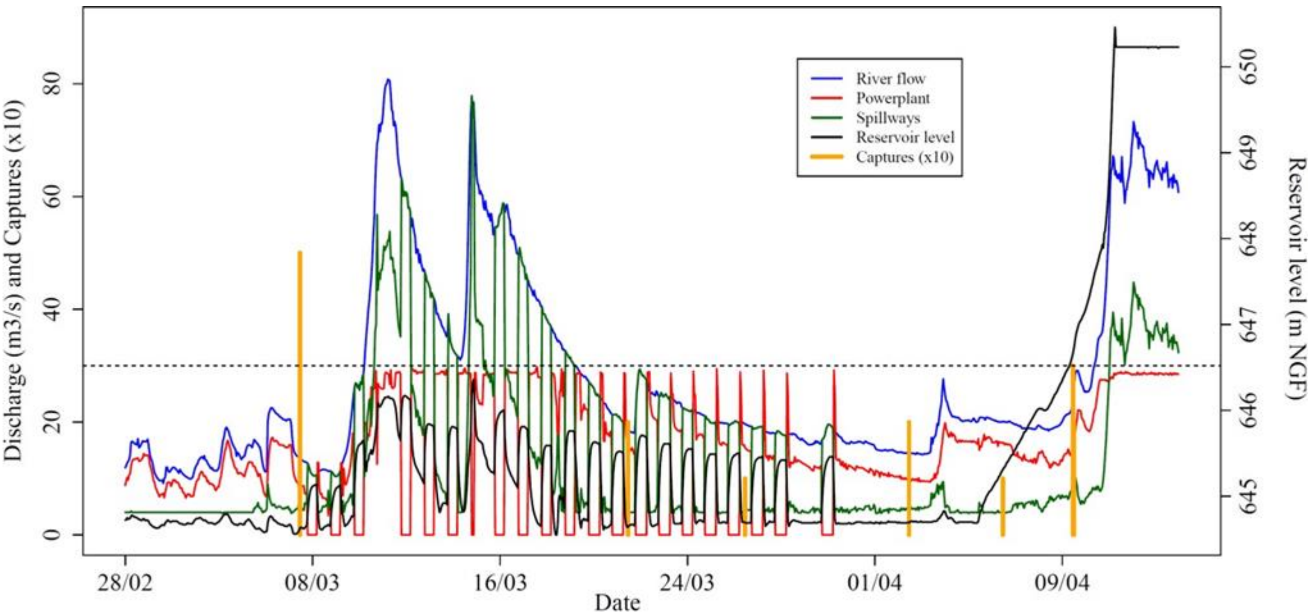


Figure 2.1.15: Changes in hourly river flow (blue), turbine discharge (red), spillway discharge (green), reservoir level (black) and capture at the Alleyras trap (x10) during the study period. The horizontal dashed line indicates the approximate discharge limit for the Alleyras rotary screw trap operation.

Turbine shutdown was continued for 3 nights (March 8-9, 9-10, and 10-11) but was then stopped the fourth night (March 11-12) because of the flood. The dam operators decided to restart the turbines to protect the temporary bypass. Turbines were shut down the day after (March 12 at 6pm UTC) and for 3 nights in a row. Turbines were stopped at 6pm UTC on March 15, but only for 3 hours. Again, to protect the temporary bypass, the dam operators restarted the turbines at 9pm when the hourly river flow reached about $75 m^3 s^{-1}$.

Thereafter, the turbines were stopped every night from March 16 to 29 (13 nights). During this period, although environmental conditions looked quite favorable for smolt migration, no significant captures were made, and the rotary screw traps could operate from March 19 to 29.

As smolt stocks upstream of Poutès were quite low (few spawners had reached upstream of Poutès the previous years) and it was presumed that a large majority had migrated during the two flood episodes (5 smolts were caught on March 8 at the beginning of the first), it was decided to tag hatchery smolts from the Chanteuges fish farm in order to track them during the last remaining night of turbine shutdown. 45 hatchery smolts were tagged and released on March 30 at 8:30pm while turbines had been stopped for the last night at 6pm UTC (**Table 2.1.4**).

Although the agreed shutdown quota was over on March 31, the reservoir level was low until April 9 at 11pm UTC.

Table 2.1.4: Tagging sessions in 2018.

Release date	Nb	Origin	Reservoir level	Total Length	Weight
03/08/2018	25	Wild (Chanteuges trap)	Low	147.4 ± 15.4 mm	26.7 ± 8.5 g
03/30/2018	45	Fish farm	Low	168.5 ± 7.3 mm	41.8 ± 6.1 g

Wild smolts were smaller (t-test, $P < 0.001$) and lighter (Mann-Whitney, $P < 0.001$) than hatchery smolts.

Migration dynamics
The dynamics of tagged smolt movements is presented in **Figure 2.1.13**. The cumulative percentage of detected smolts in each station are shown, except for station 3, for which passages are shown (last detection in station 3 for smolts detected downstream in station 4 or station 5).

Changes in river flow and temperature are also shown. The vertical dashed line indicates April 7, 2018, date on which the reservoir level began to be raised.

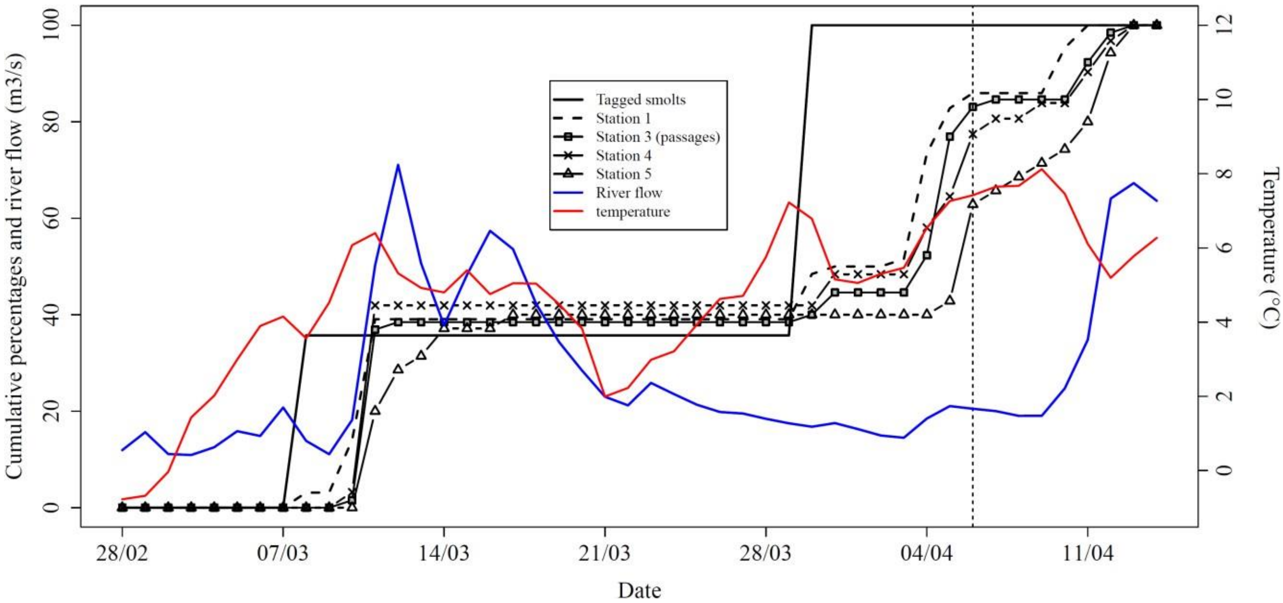


Figure 2.1.16: Cumulative daily percentage of tagged smolts (dark solid line), detected in Station 1 (dashed line), passing the Poutes dam (squares), detected in Station 4 (crosses) and detected in Station 5 (triangles). Mean daily river flow (blue) and temperature (red) are also represented. The vertical dashed line indicates the day on which the reservoir level was raised.

At low reservoir level, migration dynamics was very similar in all stations, although smolt arrival in station 5 was a little bit more gradual, as it is about 14km downstream of station 4.

All fish of the first release (N = 25) migrated during the flood of March 10-11-12 (especially during the night of March 11-12). Only 4 smolts passed the dam when the turbines were stopped. 6 tagged fish (24%) arrived at the dam during the first flood peak (night of March 11-12) when the turbines were restarted to protect the bypass: 4 passed in the bypass stretch. 5 smolts passed Poutès between 4 and 6am (UTC), when the turbines should have been stopped as they were after 20 March.

Logically, no movements happened until second release. A majority of detected smolts of the 2nd release (38/42) waited for several days and arrived in Poutès during an increase in river flow on April 4-5 and the flood on April 10-14. Consequently, most of them benefited from the low reservoir level but did not benefit from turbine shutdown. Only 2 smolts of the 2nd release passed Poutès when the turbines were stopped.

In accordance with the 2017 results, arrivals in station 1 and detections downstream of Poutès dam (detections in stations 4 and 5) began to dissociate after the raising of the reservoir level, although the phenomenon was less pronounced than in 2017. Again, this is given simply as an indication, as missed detections prevent direct comparisons.

Transfer rates and passage times

Transfer rates between stations are presented in **Table 2.1.5**. Overall, 96% of smolts were detected (67/70). Transfer from station 1 towards the Poutès dam was very high (97 % between station 1 and station 3). However, 66% of smolts detected at the dam were transferred to station 4. Finally, transfer rate to station 5 (adjusted by considering only fish detected in station 4) was 51%.

At low reservoir level (smolts detected in station 3 before April 9 at 11pm, the time at which reservoir level reached 646.36m NGF), 54 were detected in station 1 and all were transferred to station 3. Passage efficiency to the bypass stretch was 70%, whether limiting the dataset to a period when river flow was <30m3.s-1 (33 smolts), which is twice the mean annual flow, or not. Finally, transfer rate to station 5 was 66% (65% out of "high flow period").

After the reservoir was raised, 10 smolts were detected in station 1 and again, all were detected in station 3. During this period, passage efficiency was 50% (5/10). The difference in passage efficiency between low and high reservoir level was still not statistically significant ($\chi2 = 0.80$, $p = 0.37$). Finally, transfer to station 5 was 60% (3/5). Again, this difference was not significant ($\chi2 = 1.8 .10-30$, $p = 0.99$).

Table 2.1.5: Transfer rates between stations: global and sub-selections according to reservoir level or river flow when smolts entered the Poutès reservoir (detection in station 2). Number and transfer rates in brackets for station 5 were calculated according to the sub-selection of smolts detected in station 4 (detections in station 5 included fish that did not pass station 4 but passed though turbines).

	Release site	Station 1	Station 2	Station 3	Station 4	Station 5
			Global			
Nb (raw)	70	64		65	32	37
Nb (adjusted)	70	67		65	43	37 (28)
Transfer (%)	/	96%		97%	66%	/ (65%)
Reservoir at low level (before 9th April 11pm)						
Nb adjusted	/	57		55	38	32 (25)
Transfer (%)	/	/		95%	69%	/ (66%)
Reservoir at low level and river flow less than 30 $m^3.s^{-1}$						
Nb adjusted	/	36		33	23	19 (15)
Transfer (%)	/	/		92%	70%	/ (65%)
Reservoir at high level (after 9th April 11pm)						
Nb (adjusted)	/	10		10	5	5 (3)
Transfer (%)	/	/		100%	50%	/ (60%)

For all routes used by smolts (spillway, bypass or intake), passage times at Poutès (N=65 passages) are presented in **Figure 2.1.17**. All passage times are in UTC. Overall, passages were mainly "twilight and nocturnal": 80% (N=65) occurred between 6pm and 6am, 75% of which (N=39) between 6pm and 2am. For passages at low reservoir level (N=55), 82% (N=45) were recorded between 6pm and 6am, 76% (N=34) of which between 6pm and 2am. When river flow was <30 m3.s-1 (N=34 passages), 94% of passages (N=32) were between 6pm and 6am, 88% of which (N=28) between 6pm and 2am. At high reservoir level, passage numbers were low, but 70% were still between 6pm and 6am.

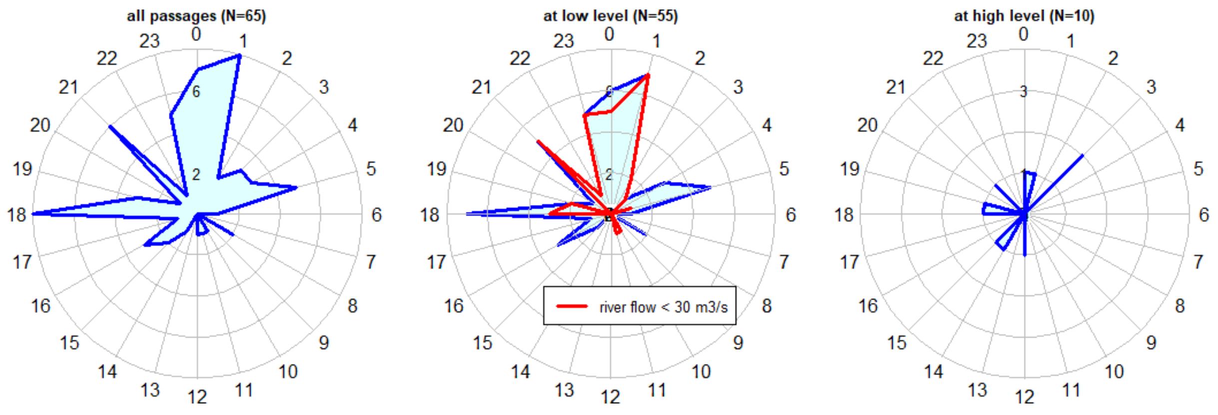


Figure 2.1.17: Radial plots of passage times (UTC) at Poutès according to reservoir level.

Focusing on twilight hours, passage distribution according to the period of the day and the reservoir level was obtained (**Table 2.1.6**). At low level, distribution was significantly modified between low and high river flow ($\chi 2$ = 20.2, p < 0.001). More daytime and twilight passages were observed when river flow was ≥30 m3.s-1. Using the distribution at low level with river flow <30 m3.s-1, no significant difference was found between low and high level, but passage numbers at high level were low ($\chi 2$ = 4.2, p = 0.12).

Table2.1.6: Period of passages according to reservoir level.

	Day		Twilight		Night	
	nb	%	nb	%	nb	%
At low level	12	22%	14	25%	29	53%
At low level (river flow < 30 m^3.s^{-1}	4	12%	4	12%	26	76%
At high level	4	40%	1	10%	5	50%

Residence time and behavior in the reservoir

As developed in the Material and Methods section, the median transfer time between station 1 and station 2 in 2017 (73 min) was used to estimate reservoir entry at low reservoir level. Median residence time at low reservoir level with river flow ≥30m3.s-1 was 2.1 h (mean = 7.4 h; range, 41.4 min to 2.8 d; 3rd quartile, 5.9 h) (**Figure 2.1.18**). Median residence time at low reservoir level with a river flow <30m3.s-1 was 4.4 h (mean = 13.6 h; range, 33 min to 4.6 d; 3rd quartile, 20.6 h).

At high reservoir level, median residence time was 17.2 h (mean = 31.3 h; range, 2.4 h to 5.8 d; 3rd quartile, 1.6 d).

A log-normal linear model confirmed that the effect of reservoir level on residence time was significant (ANOVA, F = 6.0348, p < 0.001). The model coefficients were significant except for low reservoir level when river flow was > 30m3.s-1 indicating that residence time was significantly higher at high reservoir level (t-test, p < 0.05) but not significantly lower when river flow exceeded 30m3.s-1 (t-test, p = 0.07), both compared to residence time at low reservoir level with river flow <30m3.s-1.

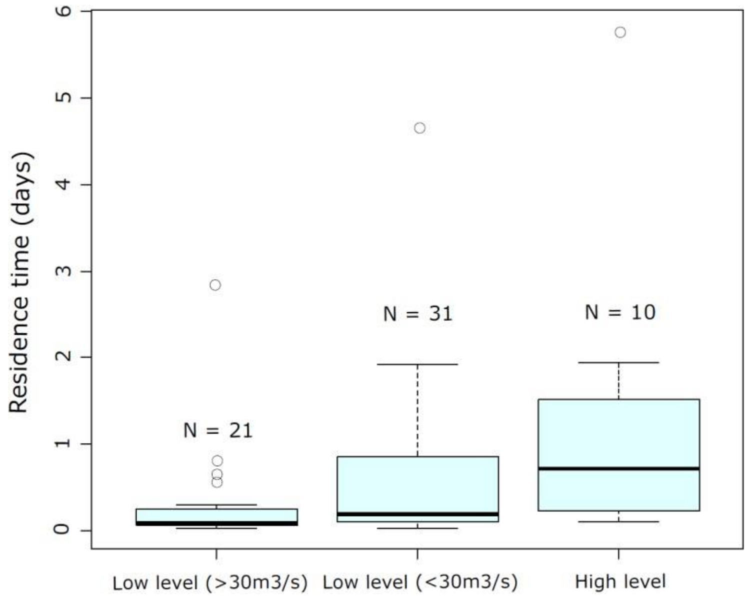


Figure 2.1.18: Residence time according to reservoir level and river flow during smolt entry.

At low reservoir level, 87% of smolts (46/53) passed the dam at the first attempt (median = 1; mean = 1.4; range, 1-7) (**Figure 2.1.19**). At high reservoir level, the median number of attempts per smolt was 3 (mean = 3; range, 1-6). 90% of smolts made fewer than 5.1 attempts. The difference in attempt between low and high level was significant (Mann-Whitney, W = 115, $p < 0.001$).

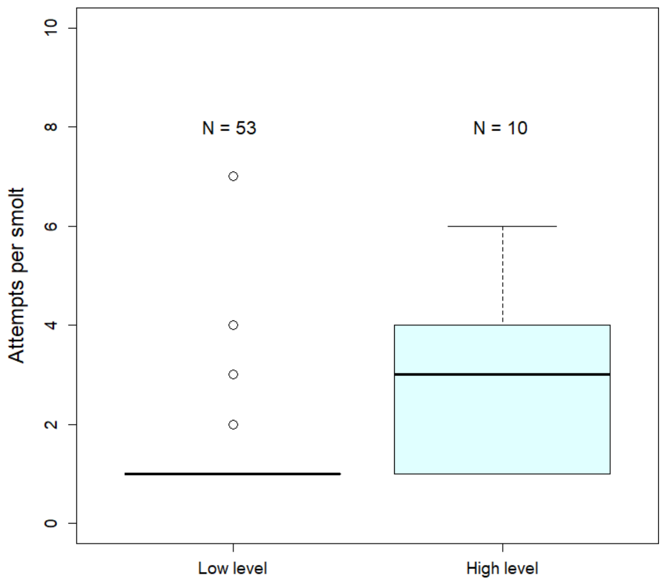


Figure 2.1.19: Number of attempts per smolt according to reservoir level.

Spatial representation of position density (**Figure 2.1.20**, pixel size 2 x 2.7m) indicated that the dam area was not correctly covered, especially upstream of the dam zone, as no hydrophones could be installed, and in the two zones where hydrophones were not retrieved (hydrophones dotted in red on

Figure 2.1.20. Nevertheless, detection density was still maximal in the north-west corner of the hydrophone array. In view of this poor spatial coverage, no UD maps were calculated in 2018.

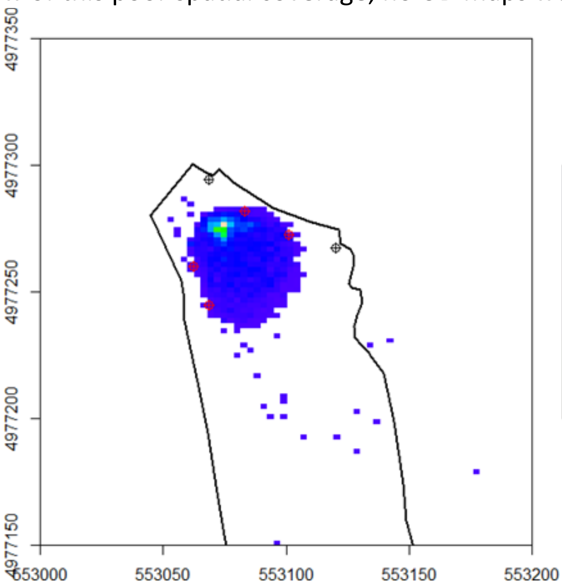


Figure 2.1.20: Spatial representation of position density (pixel size = 2 x 2.7m).

Passage routes

The spill ratio (Q spilled / Q River) seemed to be higher for smolts that were detected in the bypass stretch considering all passages and passages at low reservoir level with river flow more/less than 30 m3.s-1 (**Figure 2.1.21**). Turbined flow during passage according to passage route is presented on **Figure 2.1.22**.

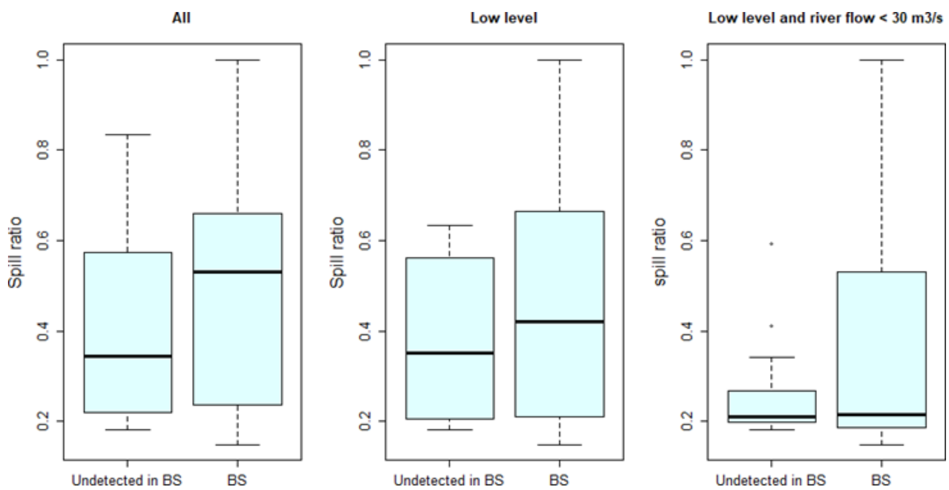


Figure 2.1.21: Spill ratio according to passage route for all passages, passages at low reservoir level and passage at low reservoir level and river flow <30m3.s-1. BS: Bypass Stretch.

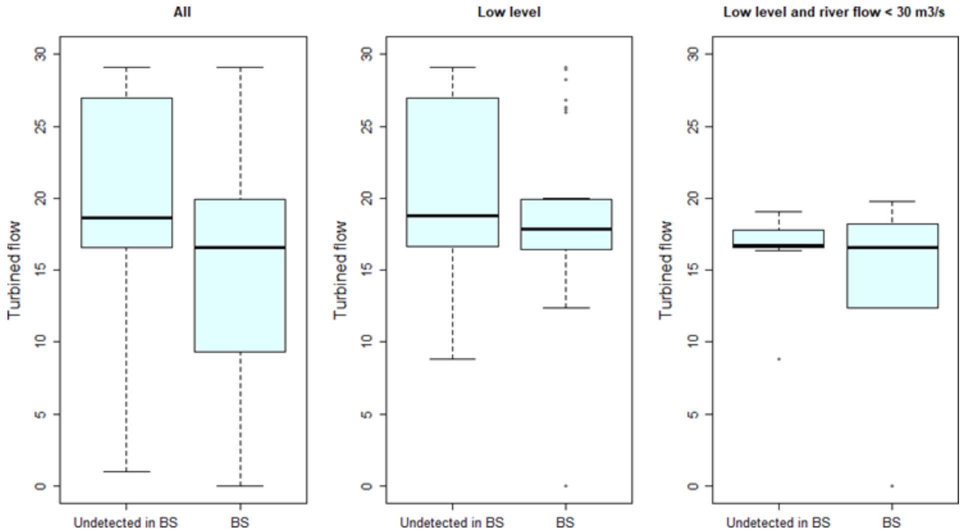


Figure 2.1.22: Turbined flow according to passage route for all passages, passages at low reservoir level and passage at low reservoir level and river flow <30m3.s-1. BS: Bypass Stretch.

Logically, some of the hydrological variables were highly intercorrelated (**Figure 2.1.23**). A GLM with a binomial distribution was built to explain passage routes, for low reservoir level passages only. Only two variables did not correlate and could be simultaneously integrated in the model: Spill ratio and Turbined flow. The interaction term between the two was also included.

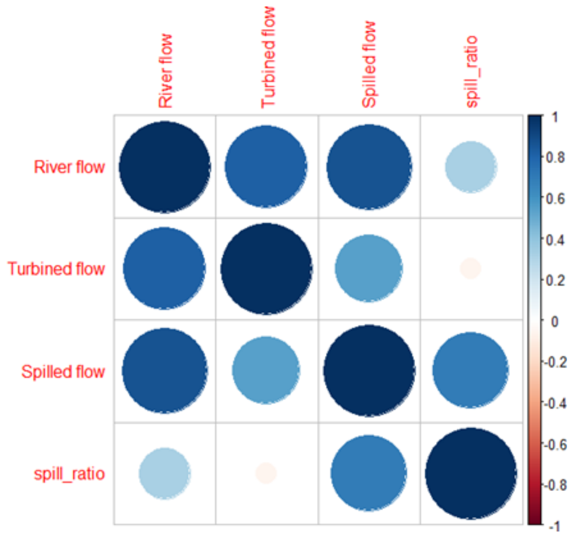


Figure 2.1.23: Spearman correlation coefficient matrix of the hydrological variables considered.

Model selection was conducted with the stepAIC procedure (R package Mass). The best model selected was the one that integrated both spill ratio and turbined flow. Only turbined flow during passage had a significant effect on escapement probability (ANOVA, p (spill ratio) > 0.05 and p (turbined flow) < 0.05). The coefficients in the model were positive for spill ratio (2.52335, t-test, p = 0.14) and negative for turbined flow (-0.11125, t-test, p-value = 0.08). **Figure 2.1.24** represents observed passages (1 for bypass stretch; 0 for unknown/turbines), predicted values in red and escapement probability modeled for different discharges in the intake (10, 20 and 28m3.s-1).

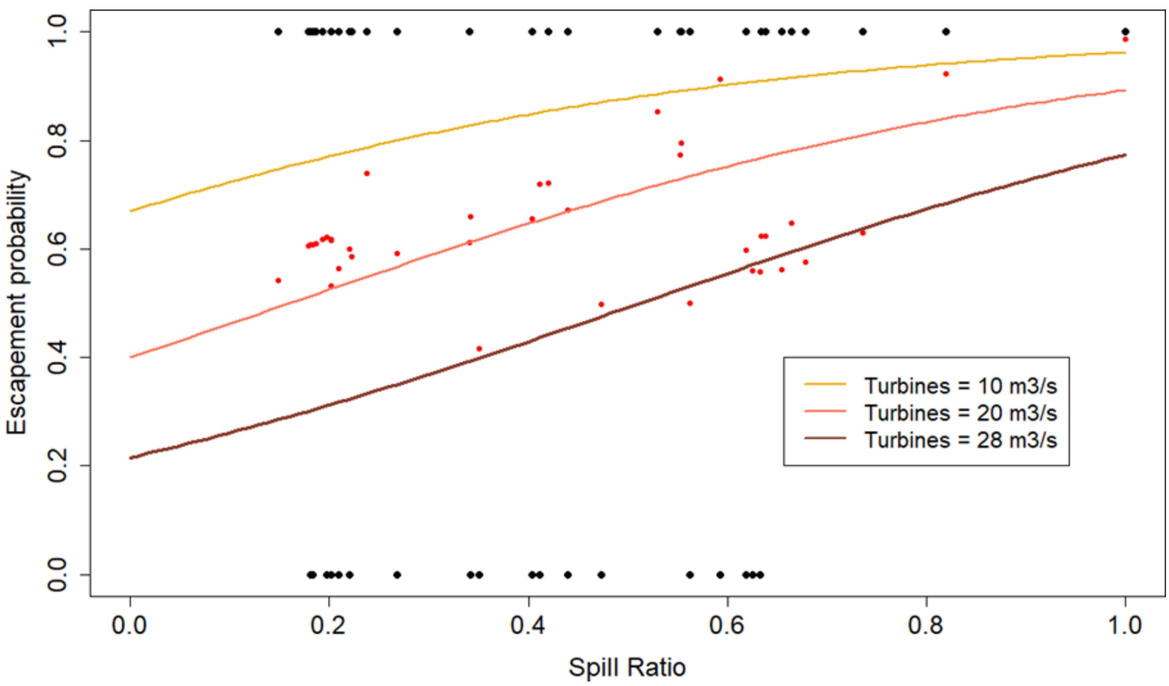


Figure 2.1.24: Escapement probability according to spill ratio for different discharges in the intake. Observed passage are dotted in black (1 for bypass stretch; 0 for unknown/turbines) and predicted values are dotted in red.

eDNA

We detected twenty-nine freshwater fish species with eDNA along the altitudinal gradient, with species richness decreasing with increasing altitude and fish richness above the impounded water almost half that below (**Table**). Conversely, invertebrate richness increased with altitude from approximately 56 species (± 6 SEM) downstream to 66 species in the impounded (± 6 SEM) and upstream waters (± 3 SEM; **Table .7**). Taxa traditionally used to indicate water quality (Ephemeroptera, Plecoptera and Trichoptera; collectively referred to as EPT) all increase in richness above the dam and impounded water (**Table**). In contrast to fish and invertebrate richness, photosynthesising organisms were at their richest in the centre of the sampled area with impounded water; with a rise in the richness of cyanobacteria (bacteria known as blue-green algae) and Viridiplantae (comprising green algae and vascular plants). However, the DNA of land plants (terrestrial Viridiplantae) was detected in highest concentration upstream and decreased with altitude.

Table 2.1.7: eDNA detection of species richness at multiple trophic levels. Mean total richness of species, and the standard error of the mean of i. fish, ii. invertebrates and iii. primary producers (photosynthesising organisms), including the richness of important functional groups, taken across sampled sites above and below the Poutés dam as well as the water impounded behind the dam

	i. Fish			ii. Invertebrates							
	Total	rheophilic	non-rheophilic	Total	Crustacea	Ephemeroptera	Plecoptera	Trichoptera	Coleoptera	Mollusca	Rotifera
Upstream	**7 ±0.4**	5.9 ±0.3	1.1 ±0.2	**65.7 ±2.7**	1.3 ±0.2	26.5 ±1.6	17.1 ±1.6	0.6 ±0.2	1 ±0.2	2.1 ±0.3	2.7 ±0.5
Impounded	**10.7 ±0.2**	8.3 ±0.0	2.3 ±0.2	**66 ±6**	1.8 ±0.3	21.2 ±2.4	11 ±1.9	0.5 ±0.2	1 ±0.4	3.3 ±0.6	7.7 ±1.1
Downstream	**16.1 ±0.3**	10 ±0.2	6.1 ±0.3	**56.3 ±5.9**	1.4 ±0.3	20.5 ±2.3	6.3 ±1	0.5 ±0.1	1.9 ±0.4	2.4 ±0.4	9.9 ±0.9

	iii. Primary producers (plants)									
	Total	Viridiplantae	Terrestrial	Streptophyta	Cyanobacteria	Red algae	dinoflagellate	Diatoms	Golden algae	Cryptophyta
Upstream	**402.7 ±15.6**	89 ±3	19.5 ±0.8	29.1 ±1.1	144.1 ±5.1	5.3 ±0.4	4.3 ±0.4	82 ±4.2	1.3 ±0.2	21.5 ±1.8
Impounded	**537 ±27.3**	129.2 ±10.3	18.2 ±1.2	30 ±1.7	177.7 ±9.8	2.3 ±0.2	6 ±0.6	93 ±3.9	1.3 ±0.3	37.2 ±1.3
Downstream	**492 ±18.8**	110.1 ±5.5	15.6 ±1	25 ±1.1	151.2 ±8.5	4.2 ±0.4	5.7 ±0.2	103.6 ±2.4	1.4 ±0.2	36.4 ±1.5

A 2.1.9 Discussion

This study aimed to assess the efficiency of adaptive management of the Poutès-Monistrol hydropower complex during the spring migration of Atlantic salmon smolts. These adaptive management "temporary operating measures" were tested for two years. They consisted in lowering the Poutès reservoir, and 1) modulating power plant operation for 20 nights in 2017 and 2) stopping turbine operation for 20 nights in 2018.

The study confirmed that lowering the reservoir level was a very effective measure to reduce the delay caused by the reservoir. A synthesis of residence times according to reservoir level and study years, excluding periods of high river flow (≥30m3.s-1) is presented in **Table 2.1.8**. Telemetry experiments were conducted in 2015 to assess the delay caused by the reservoir in normal operation (Tétard et al. 2016a). Considering all years, operating at low reservoir level reduced residence time by a factor between 20 and 34.

Table 2.1.8: Residence time in the reservoir according to study years and reservoir level.

Study Year	Reservoir level	Number of smolts tracked (excluding when river flow ≥ 30 $m^3.s^{-1}$)	Median residence time	3^{rd} quartile of residence time	9^{th} decile
2015	High	91	9.3 d	23.6 d	35.6 d
2017	Low	6	3.6 h	2.1 d	17.1 d
2017	High	18	4 d	12.5 d	17.7 d
2018	Low	31	4.4 h	20.6 h	26.6 h
2018	High	10	17.2 h	1.6 d	2.3 d
All years	Low	37	4.4 h	20.7 h	35.7 h
All years	High	119	6.22 d	19.7 d	30.6 d

In 2015, causes of the delay were identified as reluctance to enter the bypass and disorientation in the reservoir. The median number of passage attempts in the dam zone before passing downstream was 12, and 64.8% of smolts went back to the upstream end of the reservoir at least once after being detected in the dam area (Tétard et al. 2016a). At low level, no fish went back upstream (2017 only – no station 2 in 2018) and the median number of attempts was 1 (2017 and 2018). Whichever route smolts use, they quickly cross the reservoir and pass downstream.

To explore whether the temporary reservoir still induces delay, the time needed by smolts to travel the same distance could be compared with the migration speed observed in a free-flowing stretch. Over a distance of 3.9km, from station 1 to station 2, median migration speed was 20km.d-1. This is comparable with other studies although migration speed is known to vary widely between rivers and environmental conditions (Imbert et al. 2013, Huusko et al. 2017, Havn et al. 2018). Extrapolating this speed to the temporary reservoir distance (from station 2 to station 3: 700m) would imply 50.4 min to cross that river stretch. Although estimated with uncertainties, comparison with median residence time at low reservoir level shows that the temporary reservoir would still induce a delay, although short, probably linked to decrease in velocity field in the reservoir. One interesting question remains: transition from a situation with substantial delay caused by disorientation to an acceptable situation for smolt migration could be progressive, but how are acceptable hydraulic conditions to be determined that prevent detrimental delay? The case of Poutès shows that a shorter reservoir can be compatible with smolt migration (in terms of delay). This is essential information for stakeholders discussing remedial measures in other situations.

Concerning passage success, results were more mixed: at low reservoir level, passage efficiency was 65% (63% in 2017 and 66% in 2018) and was 68% (60% in 2017 and 70% in 2018) for passages with river flow <30m3.s-1 (better detection efficiency). At high reservoir level, passage efficiency was 66% (66% in 2015 (Tétard et al. 2019), 72% in 2017 and 50% in 2018). Passage efficiency seemed to be similar regardless of reservoir level, but this masks very different situations: at high reservoir level, a proportion of smolts come to the dam but never cross it. Focusing on "passing smolts", crossing dam by whichever route (bypass, spillways or intake), the rate of smolts using the bypass at high reservoir level is close to 90% (Bach et al. 2004, Tétard et al. 2016b). At low reservoir level, almost all smolts detected at the dam passed it, indicating that a higher proportion was led into the intake. Basically, this appears quite logical, as the intake is 7m below the surface at normal reservoir level but 1.5m below at low level. Nevertheless, modulating turbine operations should have reduced the risk by reducing the attractiveness of the intake. Thanks to high hydrology during both years and especially in 2017 with the modulation of the turbines, spill ratios (Q spill/Q total) during passages at low reservoir level were substantial between 20% and 74% in 2017. This shows that spilling water to divert smolts is not enough if the gap-width of the rack is not repulsive enough, especially when the hydropower plant is approaching maximum capacity. Haraldstad et al. (2018) showed that river flow negatively affected fish guidance efficiency in plants with rack gap-width between 50 and 80mm. High (>90%) fish guidance efficiencies were obtained, but only with a river flow ≤ 30% of maximum plant capacity. Moreover, it is clear that the geometry of the intake and resulting approach flow patterns must be of great importance: in the case of Poutès they might guide smolts toward the intake. Smolts typically follow bulk flow (Coutant and Whitney 2000) and, even with high spilling, bulk flow may still guide them toward the intake. This result underlines the importance of 1) stopping fish, 2) guiding them toward bypasses and 3) safely transferring them downstream, and gives credence to design criteria developed for "fish-friendly" intakes (Courret and Larinier 2008, Calles et al. 2013, Tomanova et al. 2017, Nyqvist et al. 2018, Tomanova et al. 2018). Nevertheless, efficient solutions that can be implemented in large installations are needed.

As it was concluded that the modulation led to insufficient passage efficiency after the 2017 experiment, it was decided, in coordination with local stakeholders, to entirely stop the turbines with the same 20-night quota. At first sight, this measure seemed to be very effective, but there are two great challenges: Are the passages of tagged smolts truly representative of wild fish dynamics? And is turbine shutdown effective for tagged smolts or not?

As developed in the Results section, only 11% of smolts (6/55) that migrated at low reservoir level did so under turbine shutdown. However, the 45 hatchery fish were released on March 30, when only one night of the “shutdown quota” was left. Captures in the rotary screw trap indicated that there were still some fish left to migrate, but very few considering that the rotary screw trap was in its full operating range: 2 on April 3, 1 on April 7, 3 on April 10 and 2 on April 11. Monitoring natural migration with the rotary screw trap since 2013 has shown that a majority of smolts leave upstream habitats in March, the rest migrating in April: 95% of total catches were in March 2013, 88% in 2014, 63% in 2015 (the trap was not operating from March 1st to 10th in 2015). This seems to be especially the case in years with increased river flow at the beginning of the season, such as 2013 and 2014. This phenomenon was also reported in other studies (Whalen et al. 1999, Otero et al. 2014, Teichert et al. manuscript submitted for publication). Consequently, a great majority of wild smolts may have migrated during the first two flood events in 2018. More generally, upstream of Poutès, a great majority of smolts can be thought to migrate between March and mid-April. In other studies, onset and end of migration differed depending on local context, the earliest timings being observed in southern populations (Thorstad et al. 2012). The mean duration of the main smolt run (90% of total migrants) varies between years and studies but seems to extend over a period of 30-45 days (Byrne et al. 2003, Bosc et al. 2017). During 11 years’ monitoring, Teichert et al. (manuscript submitted for publication) observed that 80% of total catches ranged between 15 and 38 days on the River Ourthe in Belgium.

As developed in the Results section, only 4 smolts of the 1st release migrated during shutdown, but 1) turbines were restarted during floods and 2) they were restarted two hours earlier in the morning until March 20th. Consequently, with two more hours of shutdown and a continued shutdown during floods, 60% of (15/25) migrated during turbine shutdowns. The other 40% migrated between 6am and 6pm, which is not really representative of the usual pattern of migration observed in March. Nevertheless, these results show that a substantial proportion of smolts can migrate during daytime and twilight during floods, even at the beginning of the migration season when they are predominantly nocturnal. During the first flood peak, after river flow reached 30 m^3s^{-1}, 38% of smolts migrated during daytime (8/21) and the mean river flow during their passage was 57m^3s^{-1} (for 5 of them, the river flow was ≥66m^3s^{-1}).

For the 2019 negotiations between stakeholders to set the last year of temporary measures, it was important to use all available smolt passage times at low reservoir level, whatever the shutdown quota, to see whether the time slot was adequate or had to be extended. Table 2.1.9 presents 3 scenarios of passage efficiency, considering that all smolts would migrate during a period when shutdowns are in place. Based on arrival times at the Poutès dam (Station 3), smolts arriving outside the shutdown time slots pass into the bypass stretch with 65% efficiency (passage efficiency at low reservoir level, see above), while the remaining 35% show a 50% probability of survival, based on mortality tests conducted in 1984 in Poutès (Larinier and Dartiguelongue 1989).

Table 2.1.9: Scenarios of survival at Poutès scale regardless of any turbine shutdown quota.

Time slot of turbines' shutdown (UTC)	Nb smolts at low level	Daily duration of shutdowns	Nb of smolts passing during shutdowns	Proportion of smolts passing during shutdowns	Proportion in bypass stretch (65% efficiency)	Global survival (50% mortality)
6pm - 6am	68	12 h	57	84%	94% (84 + 10)	97%
5pm – 7am	68	14 h	59	87%	95% (87 + 8)	97.5%
4pm – 8am	68	16 h	62	91%	97% (91 + 6)	98.5%

During the two years of telemetry studies at low reservoir level, these estimates show that between 84% and 91% of smolts migrated during turbine shutdowns, depending on the scenario, resulting in 97-98.5% global survival if 1) turbines were stopped even during floods and 2) the period of shutdowns fitted the presence of all smolts.

A turbine shutdown quota can be set by predicting operational phenological indicators such as onset, end and duration of migration when smolt migration monitoring data are available (e.g., trap data, unbiased1 videocounting in bypass). Some modeling approaches accurately forecasted smolt migration dynamics (Sykes et al. 2009, Teichert et al. manuscript submitted for publication). Nevertheless, long migration monitoring series are not always available, so there is an important need to develop transposable methods. On the other hand, the negotiation process with stakeholders will often have to find a compromise between hydropower production and mean a priori migration duration, resulting in a fixed number of shutdown nights. One serious threat arising with global warming is that migration onset is getting earlier (Jonsson and Jonsson 2014, Otero et al. 2014) and that mean duration of migration might increase (Teichert et al. manuscript submitted for publication).

Finally, based on the 2017 and 2018 results, stakeholders agreed on 2019 temporary operating measures for the last year before reconfiguration of the dam: operation at low reservoir level during smolt migration, a quota of 45 nights triggered by river flow (>20m^3s^{-1}) or by smolts captures at the rotary screw trap, and a time slot of 4pm to 8am (UTC) (4 hours' increase). These measures were not monitored but were sufficiently ambitious to suggest that smolts were and will be efficiently protected during spring 2019 and 2020, respectively.

Since the summer of 2019, work to build the "next" Poutès has begun. Construction will last 3 years. The new Poutès reservoir level will be set at 642 m NGF: i.e., 2.7m lower than during the temporary operating measures. This level will indisputably enable quick passage for smolts. Fish passage solutions will consist in the association of a physical rack (12mm gap-width) and a bypass (3-4m^3s^{-1} depending on the season, representing 11-14% of maximum intake capacity), which should achieve high passage efficiency.

The eDNA metabarcoding show clear shifts in species presence coinciding with the Poutés dam. Certain species could be diagnostic of fragmentation, for example the fish species *T. tinca*, *R. rutilus*, *A. brama* that all occured up to the impounded water of the Poutés dam (**Figure 2.1.6**: Fish presence **along** altitudinal gradient. Heatmap showing if a species of fish (column) was detected at a particular site (column). Site 20 is furthest downstream, and the red dashed line demarcates the position of the Poutés dam. Darkest squares indicate that a species was detected from eDNA in all sample replicates and white indicates non-detection.). Clearly delimited patterns of habitat fragmentation could also be witnessed in the distribution of primary producers that fix carbon down the length of the Allier tributary. The presence of greater diversity of eDNA from terrestrial plants in the upper elevations is consistent with the River Continuum Concept (Vannote et al., 1980), which models an 'ideal' river, and hypothesises that exogenous sources of carbon input are more prevalent in upper waters, giving way to autochthonous carbon production in the form of algal photosynthesis further downstream. However, eDNA metabarcoding did not detect a linear transition of plant richness from upstream to downstream as shown in **Figure 2.1.7**, where the MDS axis that explains the most variance has an evenly spaced transition between samples taken at the upper and lower reaches of the river, but not in the section of river affected by the Poutés dam.

Fish communities become less diverse immediately upstream of the Poutés dam (**Figure 2.1.5** and **2.1.6),** with non-rheophylic fish showing greater effects of fragmentation. Invertebrate richness, by contrast, become more numerous upstream the Poutés dam. This could be related to water quality, as the increased richness of EPT species is indicative of degraded water are represented more numerously in eDNA samples from higher elevations. The inverse correlation of invertebrate and vertebrate richness could also indicate the paucity of fish taxa exerting top down control on small invertebrates. Overall, metabarcoding taxa at multiple trophic levels enabled us to collect valuable data beyond how biology relates to physical barriers and physico-chemical factors, but also to biological interactions important in structuring ecological communities that are modified by physical barriers in rivers.

A2.2 CASE STUDY 4: Quoich Dam, Upper River Garry

A2.2.1 Overview and aims

AMBER's Scottish case study was led by the Rivers and Lochs Institute (RLI), University of the Highlands and Islands (UHI) - Inverness College. It focused on the assessment of ecosystem restoration needs arising from the presence and operation of hydroelectric dams on the River Garry, one of the main tributary rivers within the Ness catchment.

The two dams in the catchment are two of the five hydropower dams comprising the Great Glen Hydropower Scheme (hereafter GGHS), the other three being located on the River Moriston. A very significant reduction in the salmon population of the River Garry following installation of the dams, and the ongoing efforts at mitigating these impacts, prompted the choice of this river system as the case study for applying the barrier impact tools and adaptive management framework developed within AMBER.

Understanding the conservation challenge of this iconic and economically important fish species requires consideration of broader river ecology and connectivity issues, as well as of the social, cultural and economic context, as described in the following case study aims:

1. Characterise the **habitat downstream of existing barriers** within the GGHS, to identify potential issues that might be impacting fish populations, using a variety of tools and methods,

including water sampling for eDNA and water quality assessment, drone imagery, habitat surveys and deployment of temperature sensors.

2. Report on current knowledge of **salmon smolt escapement** through existing hydropower barriers and establish, using a salmon eDNA barcoding approach, whether the Caledonian canal (running parallel to the Oich and Ness rivers further downstream from Garry dam) acts as a barrier in the migration of salmon smolts out to sea.

3. Investigate the **historical, social, ecological and economic implications of the construction and operation of the hydropower scheme**, to the present day, through archive research and engagement with stakeholders and the local community.

4. Develop an **adaptive management framework for the catchment** to provide recommendations for future research/management to improve its ecological status and mitigate for the impacts observed.

A2.2.2 Tasks and partners involved

Development of the case study was made possible through a variety of different partnerships. At the onset of the project, the RLI partnered with the Ness District Salmon Fishery Board (hereafter NDSFB) and with Scottish and Southern Energy (SSE), the hydropower company that owns the Great Glen Hydropower Scheme, to discuss project progress and operations. Said partnership was already in existence prior to the launch of AMBER, in the form of the "Upper Garry Salmon Restoration Project", a selective salmon breeding and stocking program based on identification and promotion of the original dwindling salmon population through genetic analysis, which will be described in more detail in section A2.2.5.2.

The broader adaptive management and tool development approach underpinning AMBER involved a broader set of collaborations. During the case study, the following activities were completed in partnership with additional institutions:

- Development of the eDNA tool for barrier assessment in collaboration with Swansea University and the University of Oviedo

- Drone survey and sediment analysis in collaboration with Shobhit Pipil, Patrice Carbonneau and Martyn Lucas (University of Durham, Geography department, AMBER partners).

- MesoHABSIM habitat assessment in collaboration with Piotr Parasiewics (S. Sakowicz Inland Fisheries Institute, Poland) and Zbigniew Kaczkowski (Department of Applied Ecology University of Lodz, Poland), both AMBER project partners.

- Placement of temperature sensors below barriers in collaboration with Faye Jackson and Pauline Proudlock as part of the Scotland River Temperature Network intiative, led by Iain Malcolm at Marine Scotland Science (MSS), the scientific division of Marine Scotland.

- Discussion on barrier management practices in Scotland with Kjersti Birkeland and Alistair Duguid at the Scottish Environmental Protection Agency (SEPA).

- Investigation of historical, cultural and linguistic background for the case study area (Gaelic-speaking at the time the dams were installed), in collaboration with Professor Hugh Cheape (based at the National Centre for Gaelic Language and Culture - Samhal Mor Ostaig College UHI, hereafter SMO), and through the work of Mairi Innes, joint MRes student between the RLI and SMO, and funded through AMBER.

- Interviews and workshops with members of the local community with support from the Glengarry Heritage Centre (Veronica Sandham) in Invergarry.

- Water quality sample collection and analysis conducted in parallel with eDNA water sample collection, in collaboration with Drs Paul Gaffney and Mark Taggart at the Environmental Research Institute UHI (ERI)

- Processing of DNA samples for a subset of DNA and water quality locations to send to the Funaqua consortium, whose remit is to investigate aquatic fungi biodiversity across the world, with a view to assessing fungal biodiversity in the context of hydro power (as an addition to invertebrates, diatoms and fish)

Within the constraints of the primary focus of the project on the Upper Garry, a catchment-wide approach (the hallmark of any adaptive management strategy) was sought, and the core eDNA analysis of barrier impacts for the Great Glen Hydro Scheme was extended to:

- eDNA analysis of Loch Ness, as part of the Loch Ness Hunters project, providing additional information in terms of species composition and lake ecology to compare and contrast with Loch Quoich and Loch Garry (both impounded by hydropower dams) – data will be presented and a full comparison undertaken once the primary Loch Ness paper is published.

- eDNA analysis of the presence of salmon in the Caledonian Canal (as outlined in aim 2 and in section A2.2.11), run in parallel to a smolt tagging experiment (part of the Missing Salmon Project) aimed at quantifying the impact caused by the Caledonian canal on the downstream migration of smolts from the Garry.

Finally, the AMBER project coincided with another initiative, the “Garry Dam Screens Project” led by case study partners, SSE and NDSFB, to investigate the impact of the screens placed on Garry Dam to shield smolts from going through the hydropower turbines when the plant is in production. An assessment was made of the effect of the turbines on smolt survival when the screens were removed, to see whether lack of screens could potentially improve smolt escapement. The results are outlined in section A2.2.5.2.

As can be seen from the above list of partners and activities, the Ness catchment has been under intense study for the past five years, through AMBER and other initiatives, and there is great potential for a comprehensive adaptive management framework to be developed, bringing together researchers and relevant stakeholders.

A2.2.3 The Ness catchment

The Ness catchment is the largest in the North Highlands and drains 2,103 square kilometres of land. It is oriented along the axis of the Great Glen fault, running through the Great Glen from southwest to northeast and its key feature is Loch Ness, the largest lake in the United Kingdom by volume, and second largest by size. Along the Glen, south of Loch Ness, lies Loch Oich, to which it is connected by the River Oich. North of Loch Ness, the catchment drains into the North Sea through the River Ness. Various tributaries flow into Loch Ness (Rivers Enrick, Coiltie, Foyers and Moriston to the West, and Foyers, Farigaig and Tarff to the East), and further upstream into Loch Oich (the River Garry, and its own main tributary, the River Kingie) (**Figure 2.2.1**).

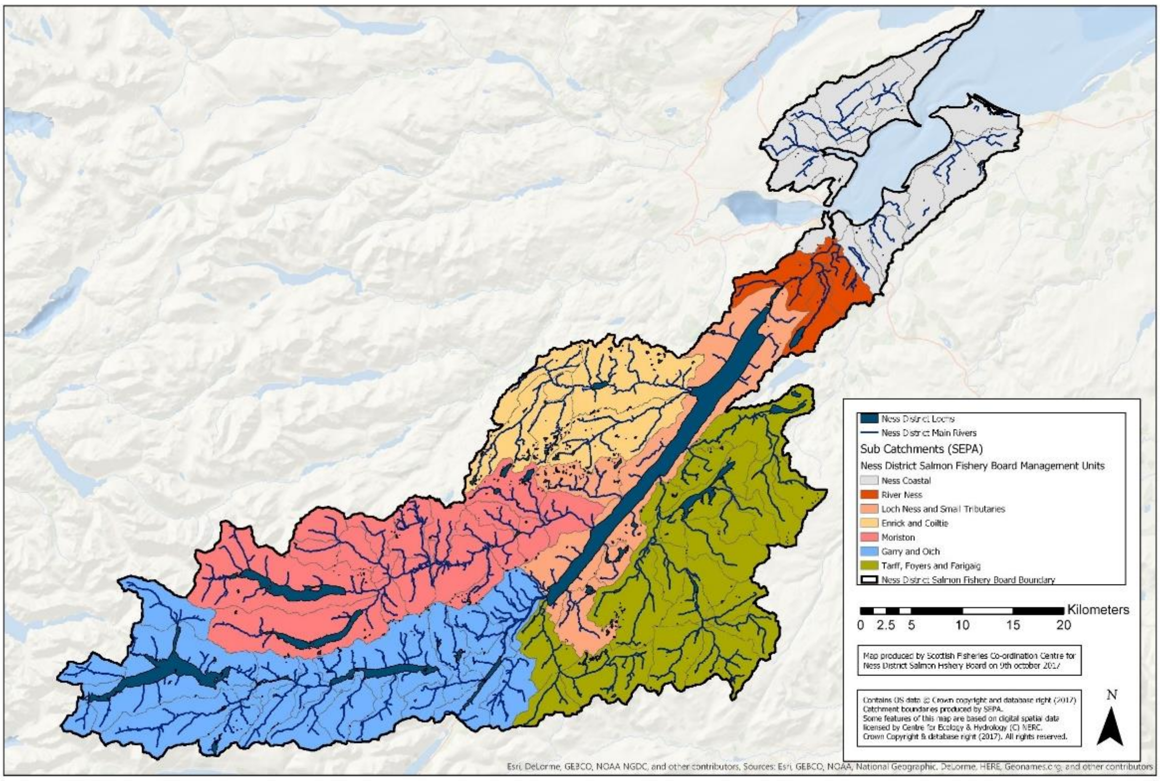


Figure 2.2.1. Ness Catchment and subcatchments (image courtesy of the Ness District Salmon Fishery Board).

The River Ness is relatively short, and the catchment dominated by the two longest watercourses in the southwest, the Moriston and Garry Rivers, as shown in the simplified catchment map (**Figure 2.2.2**).

The Garry and Moriston rivers are of additional significance due to the fact that the main lochs beside Loch Ness and Loch Oich are located in the Garry and Moriston subcatchments, with Loch Garry and Loch Quoich on the Garry, and Loch Cluanie and Loch Loyne on the Moriston (see **Figure 2.2.3**). All these Lochs are dammed, as is the smaller Dundreggan reservoir on the lower Moriston, which was created by placing the dam over a pre-existing waterfall. Given that these subcatchments comprise some of the rainiest areas in Scotland, they were considered a prime site for hydropower development.

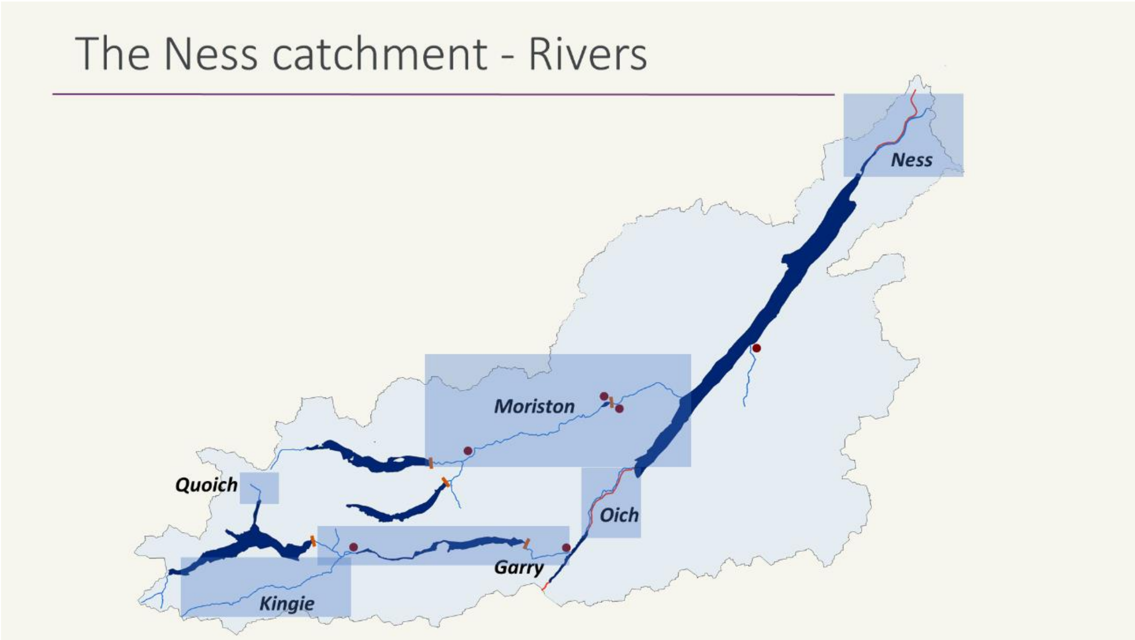


Figure 2.2.2. River Ness catchment - main rivers (orange rectangles = hydropower dams, red circles = power stations).

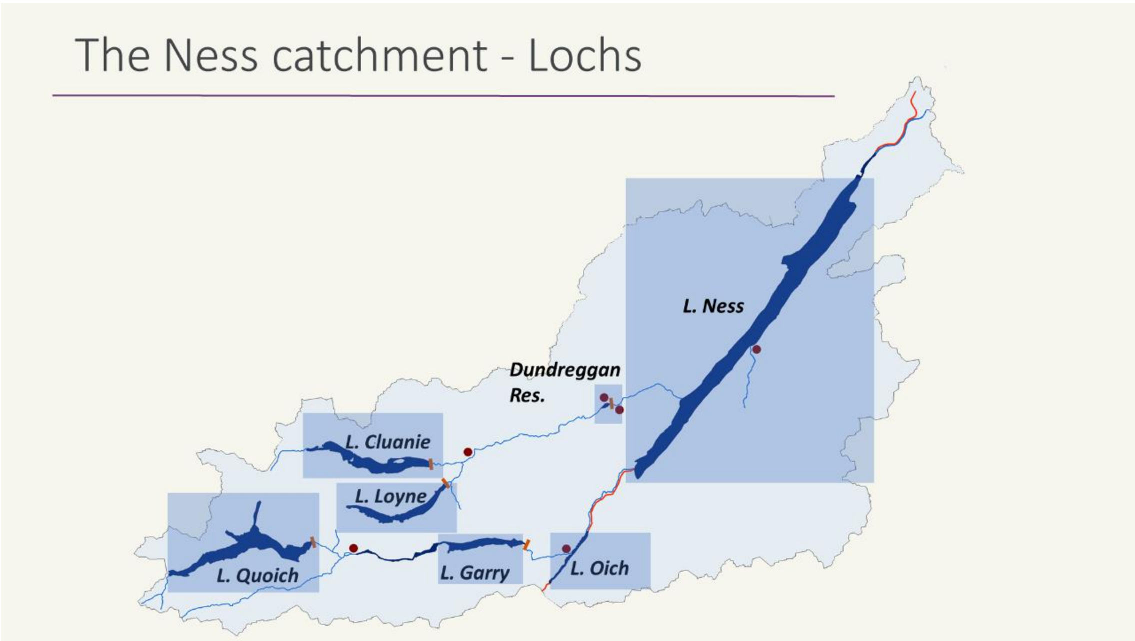


Figure 2.2.3. River Ness catchment - main lochs (orange rectangles = hydropower dams, red circles = power stations).

A2.2.3.1 Present-day demographics and land use

To understand the social and economic impact of the GGHS, it is important to explore the history and demographics of the area in which it was developed. Glengarry, the case study area, is located in Ward 11 of the Highland Council area (Caol and Mallaig), whose population is estimated at 8246 in 2018 (National Records of Scotland Web, 2013), over an area of 2,043 Km^2. The population density of 4.343

ind / Km^2 is much lower than the average for the whole of Scotland (67.2/km^2), and low for the Highlands area (9 ind / Km^2), which already has the lowest population density in Scotland (National Records of Scotland Web, 2016).

The population resident in Glengarry (using postcode data – PH35, broken down into Glengarry S00117853 and Invergarry S00117854) is currently (2011 census) 275 individuals, with a total number of 142 households (main settlements shown in yellow in Figure 2.2.4). Notwithstanding, or possibly due to, its remoteness there has been significant immigration from England and Wales over the past decade compared to the average for Scotland (2011 census). This is not a new trend, as will be outlined in the next section, and the composition, demographics and spatial distribution of the local community has undergone dramatic changes over the last two centuries. Historically, at times, the population is likely to have been four-fold greater and a great number of former settlements no longer exists. As such, the barren appearance of much of this land today is due to centuries of social change, rather than being its default natural state.

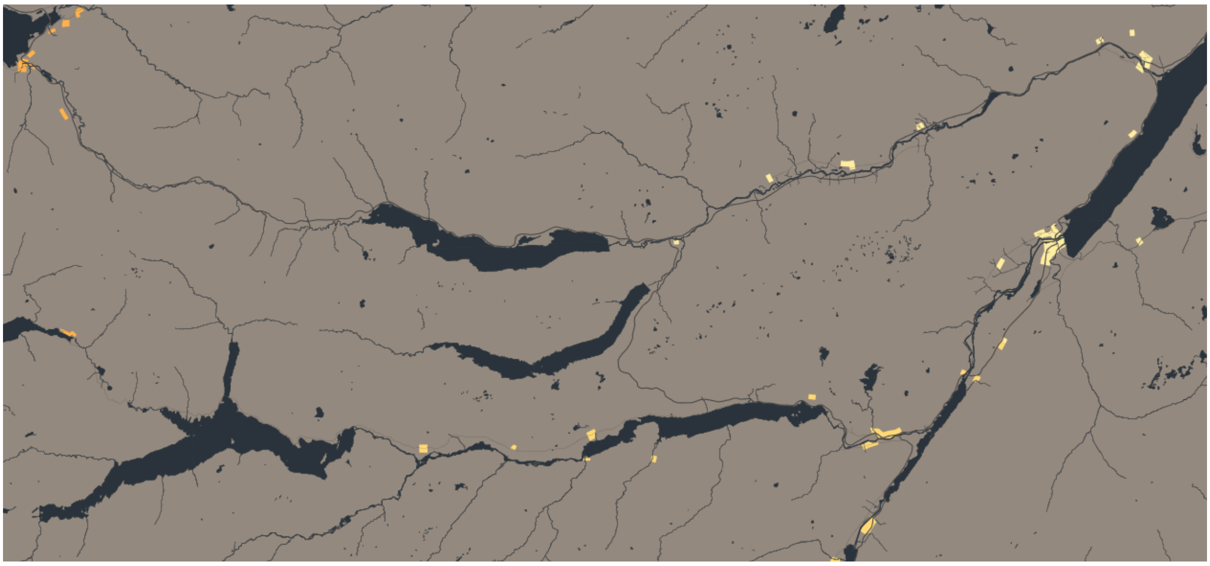


Figure 2.2.4. Main settlements in Glengarry and Glenmoriston in 2011 (Scotland Census Data Explorer - Area Profiles, https://www.scotlandscensus.gov.uk/ods-web/area.html#)

A2.2.3.2 Early catchment history (1700-1900)

Historically, the Ness catchment was a "frontier line" of strategic importance as part of the consolidation of the Union of 1707 between Scotland and England (particularly with respect to the Highlands). This is evidenced by the line of forts built along the Great Glen around that time to suppress any Highlander rebellion (from south to north: Fort William [1690], Fort Augustus [1729-1742] and Fort George [1748-1769]).

After dissolution of the traditional clan structure, at the end of the 18th and throughout the 19th centuries, land ownership changed dramatically, as did land use, following general industrialisation trends favouring intensive agricultural and industrial processes throughout the United Kingdom. The ensuing disputes relating to land ownership and the rising rent costs drove many into poverty, giving rise to a wave of emigration. Emigration from Glengarry took place as early as 1773 to Canada and

America (Chisholm, C, 1876; Dobson, 1994; McLean, 1991), and in such numbers that a prominent settlement of Highlanders was named after the Glen: Glengarry County, in Ontario, Canada. Its impact on the area was highly significant, to the point that one century later it was written that these events "drained the cream of manhood of Glengarry, to the great detriment of the district" (Fraser-Mackintosh, 1897).

Significant emigration continued until the 1850s, as part of what became known as the "Highland Clearances", spurred by the introduction of commercial sheep farming, which contributed to a significant proportion of the population being internally displaced or encouraged / forced to emigrate (McLean, 1991). The original inhabitants were often relocated to the coasts or overseas, while new settlers from the lowlands of Scotland came in as sheep farmers. Sheep farming was for a while the main source of employment in Glengarry, until Australia and New Zealand rose to prominence by the 1850s and started dominating the global market for sheep products, which caused the industry in the Scottish Highlands to experience a massive decline.

Second only to sheep farming, the forestry sector became a main source of employment, prompted in particular by the need for timber to build the Caledonian Canal (works beginning in 1803). (Steven and Carlisle, 1959). At present woodland cover in the catchment (mostly in the form of plantation) covers 37,190 ha (20%), which is approximately 2% higher than the national average and 6% higher than the Highland average.

In addition to sheep farming, the land was further alienated from the local population by the creation of sporting estates. By the late 19th century the stalking of game and salmon fishing had become the most popular and profitable ventures (Robbins and Fraser, 2003), attracting rich tourists to the Highlands.

The events described so far had a profound impact on the local community but there were also additional social, cultural and linguistic implications of emigration, immigration and modernisation in Glengarry, an area inhabited for many centuries by Gaelic speakers. The use of Gaelic has now virtually disappeared from Glengarry, partly through active discouragement until relatively recent times by the central government, and partly through the rise of a mixed English-Gaelic speaking community. However, at the time the hydropower was being developed in the Highlands, Gaelic was sufficiently widespread to warrant adverts promoting hydropower to be also written in Gaelic (see section A2.2.4, **Figure 2.2.**6 and Supplementary Materials S1.1b).

The prominence of Gaelic culture within the local community prompted an ongoing collaboration with SMO (see section A2.2.2) to investigate the use of freshwater by the local Gaelic community before the GGHS was put in place, and its response to the latter. Work is still ongoing through a joint Mres student between SMO and RLI, Mairi Innes.

Following the societal change described above, Gaels in the Highlands could no longer make the same use of the fishing that local rivers offered, due to enforcement of anti-poaching laws (such as the 'Night Poaching Act 1828') (Wightman et al., 2002). Relevant here is a Gaelic proverb which summarises the attitudes of the Gaels at this time and provides an indication to the social tensions: "the fish that was yesterday miles from the land was claimed by the landlord the moment it reached the shore" (Wightman et al., 2002).

A more in-depth overview of the topics covered in this section is provided in a monograph by Professor Hugh Cheape, as Supplementary Materials S1.1a to this document.

A2.2.3.3 The Caledonian Canal (1803-1822)

One of the potential barriers to fish migration in the Ness catchment, the Caledonian Canal was completed in 1822, connecting Inverness to the North-East with Fort William to the south-west. The series of canal stretches link natural waterbodies such as Loch Ness and Loch Oich, for a total navigable length of 60 miles (Mudie, 1842).

The Caledonian Canal was first conceived as an alternative shorter and safer route to navigating around the north coast of Scotland, specifically for the Baltic Timber Trade, though its intended purpose was never fulfilled, and from its onset operated at a deficit (Priestley, 1831). Over time it instead became a tourist attraction. Its construction was viewed as a way of generating employment in the Highlands, whose population was being severely affecteded by the Highland Clearances.

Interestingly, shortly after completion there was a severe drought, which caused the water level of Loch Oich to be too low for the canal to operate, and engineering works were carried out at the outflow of Loch Garry and Loch Quoich to facilitate release of water from the catchment's upper reaches on demand. This was achieved mainly by building a side channel on Loch Quoich in 1825-1826, making this undertaking an early precedent to the later development of hydropower. Flow regulation was thus an important concern in the Garry catchment from the time of the Caledonian Canal.

Figure 2.2.5 outlines the main barriers present in the Ness Catchment - the Caledonian Canal and the GGHS (discussed in section A2.2.5).

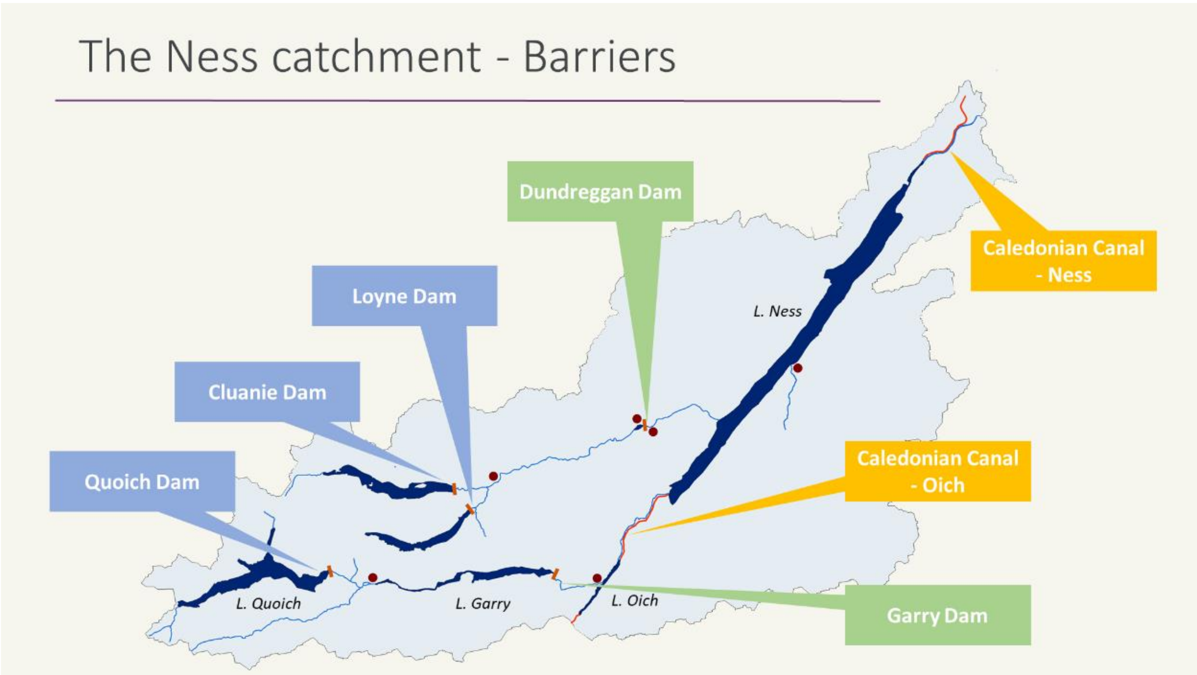


Figure 2.2.5. Main barriers in the River Ness catchment. Passable hydropower dams have green labels, impassable blue. Caledonian canal in orange.

A2.2.4 Hydropower

At the end of the 19th century, in the UK, the first hydropower dams were built, and they were small and privately-owned, supplying energy to their immediate vicinities. The first such dam in the Highlands was built in Fort Augustus in 1890, and belonged to the monks of the local Benedictine Abbey (Lea, 1969; Wood, 2010). A second phase saw the development of hydropower dams to power the smelting of aluminium, and Lochaber saw the installation of a successful plant, still in operation in the 2010s. However, by the 1930s any further expansion of this industry to other sites had become financially unviable, given that other countries such as Canada had sites that were better suited to provide the high energy required to make the process economical (Lea, 1969).

Hydropower development in the Highlands of Scotland was reconsidered as part of the development of the UK's National Electricity Grid, which became fully operational in 1938. From its inception, it was already geared to receive electricity from the Grampian Hydropower Scheme (Tummel and Rannoch dams were at the time the northernmost power stations in the Grid) , and it was intended that any further hydropower development would feed to different degrees into the National Grid (Lea, 1969). Selling electricity to the National Grid would afford the profits necessary for any further hydropower scheme to be viable, although opponents of the scheme contended that the Highlands would become the "electrical milk cow of the industrial south".

Given the far-ranging implications of the large-scale hydropower planned for the Highlands of Scotland and the significant local opposition at least to some of the proposals, it was deemed best for the entire project to be coordinated in the public domain, and Highland water resources were nationalised in 1943, with the North of Scotland Hydro-Electric Board (NoSHEB) appointed to oversee the development of hydropower. It is as part of this development that the GGHS was constructed (Burnett, 2001), among several other schemes (Scottish and Southern Energy, 2005).

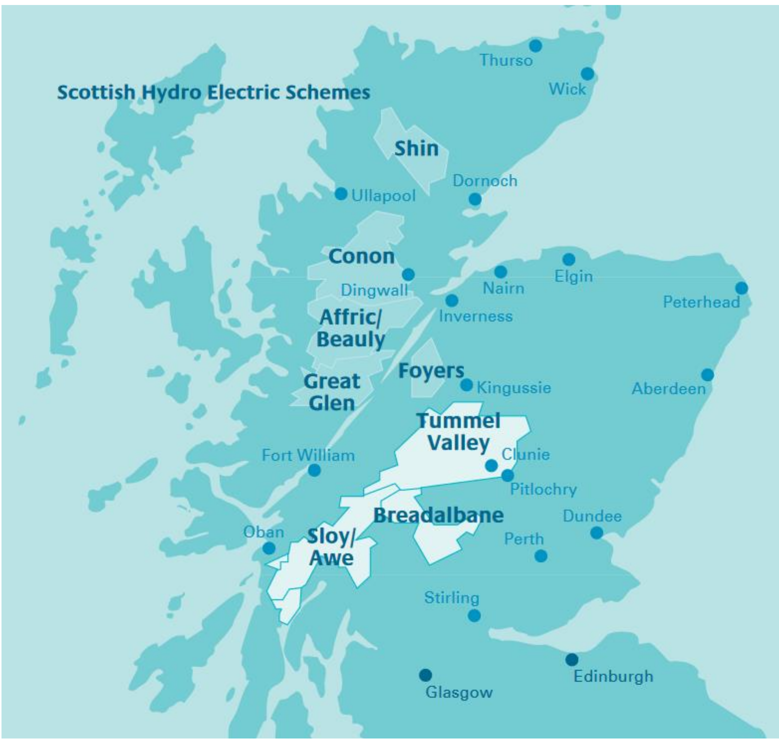


Figure 2.2.6. Scottish Hydro Electric Schemes, reproduced from "Power from the Glens" (Scottish and Southern Energy, 2005), with kind permission from SSE.

As clearly shown by the advertisement in **Figure 2.2.7**, encouraging housewives to move away from oil lamps and cooking on a fire, the arrival of hydropower was very strongly associated with the arrival of modern life in the Highlands, through the provision of electricity, and the creation of much-needed local employment.

Figure 2.2.7. Advertising for hydropower in the Highlands by the North of Scotland Hydro-Electric Board (full explanation and translation in Supplementary Materials S1.1b).

A2.2.4.1 Hydropower in context

By 1965, 54 main power stations and 78 dams had been built across the Highlands, with a total capacity of more than 1,000 MW, 110 of which generated by the Great Glen Hydro Scheme, a four-fold increase in hydropower energy production since 1944 (see **Figure 2.2.8**). In 1944 it was calculated that hydropower development would contribute to ~3% of the UK's energy production, and in absolute numbers the prediction was correct, however hydropower's relative contribution did not increase, as the UK's energy production also nearly quadrupled in the same period of time (see **Figure 2.2.9**). Therefore, the relative contribution of hydropower remained below 1% and has remained so to this day: very few large hydropower schemes were built since the 1960s, because of the very limited number of additional suitable sites.

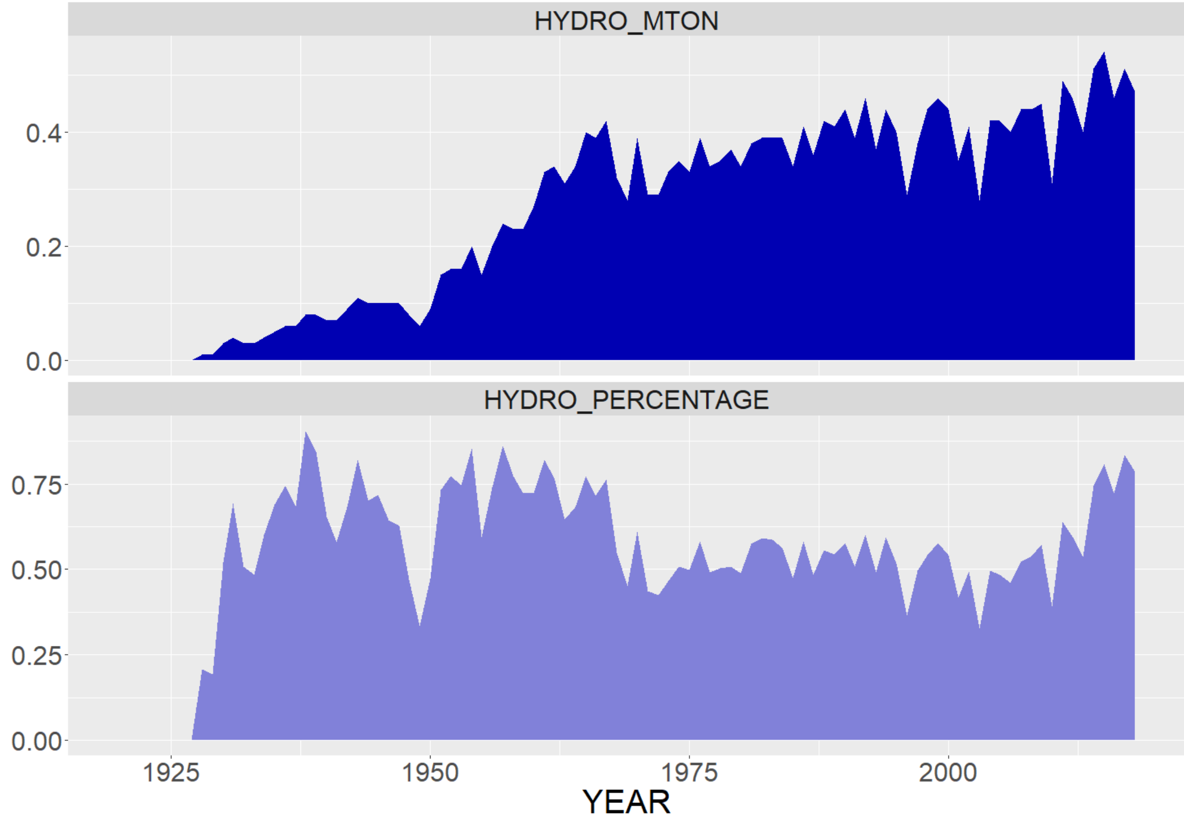


Figure 2.2.8: Absolute (MTON) and relative (Percentage) contribution of hydropower to the UK energy production (1920-2018). Source: Digest of UK Energy Statistics (DUKES) 2019 .

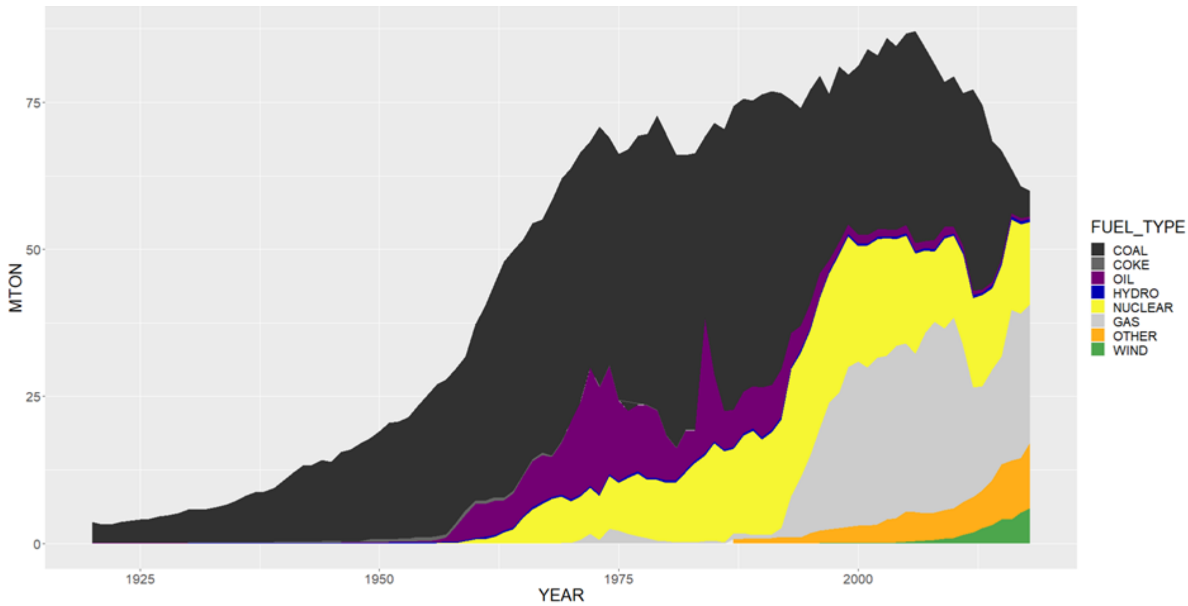


Figure 2.2.9. UK Fuel input for electricity generation (1920-2018). Source: Digest of UK Energy Statistics (DUKES) 2019 .

While hydropower currently does not represent a very significant percentage of the energy mix in Scotland, it still plays an important role: given its ability to produce electricity on demand at short notice, it operates strategically to complement wind power in unfavourable conditions for energy production by wind farms, and to cope with spikes in energy demands at peak usage times.

As mentioned above, it is believed that large-scale hydropower in Scotland has reached capacity, and while EU incentives for renewables made it financially viable for a few hundred micro-hydropower stations to be built around Scotland in the period between 2000 and 2010, there is now very limited incentive for further expansion.

On the contrary, wind energy is now booming, and within the Ness catchment approximately 22, 218 ha of land for wind farms have been developed, approved or under application, potentially covering 12% of the catchment area (**Figure 2.2.10**). Interestingly, a single scheme in Glenmoriston, the Beinneun wind farm, has an installed capacity of 109 MW, roughly equal to the capacity of the entire GGHS. Increased wind energy generation means that during windy spells hydropower needs to be shut down or else too much electricity would be generated, beyond the capacity of existing transmission lines. Many impounded lochs are thus kept at low levels (drawdown) so that during windy spells with no production the water can accumulate again, rather than spill over if levels were kept higher (A. Stephen, SSE, pers. comm.).

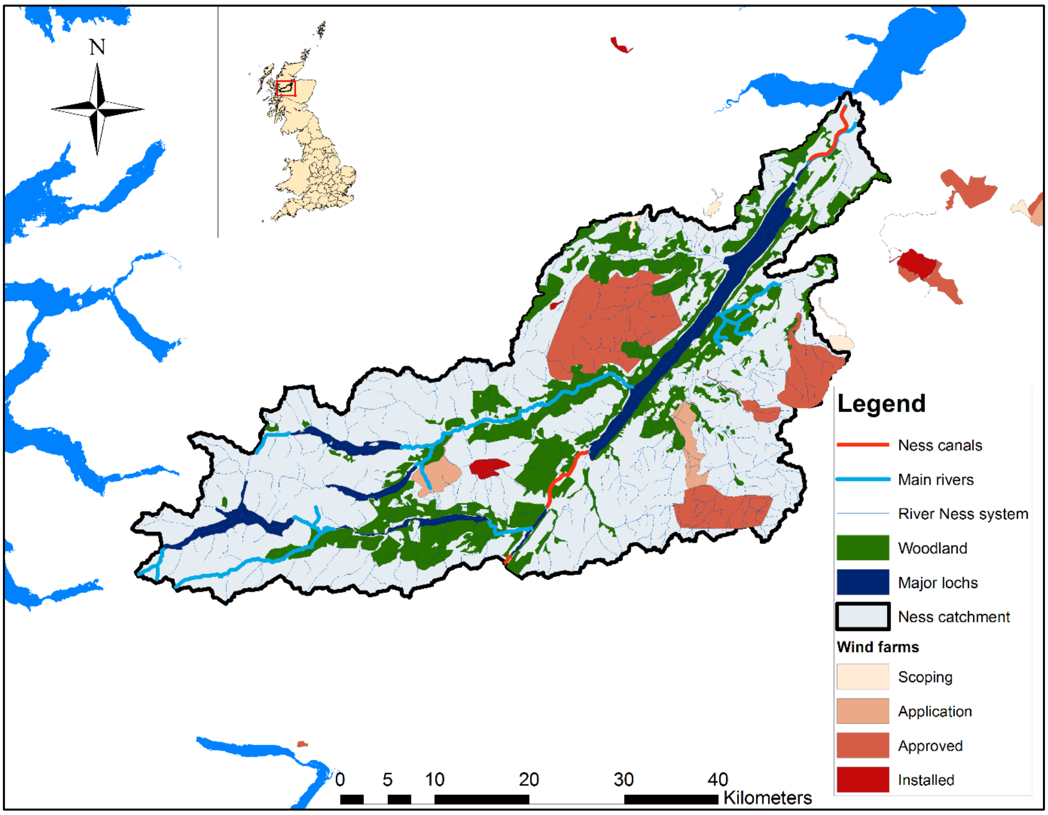


Figure 2.2.10. Watercourses, woodlands and windfarms in the Ness catchment.

A2.2.5 The Great Glen Hydro scheme (GGHS)

Design of the Great Glen Hydro Scheme (GGHS) had been discussed in various forms in the 1920s and 1930s, and was eventually finalised in 1943, as part of the overall efforts by the North of Scotland Hydro-Electric Board to develop hydropower across the Scottish Highlands, as described in the previous section. Construction of the dams comprising the scheme was completed between 1955 and 1962. As mentioned in section A2.2.1, there are five dams within the scheme, two in the Garry catchment (Quoich and Garry dams) and three in the Moriston (Cluanie, Loyne and Dundreggan dams). Quoich Dam, on the upper Garry, is impassable for migratory fish, while Garry Dam, in the lower catchment, has a Borland lift for fish passage, as does the lower Moriston dam (Dundreggan). The dams in the Upper Moriston (Cluanie and Loyne) are both impassable.

A2.2.5.1 Barrier Impacts

Adult salmon numbers ascending to the Upper Garry have declined over 10-fold since the 1950s. In contrast, the fish pass at Dundreggan Dam made Moriston salmon runs possible (the site of the dam was previously an impassable waterfall), and these are stable or increasing (**Figure 2.2.11**).

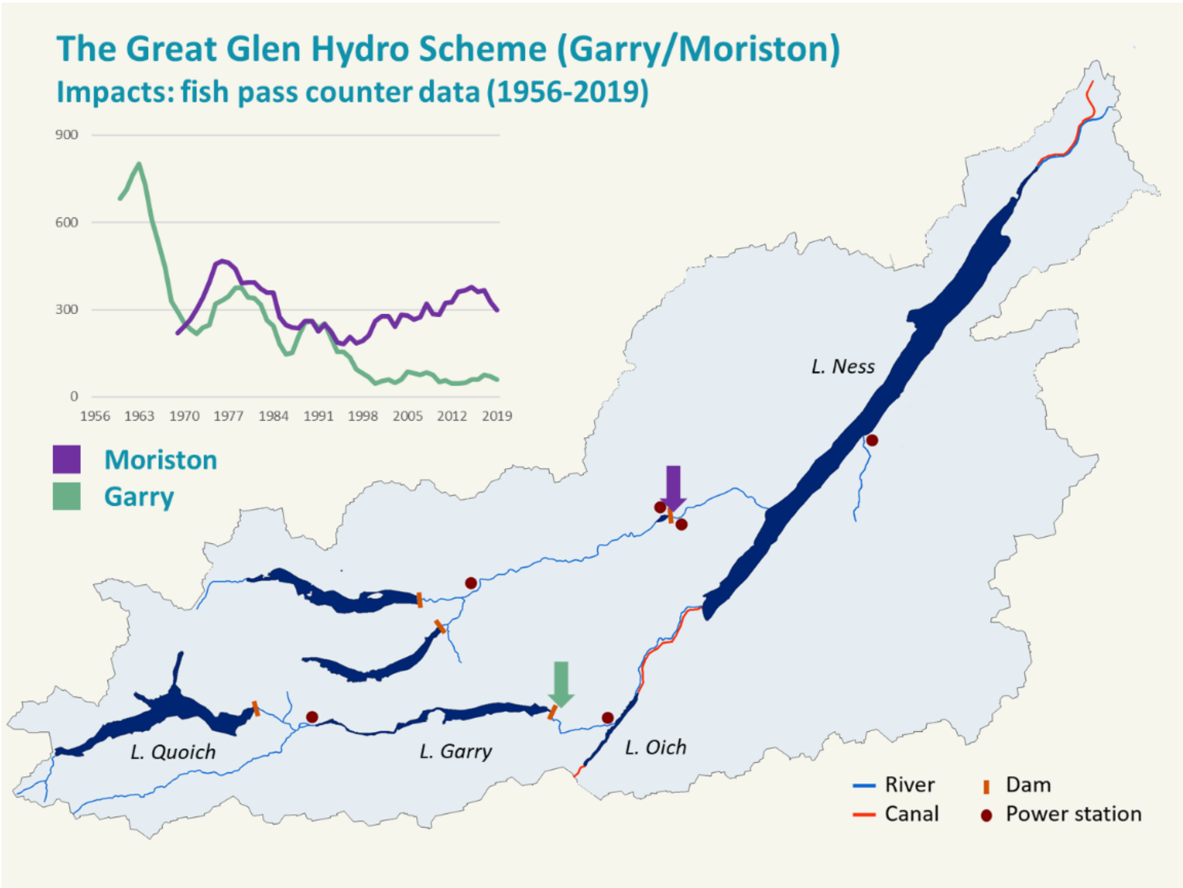


Figure 2.2.11. GGHS installation and salmon population decline on the River Garry. 5-year average number of salmon recorded by the fish counters on the fish passes on Dundreggan (purple) and Invergarry (green) dams between 1956 and 2019.

Flooding due to hydro dams has eliminated 40% of salmon habitat and some of the remaining habitat has been altered in character. Alterations on the Gearr Garry below Quoich Dam are hypothesised to arise from sourcing of compensation flows from the bottom of the reservoir affecting water temperature and chemistry, stream sediments and, thus, habitat quality and biodiversity. No salmon spawning or juveniles now occur in the Gearr Garry and salmon production from the remaining accessible habitat is lower than expected. The causes for the loss of productive capacity need to be established and mitigated, with the situation potentially confounded by:

- Legacy issues from a fish trap (heck) below the confluence of the Gearr Garry and Kingie preventing spawning upstream and use of ascending salmon for broodstock for stocking above the trap and elsewhere (heck in Figure 2.2.12 below);
- Two invasive species, pike and minnows, that increase predation and competition for food resources;
- Interactions between wild and farmed salmon, through escapes from a smolt-rearing facility for farmed salmon in Loch Garry (now run by MOWI, cf. section A2.2.12.3) and erosion of local population adaptation;;
- Erosion of local population adaptation through interbreeding with farm fish deliberately stocked in earlier years;
- Changes in salmon production capacity due to environmental changes, the introduction of commercial forestry and new farming practices;
- Increased smolt mortality from downstream barriers (Garry dam) and hydrological alterations (e.g. two water diversion weirs associated with the Caledonian canal).

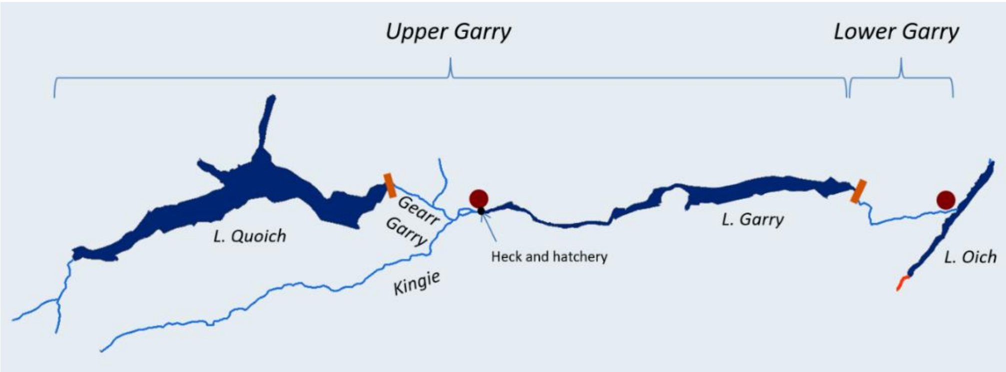


Figure 2.2.12. River Garry subcatchmenet, with main tributary (Kingie). Orange rectangles indicate barriers, and red circles indicate power stations. The fish barrier (heck) and hatchery are located adjacent to the Quoich power station.

A2.2.5.2 Barrier management and mitigation on the Garry

In 1943, the Fisheries Committee, when advising on the Garry hydropower scheme, recommended that Loch Quoich water levels not be altered and that a fish pass should be put in place on Quoich Dam, in order to safeguard what were believed to be key areas for salmon spawning in the Garry system (Watt, 2004). However, the fish pass was not installed, and the Explanatory Memorandum associated with the scheme made it clear that once the dam was built the available spawning and nursery habitat upstream was severely limited and the mitigations suggested were impractical (A. Stephen, SSE, pers. comm.).The first mitigation measure put in place on the River Garry to compensate for the loss of spawning habitat upstream of Quoich Dam (works completed in 1955) was the installation of a fish barrier below the dam to collect broodstock and rear eggs in a hatchery for stocking purposes.

Figure 2.2.13. Quoich Dam – aerial drone photograph 2018 (taken by Shobhit Pipil, University of Durham).

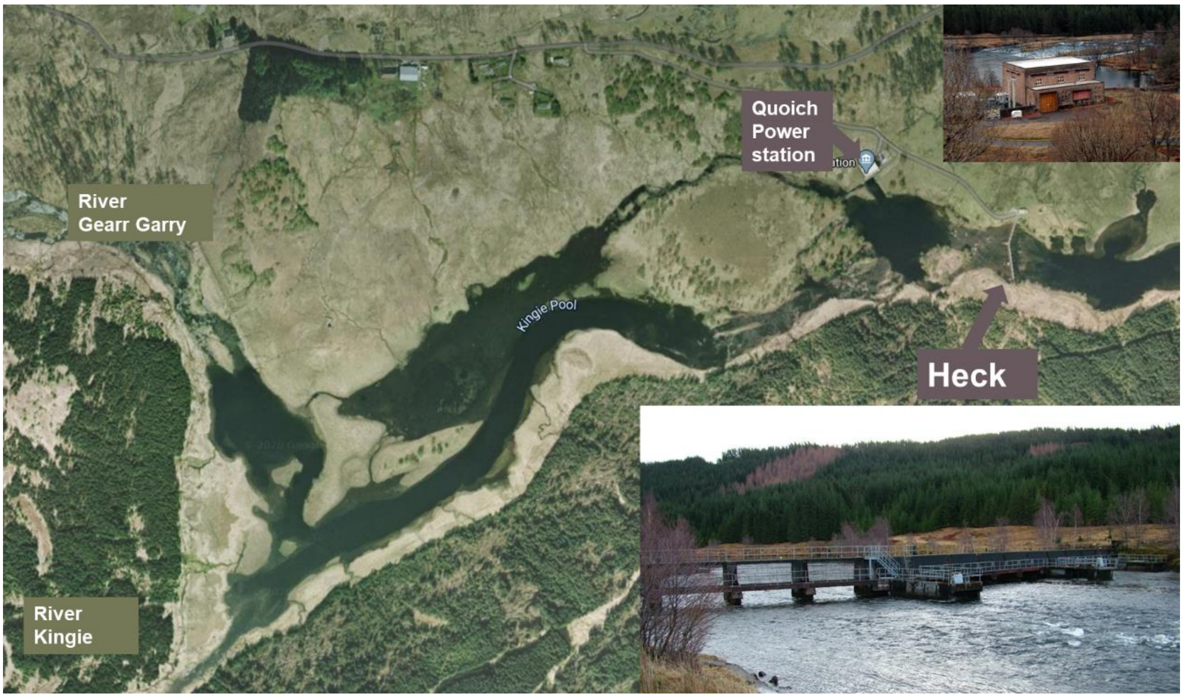


Figure 2.2.14. Fish barrier (heck) downstream of confluence between the Rivers Gearr Garry and Kingie, and Quoich power station (photos overlaid on Google satellite image).

Unfortunately, this mitigation measure was not only ineffective but detrimental, because, against the advice of not only of the Fisheries Committee but also of the local community, the barrier was placed downstream of the confluence of the Gearr Garry and Kingie. Most likely for ease of construction, given its location, adjacent to Quoich Power station (cf. **Figure 2.2.14**, and **Figure 2.2.21** for the entire Gearr Garry from Quoich Dam down to the confluence with the Kingie). The position of the fish barrier prevented any salmon from accessing the River Kingie, which had suitable spawning habitat. In addition, the eggs belonging to the salmon caught in the barrier were not reared to necessarily then be stocked back into the Garry, but were often sold to proprietors on other rivers, and salmon originating from elsewhere was deliberately released in the Garry. These two measures simultaneously reduced the size and affected the integrity of the native population, to the point that in 2003 only one fish entered the fish trap, and the hatchery was no longer operational, potentially needing investigation / refurbishment due to episodes of high fish mortality (Watt, 2004).

This dramatic situation prompted the NDSFB to commission a series of studies, two by J Watt (2004 and 2006) and one by E Verspoor (2012), to assess the ecological status of the Upper Garry. The work associated with these studies was funded and initiated by SSE. In addition to an assessment of the impact of the fish barrier on the availability of juvenile and spawning habitat, the 2004 report (Watt, 2004) comprised a review of existing data, and a habitat and a macroinvertebrate survey. The report highlighted the following findings:

- Rod catches at Tomdoun Hotel (1973-2003) in the Upper Garry suggest that the resident brown trout population might also be compromised by the current habitat conditions.
- The stocking of hatchery-reared fry in the Gearr Garry and Kingie was not productive and very few juveniles were subsequently found (1993 survey)
- The mapping of juvenile and spawning habitat on the Rivers Kingie and Gearr Garry suggested that removal of the fish barrier would dramatically increase availability of said habitats.
- The distribution of acid-intolerant invertebrate species suggested that the Gearr Garry immediately downstream of Quoich Dam implied a certain degree of acidification, that warranted more investigation, but otherwise no such indication was found elsewhere.

The report recommended removal of the fish barrier (which took place in the winter of 2004), and the development of a new fishery management plan.

Watt produced his second report in 2006, after conducting extensive electric fishing in 2005 in the catchment to assess salmon distribution. The report showed rapid colonisation of the Kingie after removal of the fish barrier, with fry present at 13 out 16 sites (at levels higher than when stocking was taking place), and no evidence of salmon on the Gearr Garry.

A further scoping study was conducted in 2012 by Professor Eric Verspoor (RLI), who recommended the development of a supportive breeding, supplemental stocking programme. This translated into the initiation in 2013 of the Upper Garry Salmon Restoration Project (UGSRP), a partnership between SSE, the Ness District Salmon Fishery Board (NDSFB), Marine Harvest (now MOWI) and RLI (with support from the Scottish Environment Protection Agency and Scottish Natural Heritage) to develop the breeding and stocking programme. Smolts were trapped, reared and genetically profiled to cross them appropriately and target among the trapped smolts those that are most likely part of the original (non-farmed / non-stocked) population. The eggs were placed in the Kingie for the first time in 2019, and fry were detected by electric fishing in the autumn: the results are therefore considered to be encouraging (NDSFB annual report 2019).

Another development that is closely connected with the restoration of the Upper Garry salmon population and to barrier management in the catchment, is to ensure maximal smolt escapement from the upper catchment through Garry Dam, the “Garry Dam Screens Project” (see section 1.1.2).
SSE commissioned APEM Ltd to undertake smolt passage trials to determine the survival rate through the turbine and tailrace screens, which was estimated at 86%, and considered satisfactory (NDSFB annual report 2019). The turbine intake screens (against which smolts would end up being squashed

because of the strength of the current) will thus be removed in early 2020 (and tailrace screens changed to cause less damage to fish), in time for the migration of the first smolts arising from the above-mentioend stocking programme (NDSFB annual report 2019). Monitoring of smolt behaviour at the intake has taken place using acoustic camera equipment and data is still to be evaluated (A.Stephen, SSE, pers. comm.).

This AMBER case study, a partnership with SSE and NDSFB, aims to put the UGSRP, and other initiatives, into a comprehensive biological-socio-economic barrier assessment and ecosystem restoration framework to advance understanding of biodiversity impacts, mitigation needs and optimal management solutions.

Mitigation of barrier impacts on and recovery of the upper Garry salmon stock is important because it delivers larger numbers of salmon for the most valuable spring fishery in the lower Ness system; angling and salmon fishing-related activities are a key economic sector in the area. However, barrier biodiversity impacts may also prove to bear upon other diadromous species (for example, eel and lamprey), and freshwater resident species such as Arctic char and brown trout, the latter supporting a locally important historical angling fishery in the upper Garry catchment, which might be currently indecline,asdescribedabove.

NDSFB, an organization of fisheries owners, and the SSE, an organization that manages hydro power facilities, both have a statutory responsibility for managing salmon fisheries and are stakeholders and partners in this case study. The third stakeholder, the Scottish Environmental Protection Agency (SEPA), is responsible for monitoring and restoring water quality under the European Water Framework Directive.

A2.2.5.3 Landslide downstream of Quoich Dam

Further unexpected impact in the Quoich dam area came in the form of a landslide that narrowly missed Quoich dam itself, as its impetus was absorbed by the large spillway designed for the barrier. The landslide took place in November 2018 spreading 9,000 tonnes of material over a mile, which caused dam operations to cease, road blockages, destroying an electricity and telephone pylons causing 20,000 homes to go without electricity. Significant amounts of sediment made it into the river, causing substantial habitat change, as will be discussed in section A2.2.10.

Figure 2.2.15. Landslide downstream of Quoich Dam (before and after). Top left: view of Quoich Dam in August 2017; top right: view from Quoich Dam spillway (same date); bottom: composite photo of Quoich Dam and landslide in August 2019.

A2.2.5.4 Current ecological status

In a report compiled by Scottish Natural Heritage (SNH, 2001), the two key pressures on the Ness catchment (as part of Zone 7, Northern Highlands) in terms of freshwater are water regulation (classed as major), and afforestation and forestry practice (classed as intermediate). Looking more closely at the EU Water Framework Directive ecological status classification of waterbodies in the Ness catchment, as carried out by SEPA, the upper River Garry has been given poor status (**Figure 2.2.16**).

> *"River Garry – Loch Poulary to Loch Quoich is a river (ID:20256 in the River Ness catchment of the Scotland river basin district. The main stem is approximately 7.3km in length. The waterbody has ben designated as a heavily modified waterbody on account of physical alterations that cannot be addressed without a significant impact on water storage for hydroelectricity generation. "*

The poor ecological condition is however not due exclusively to its heavily modified nature, but to "unknown pressure on water animals and plants". SEPA explains:

> *"Our 2014 assessments indicate that fish populations in this water body may not be in a good condition. However, we have not yet been able to identify the cause."*

Identification of these unknown pressures and of any indication that these pressures might be arising or exacerbated by the presence of the dam was one of the aims of this case study.

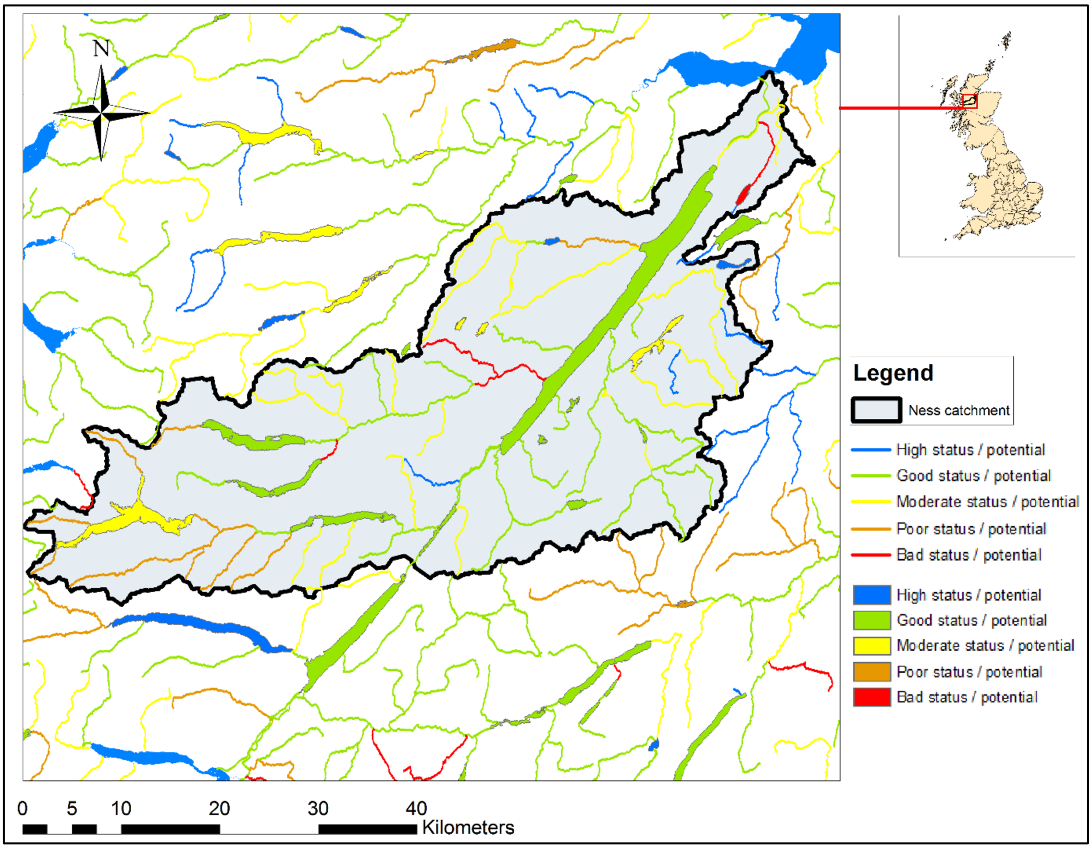


Figure 2.2.16. Overall condition of surface waters in the Ness catchment (2014), as part of the WFD assessment, retrieved from https://www.sepa.org.uk/data-visualisation/water-environment-hub/

A2.2.6 AMBER GGHS impact assessment – experiment design and tools

Beyond assembling available background information, a specific operational aim of this AMBER case study was to test the suitability of tools such as eDNA and drone mapping to assess current GGHS impacts.

The experiments were designed to assess the impact of GGHS on the catchment at different scales in respect of:

1. all hydropower dams in the scheme using eDNA and water quality data
2. a detailed consideration of Quoich dam, by comparing the downstream stretch of the Garry (Gearr Garry) with the River Kingie, given its unimpacted state, focused on eDNA and water quality but encompassing temperature sensor and drone data.
3. the impact of the landslide downstream of Quoich dam, a drone-based habitat mapping and MesoHABSIM (cf. section A2.2.10).

In order to understand the current habitat status downstream of Quoich Dam, a comparative approach was adopted. eDNA and water quality samples were taken upstream and downstream of all five GGHS dams, with the addition of sampling of further river stretches downstream of each dam, and a control loch outflow partly impacted by barriers - Loch Arkaig, just south of the GGHS); it has a weir that blocks half of its flow while the rest is left free-flowing. The control site was chosen because it resembles Loch Garry and Loch Quoich in terms of size, geology and orientation.

Unfortunately, however, the outbreak of the coronavirus epidemic in the UK, followed by lockdown, has had a significant impact on the ability to complete the assessments mentioned above, given that:

- It was not possible to complete the eDNA sequencing (three sequencing runs out of four), so data is lacking for key samples on the Moriston River.
- Access to drone image processing computers was lost (implications explained in section A.2.2.9)
- Temperature sensor data could not be downloaded, so temperature data is currently unavailable.
- A stretch of the Gearr Garry was not repeated using the MesoHABSIM approach (see section A2.2.10)
- A student project aiming to undertake kick sampling downstream of Quoich dam to confirm results obtained by Watt (2004) and compare with eDNA results had to be cancelled.

A 2.2.7 GGHS impact assessment – eDNA

Metabarcoding was selected as the method of choice for investigating the current ecological status of the rivers affected by the GGHS, in order to characterise the presence / absence of as wide a number of fish, invertebrate and diatom species as possible. The design of the experiment involved sampling a loch together with downsteam sites, to allow a comparison between different lochs and betewen different rivers, with the working hypothesis that clear patterns separating sites impacted by barriers from others would be found. The same water samples were also analysed in terms of water quality, as discussed in section A2.2.8. **Figure 2.2.17** outlines the sampling sites chosen, and Table 1 provides further detail for each sample.

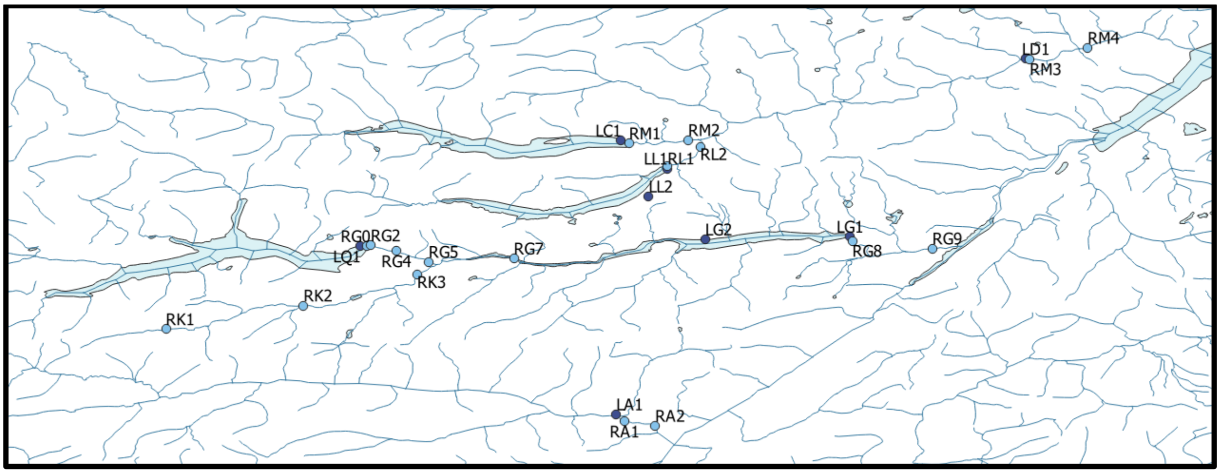


Figure 2.2.17. Map of eDNA and water quality sampling sites (Loch Arkaig is not visible as only Ness catchment lochs are on this map. Its outflow corresponds to point LA1.

A2.2.7.1 Methods

eDNA samples (see **Table 2.2.1**) were collected in batches between August and October 2019, and each site was analysed in triplicate, with around ~600ml filtered using a vacuum manifold. The extracted DNA was then amplified by PCR using primers for the three markers chosen (12S for fish, COI for invertebrates and rbcL for diatoms) and the PCR products were sequenced in-house using an Illumina MiSeq (for the complete methods, please refer to Supplementary Materials S1.2). A first round of sampling and sequencing was performed in 2018 for the 12S marker, but significant levels of contamination were found in the samples for some fish species, so the data is not presented here, and improvements were made to the protocol. The 2019 data presented here has very low contamination background.

Table 2.2.1: eDNA and Water quality sampling sites, split into six systems each comprising of a loch sample, upstream of dam, a river sample downstream of dam and a further river sample ~1km downstream of the dam.

code	type	site name	type	system	coordinates	
LD1	Loch	Dundreggan	upstream of dam	A-Dundreggan-Moriston	57.20245	-4.72236
RM3	River	Moriston	downstream of dam	A-Dundreggan-Moriston	57.20233	-4.71931
RM4	River	Moriston	1 km further downstream	A-Dundreggan-Moriston	57.21021	-4.67872
LC1	Loch	Cluanie	upstream of dam	B-Cluanie-Moriston	57.14536	-5.00549
RM1	River	Moriston	downstream of dam	B-Cluanie-Moriston	57.14343	-4.99988
RM2	River	Moriston	1 km further downstream	B-Cluanie-Moriston	57.14573	-4.95849
LL1	Loch	Loyne	upstream of dam	C-Loyne	57.12576	-4.97292
RL1	River	Loyne	downstream of dam	C-Loyne	57.12764	-4.97291
RL2	River	Loyne	1 km further downstream	C-Loyne	57.13289	-4.95753
LQ1	Loch	Quoich	upstream of dam	D-Quoich-Gearr Garry	57.07132	-5.18789
RG2	River	Gearr Garry	downstream of dam	D-Quoich-Gearr Garry	57.07203	-5.18082
RG4	River	Gearr Garry	1 km further downstream	D-Quoich-Gearr Garry	57.068	-5.163
RG5	River	Gearr Garry	additional site	Gearr Garry	57.06058	-5.14027
RG7	River	Gearr Garry	additional site	Gearr Garry	57.06286	-5.08062
LG2	Loch	Garry	additional site	Gearr Garry	57.07618	-4.94657
LG1	Loch	Garry	upstream of dam	E-Garry	57.07813	-4.84525
RG8	River	Lower Garry	downstream of dam	E-Garry	57.07523	-4.84359
RG9	River	Lower Garry	1 km further downstream	E-Garry	57.0699	-4.78753
LA1	Loch	Arkaig	upstream of dam	F-Arkaig	56.95385	-5.00888
RA1	River	Arkaig	downstream of dam	F-Arkaig	56.94795	-4.99401
RA2	River	Arkaig	1 km further downstream	F-Arkaig	56.94586	-4.98162
RK1	River	Kingie	additional site - September only	Kingie	57.01343	-5.32433
RK2	River	Kingie	additional site - September only	Kingie	57.03001	-5.22784
RK3	River	Kingie	additional site - September only	Kingie	57.05172	-5.14827

A2.2.7.2 Bioinformatics analysis

The DNA sequence reads generated were processed using the Dada2 pipeline (Callahan et al., 2016), and then the resulting Amplicon Sequence Variants (ASVs) were further filtered by size and by the degree they were shared between samples and sites using a series of custom R scripts, available upon request. Beta diversity analyses were performed in R (R Development Core Team, 2020) using the betapart package. The filtered ASVs were blasted against the Ncbi database using blastn and then the taxonomy of the best hit was extracted with Megan (Huson et al., 2016) and parsed with R package taxize to generate Operational Taxonomic Units (OTUs). When multiple ASVs mapped to the same OTU, the read depth of each ASV was combined together to generate an OTU read depth, and futher filtering was conducted on OTUs, with data summarised by site rather than by sample.

A2.2.7.3 Results overview

20 out of 24 sites were analysed (leaving out Cluanie and Dundreggan Dam on the Moriston, and associated points), as due to the coronavirus pandemic it was not possible to complete a fourth sample run for these last samples for the tree markers. That leaves 12 missing samples per marker (4 sites x 3 replicates), and 2 out 5 dams un-analysed.

The 12S fish marker produced 25 filtered ASVs, resulting in 10 filtered OTUs. The COI produced 100-fold more filtered ASVs, and 901 filtered OTUs. RbcL yielded less OTUs than COI (171), as would be expected, given that it targets a narrower taxonomic range (**Figure 2.2.18**).

MARKER	ASV_NO_UNFILTERED	ASV_NO_FILTERED	OTU_NO	OTU_NO_FILTERED
12S	108	25	10	10
COI	13116	2562	1435	901
RBCL	733	448	225	171

Figure 2.2.18. ASV and OTU filtering results for 12S, COI and RbcL. _NO_ stands for number.

A2.2.7.4 Assessment of beta diversity

An assessment of beta diversity dissimilarity between sites was carried out prior to conducting a more nuanced analysis of indicator species presence/absence (analysis on-going). This was to ascertain broad trends and patterns in the data.

Differences between sites, in respect of presence/absence of OTUs (operational taxonomic units), were estimated by generating a dissimilarity matrix accounting for spatial turnover (replacement), measured as Simpson pair-wise dissimilarity (Baselga, 2012) and visualised using hierarchical clusters, using R package betapart (Baselga and Orme, 2012). The index was computed for COI and rbcL, given that these both had a sufficient number of OTUs to attempt the analysis, while the 12S data was not included. COI and rbcL provided similar results such that the two OTU lists were combined to run the index on both datasets simultaneously.

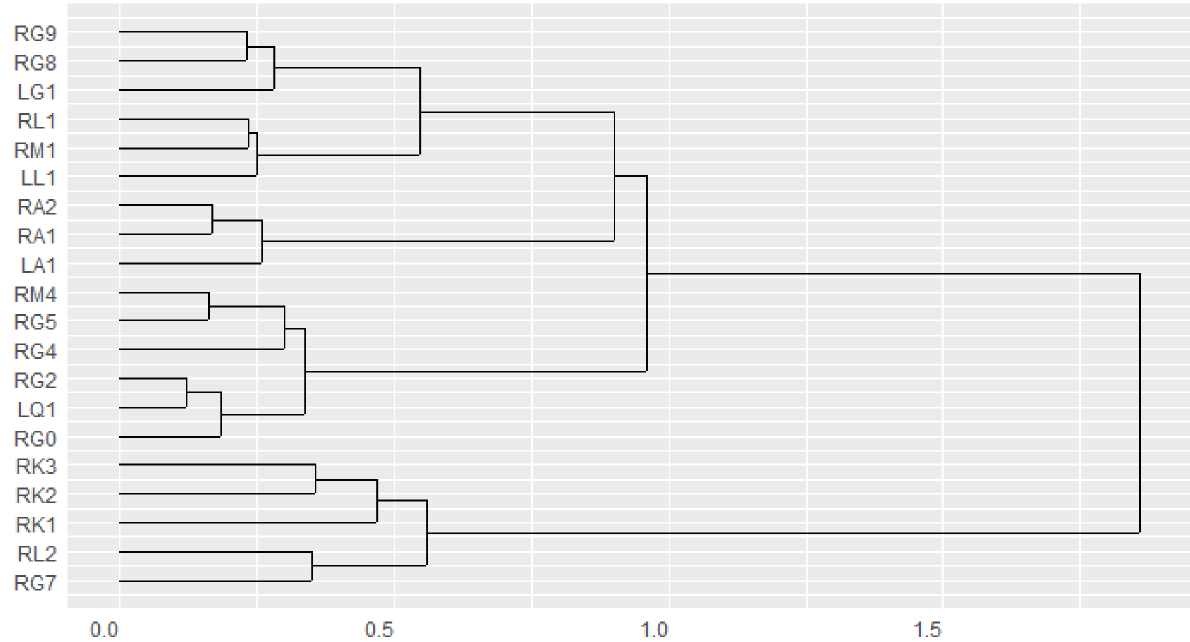


Figure 2.2.19. Hierachical clustering of sampling sites on the Garry (LQ, RG, LG), Moriston (LL, RL) and Arkaig (LA, RA). COI and RbcL OTU presence / absence combined together.

The dissimilarity index failed to identify any discontinuity in community composition below the dams included in the analysis (Quoich, Loyne and Garry dams). Perhaps unsurprisingly, it also showed continuity between the biodiversity identified in the lochs and in the associated downstream rivers, with clear clustering of the Quoich dam with the Gearr Garry (LQ1 to RG5), of Garry dam with the lower Garry (LG1 to RG9), of Loch Arkaig with the River Arkaig (LA1 to RA2), and the River Kingie forming a separate branch. The sites on the Moriston appear more scattered though this impression that might change once the missing points are added to the analysis. These findings mirror the water quality results discussed in the next section.

Each of the upper loch + river mini-systems (Quoich dam and Loyne dam, with Loch Arkaig as control) was processed so as to see whether an OTU signal from rivers might be confounded by the presence of eDNA flowing down from the various lochs and to remove any OTUs found in both the lochs and the rivers, thus hoping to get a river signal. However, they actually reconstituted the full OTU complement when the "river OTUs" were combined from the different pools and no truly river specific OTUs were identified.

The results establish the broad pattern across the catchment. The next steps need to be a more detailed assessment of the invertebrate and diatom species present and absent at each site. As part of this, a comparison of relative abundance of each OTU at different sites should be considered.

A2.2.7.5 Fish species distribution (eDNA)

Given the limited number of fish species present, it was possible within the time constraints to validate the species detected and assess their distribution across sites. The key observations were:

- Salmon are detected (in one out of six replicates) in Loch Quoich, above Quoich dam, which is impassable, whereas it is not detected above Loyne dam (also impassable)
- Char are detected in Loch Quoich, Loch Loyne and Loch Arkaig but also at low levels in one of three replicates on a site on the Kingie
- Assuming that the signal detected at RG0 and RG2 for char (and possibly for salmon) is coming from Loch Quoich, it is possible to estimate that the salmonid eDNA signal detected in the water is disappearing somewhere between RG2 and RG4
- Eels are able to travel past Garry dam as far as the Kingie (the 2018 data shows presence also on the Gearr Garry, potentially as far up as RG2, very close to Quoich Dam) but were not detected above Quoich nor Loyne dams.
- Pike occur on the Gearr Garry and Kingie, as expected given their known introduction from Loch Oich/Lower Garry to the pool at the confluence between Kingie and Gearr Garry.
- Trout and minnow are ubiquitous in all waterbodies while three-spined stickleback and flounder have a more scattered distribution.

Figure 2.2.20. Fish species presence / absence across available sampling sites, divided by river system (Garry, Moriston, Arkaig). Naming convensions given in previous figure. RGO is the outflow from Quoich Dam. Red lines indicate impassable barriers, green lines passable barriers.

It should be noted that strict presence/absence might give what are likely to be false positives. This approach does not take into account read number above the chosen threshold. Analysing the data to provide an assessment of relative abundance might provide a more nuanced picture and a more robust species account. Furthermore, eDNA should be combined with other validation methods to confirm what might be unlikely results, such as the presence of salmon above Quoich dam. Presence of eDNA in only one of three replicates of a sample could indicate contamination during the sequencing run but also low abundance: further work looking at the proximity of sample wells in the sequencing plate layout is also needed to rule out sample cross-contamination as an explanation. Nevertheless, it is intriguing that the signal for salmon in Loch Quoich might be present across three samples (LQ, RG0 and RG2, three individual replicates in total), and that it is higher, by a significant margin (87-1604 reads vs a maximum of 27 reads), than the number of reads detected in the experimental blanks. This is consistent with the possibility that a landlocked salmon population has developed above in Loch Quoich, something that is possible in a hatchery and has evolved in many river systems across the species range (Webb, et al., 2007).. On the other hand, it is much more unlikely that the signal for charr detected in the Kingie is correct, given the habitat preferences of this species in Scotland, and the lack of any detection of the species in the various electrofishing surveys of the river undertaken to date. Furthermore, charr was detected in only one sample. Thus, further study on these questions is needed and the salmon result on Quoich dam will be initially confirmed by salmon-specific qPCR. If that assay confirms the presence of salmon, then another route to confirm the finding would be to gill net Loch Quoich to see whether salmon can be caught.

A2.2.8 GGHS impact assessment – water quality

A subset of eDNA sampling points was chosen for water quality analysis, in order to identify any potential correlation between biotic (species presence/absence) and abiotic (water chemistry) factors. The samples were chosen to provide water quality upstream and dowstream of the five GGHS dams (see **Table 2.2.1** in previous section for sample overview). Samples were collected on five occasions from 21 sites across the Ness River system between June and November 2019, to investigate water quality in the system and any changes across the summer and autumn seasons. eDNA samples were collected simultaneously on three water quality sampling occasions. The pH, electrical conductivity and temperature of samples were measured in the field using a Hanna HI991300 meter. Detailed methods and results can be found in Supplementary Materials S1.3.

A2.2.8.1 Summary

- No clear effects of barriers on water quality were observed – very little difference between upstream (loch sites) and downstream (river sites) of dams
- This was the case for all parameters measured, there were occasional differences between loch and river sites for some parameters such as suspended solids at some sites (but this may be an artefact of sampling at the loch edge) and also for metals, but only in the Loyne system.
- Occasional differences in concentrations of metals and major ions in the Loyne system (e.g. peaks in concentration sometimes in the loch and sometimes in the river) may be related to the flow of water through the dam during sampling (sometimes full flow, sometimes minimum flow). This was not consistent across all sampling occasions to be determined as a clear effect of the dam on water quality.
- The results suggest that in general, water quality within the GGHS system and River Ness catchment appears to be high in pH, with low nutrient and low pollutant concentrations across all sites over the five sampling occasions, which is a positive result in terms of the potential implications for salmonid habitat suitability.

A 2.2.9 GGHS impact assessment – drone mapping and analysis

Drone mapping of selected sections of the Garry and Kingie rivers was deployed in order to analyse physical habitat conditions. This has allowed the production of high-resolution images providing a much better resolution for physical habitat condition when compared to any available satellite images. The output of the drone data creates a baseline of information useable for a range of applications that include high resolution topography and bathymetry (Carbonneau and Dietrich, 2017; Woodget et al., 2015) and grain size mapping (Carbonneau et al., 2018, 2004).

A2.2.9.1 Flight path design overview

The drone survey is divided into four parts (**Figure 2.2.21** and Supplementary Materials S1.4):

1. The Gearr Garry, a section of the River Garry between Quoich dam and its confluence with the River Kingie (surveyed length 2.89Km). The surveyed river stretch has a drop in elevation of 61m (from 171 to 110m), with a gradient of 0.210 (m-m/m). This section has the highest gradient among all four drone survey sections.
2. River Kingie (downstream section); surveyed between Lochan nan Sgùd (on Kingie) and the confluence with the Garry (surveyed length 3.99Km long). The surveyed river stretch has a drop in elevation of 34m (from 144 to 110m), with a gradient of 0.0085 (m-m/m).
3. River Kingie (mid section); (surveyed length 1.99 Km). The surveyed river stretch has a drop in elevation of 21m (from 167 to 146m), with a gradient of 0.0105 (m-m/m)
4. River Kingie (upper); headwaters reach section (3.74Km**Error! Reference source not found.**). T he surveyed river stretch has a drop in elevation of 15m (from 183 to 168m), with a gradient of 0.0039 (m-m/m).

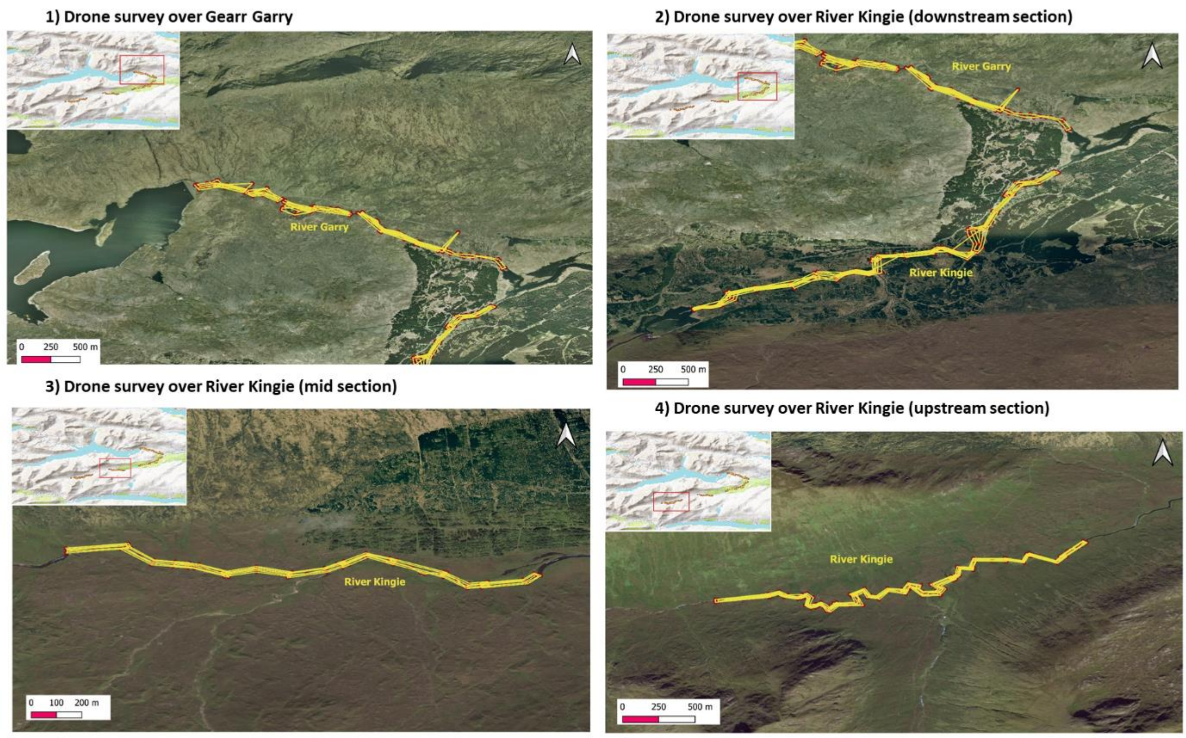


Figure 2.2.21. drone flight path overview (individual images can be viewed in Supplementary Materials S1.4).

A2.2.9.2 Image processing and analysis

The first phase of the survey covered the River Garry section between Quoich dam and the Kingie pool (confluence zone). The second phase of the survey covered three distinct river morphological sections of the river Kingie: (a) headwater zone, (b) transport zone and (c) transition zone, which includes the transport and deposition sites upstream of the confluence with the River Garry.

Existing moderate to high resolution satellite images for this study site are limited and unsuitable for detailed physical habitat mapping. This includes Google Earth imagery, which has limited temporal resolution for Kingie and Garry river area (only one image from 2005). Thus, the drone survey plays an essential role in the creation of a high-resolution image repository for the river section, which includes an active river section and some parts of the flood plain / riparian zone.

Drone mapping was performed with a consumer-grade DJI P4 drone. High-resolution multi-view stereo images were captured at three different heights: 60m, 30m and 15m. The 60m images are oblique images (tilted towards the Area of Interest, at an angle of 45^0). The second set of images at a height of 30m are taken vertically (nadir). The third set of images, captured at an elevation of 10–15 m, give a close view of gravels that can be used to calibrate grain size mapping algorithms (See AMBER deliverable 2.4 and Carbonneau et al., 2018).

The multi-view stereo images captured on the Rivers Gearr Garry and Kingie were processed on proprietary image processing software (Metashape by Agisoft). The processing pipeline comprises image alignment, bundle adjustment and point cloud estimation, using the Structure from Motion (SfM) workflow. This delivers high density point clouds for the XYZ shape of the landscape and allows production of high quality ortho-imagery.

A2.2.9.3 Analytical outputs

Due to lockdown conditions in the UK, access to drone imagery was lost during production of this report. The data will be made available to the project team and beneficiaries once the disruption associated to the covid-19 pandemic passes. Given the impact of lockdown, further analysis of the imagery for this report as outlined in the preceding paragraph was not possible and will be completed in the context of future publications arising from the case study materials.

The planned analyses include:

- high resolution topography
- Before after landslide analysis
- habitat mapping using the MesoHABSIM approach (see section A2.2.10)

Beyond this, bathymetry can be analysed for the surveyed areas, but this would not cover deep pools. Grain-size mapping is also possible, providing a static grain estimate for the time of the survey.

Drone mapping can potentially provide further information, if hydrological and sediment transport models can be generated. These two models then feed into physical habitat mapping. Physical habitat mapping could be possible in the future provided that ancillary data is made available, as discussed in the next section.

A2.2.9.4 Physical habitat mapping: future potential

Catchment-scale hydrological and sedimentological changes can affect channel shape and habitat composition. The latter is controlled by different discharge scenarios at the reach scale and by the resulting sediment transportation and deposition patterns. Long-term hydrological modelling becomes essential for the assessment of those reach sections that may experience high erosion or deposition events, but modelling can also include reaches where flow is artificially regulated. From a sedimentological and physical habitat perspective, hydrological modelling provides crucial information.

Development of a distributed hydrological model and grain-specific sediment routing, a prerequisite for modelling physical habitat suitability, depend on the future availability of a set of ancillary data, which were identified as knowledge gaps in this catchment, first and foremost flow data from a discharge gauge site capturing the outflow of the Gearr Garry and Kingie, ideally located at a certain distance downstream of the Quoich Power Station outflow. Drone mapping data constitutes an asset that can help make the case for the additional resources need for the currently missing data to be collected. Due to time and budget constraints, building of these additional resources (gauging station, etc. see below) this was not achievable within the timeframe of the project, but will hopefully be possible in the near future.

The data required in any hydrological model, whether thematic, gridded or gauged falls in the following categories:

1. Flow measurement (gauging site) at the catchment outflow site
2. Deviation, where a dam is present in the catchment, of the hydrological response of the catchment from the natural response, encompassing dam water release data and reservoir properties (standing water data)
3. Sediment monitoring records collected with a bedload sampler (i.e. Helley-Smith sampler) at the catchment outflow site, for the purpose of calibrating the sediment modelling output.
4. Digital elevation model.
5. Climate input data (Precipitation, Temperature, Solar radiation, wind velocity and relative humidity). All five parameters are required.
6. Land use data
7. Soil database (i.e. soil properties)

Here is a commentary on the current data status for the catchment under consideration (Rivers Gearr Garry and Kingie) with the numbering matching the data requirements listed above:

1. There are no gauging sites in the Garry catchment, as can be seen in **Figure 2.2.22.** A suitable location for a gauging site could be a lack of discharge gauge sites for the Rivers Kingie and Garry (Error! Reference source not found.). ✗
2. Quoich dam diverts some of the water that would be flowing down the Gearr Garry into an underground tunnel that opens at the Kingie pool (where the power station was built). Water release data from both the dam into the Gearr Garry and from the turbine tunnel opening into the Kingie pool is required, and this data is available. ✓
3. No bedload sampler installed at the catchment outflow ✗
4. A digital elevation model is available ✓
5. Precipitation, Temperature, Solar radiation and wind velocity. It is currently unknown whether relative humidity is recorded in a weather station close enough to the target catchment. Lack

of ground weather station in the proximity to the study area also acts as a bottleneck for weather generator option to simulate weather parameter which is not available. ✓✓✓✓?

6. Available at https://www.geomni.co.uk/ukland ✓
7. Available as the Harmonised World Soil Database, provided by FAO. ✓

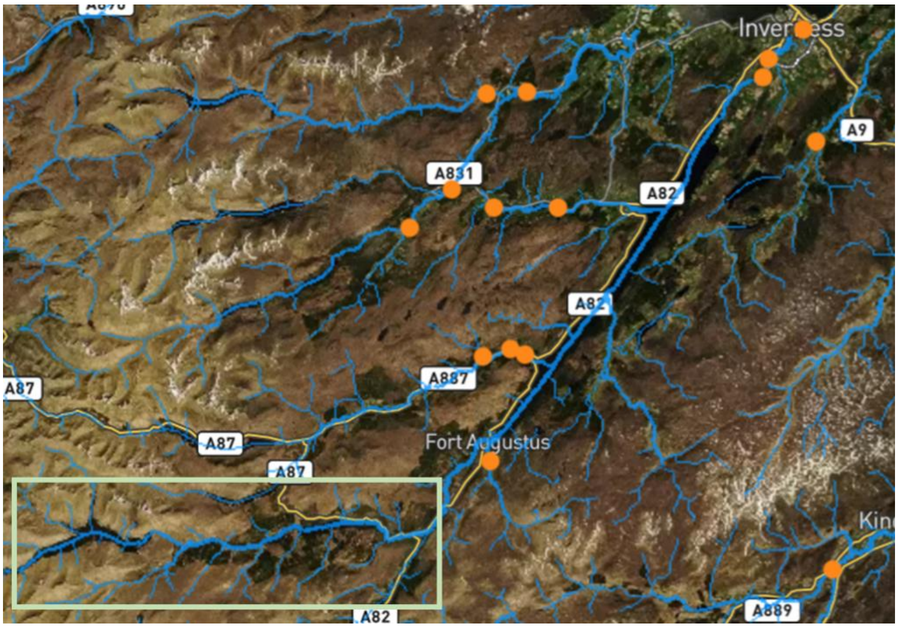


Figure 2.2.22. Discharge gauge sites (orange dots) in the Ness catchment. The Garry subcatchment (green box) has none (image from the National River Flow Archive web portal).

Availability of the missing parameters listed above would result in the ability to perform hydrological modelling and merge sediment size information using a tool like CASCADE (Tangi et al., 2019), which simulates the resulting grain size-specific sediment flux. This information would be helpful to ascertain the possible physical habitat changes associated with fine particle movement in the river network. In turn, grain size defines the available physical habitat in the river network. Salmonids spawn in gravel beds (redds) of a particle range 0.2 -6.3mm (Giller, P.S., Giller, P. and Malmqvist, B., 1998, p.43). Too coarse particle size is unsuitable for redds while too fine particles can increase the mortality of fish eggs and fry as well as harm fish gills. Therefore, information on sediment routing and dynamics can provide insight for prioritising fish habitat management and mitigation of impacts.

A2.2.9.5 Conclusions

Nearly 12km over four river stretches comprising the Gearr Garry and key sections of the River Kingie were surveyed with a drone and high-quality images captured. The drone survey was repeated twice for the Gearr Garry, the second time to map the impact of the landslide downstream of Quoich Dam. An image-based before/after comparison of the impact of the landslide is on-going (data processing not currently possible due to lockdown). The drone survey provided the necessary images to perform a more detailed habitat assessment and modelling using the mMesoHABSIM approach (see next section, A2.2.10).

The data is now available to the project for further habitat characterisation and as a long-term data point that provides a benchmark for future monitoring. Further habitat modelling based on the development of a hydrological model could be possible in the mid-term, provided the data gaps identified can be addressed. From an adaptive management perspective, the drone survey has had both immediate application (MesoHABSIM) and implications for the development of more detailed monitoring plans based on a wider set of parameters, which at a minimum would require installation of a gauging station and bedload sampler in the Upper Garry downstream of Quoich power station.

A 2.2.10 GGHS impact assessment – MesohabSIM analysis

Thanks to the image data made available through the drone mapping (see previous section A2.2.9), a MesoHABSIM habitat assessment was performed for the Gearr Garry downstream of Quoich dam on September 2018, to determine the current mesohabitat composition. The initial design involved running the survey at various flow conditions, but given that Quoich Dam is regulated and remains at the same flow except from a short window in October where more water is released (which was missed due to other commitments), only one pass was made. A second pass was added after November 2018 (December 2019) to assess the impact of a landslide affecting the portion of Gearr Garry immediately downstrem of Quoich Dam. To carry out the MesoHABSIM assessment it is best to have a matching drone image, so an extra drone flight over the Gearr Garry was carried out (see section A2.2.9) making possible a comparative assessment of the habitat before and after the landslide (**Figure 2.2.23a**).

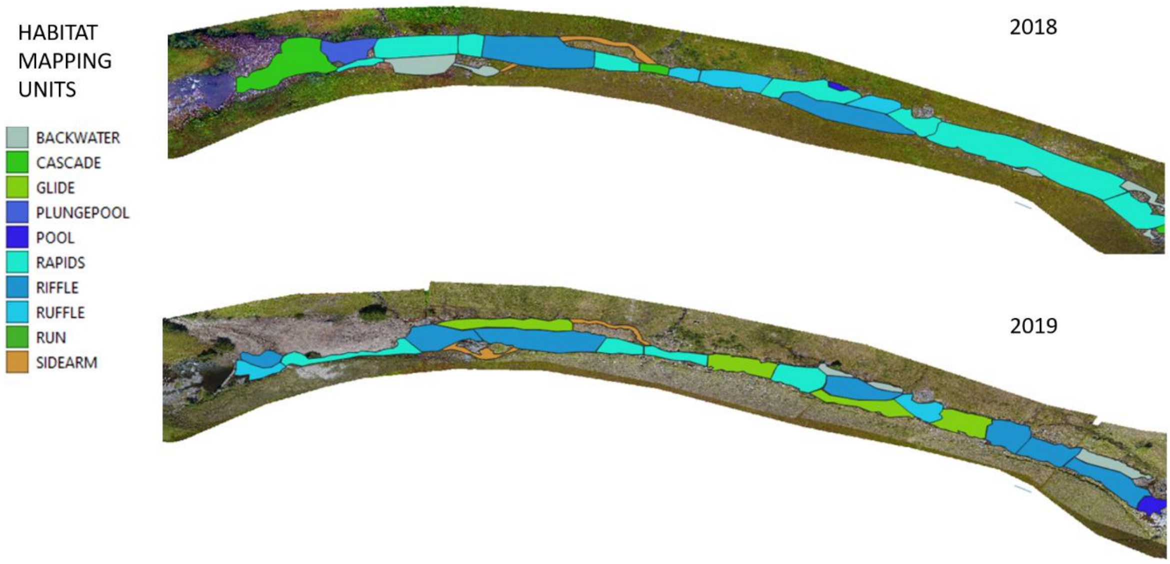


Figure 2.2.23a. Habitat assessment comparison, pre- and post-landlide**.**

Habitat units changed as a consequence of channel shape and depth alterations, due to the influx of sediment, resulting in a narrowing of certain sections, but, apart from the first section which has changed dramatically, the changes are more subtle. Modelling habitat suitability based on fish guild habitat preference allowed for more nuanced observations of habitat change, as shown in **Figure 2.2.23b.** These changes suggest a shift in habitat from highly rheophilic species like salmon to generalist and water column species, such as pike and minnows, respectively. The change resulted in a fish guild composition that is more in line with the expected European macrohabitat river type distribution (FCMacHT) for northern rivers (87% similarity). The habitat suitability changes for these three fish guilds are further illustrated in **Figures 2.2.23c-e**, where green indicates good suitability, yellow indicates average suitability, and red poor suitability. In addition, **Figure 2.2.23b** shows that

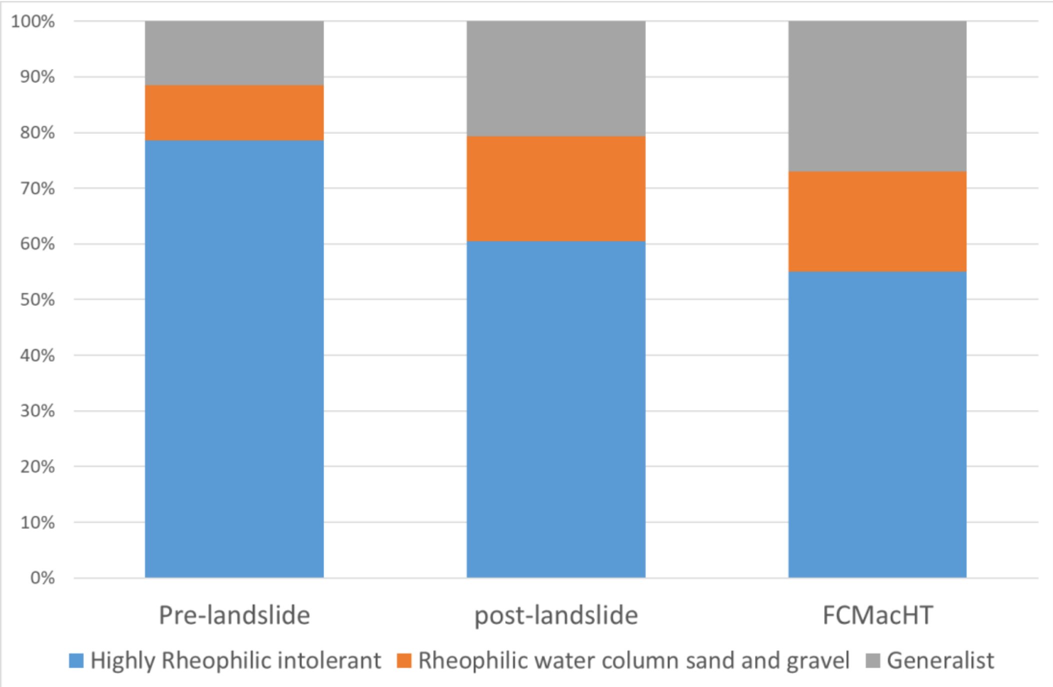


Figure 2.2.23b. Fish guild composition, pre- and post-landslide

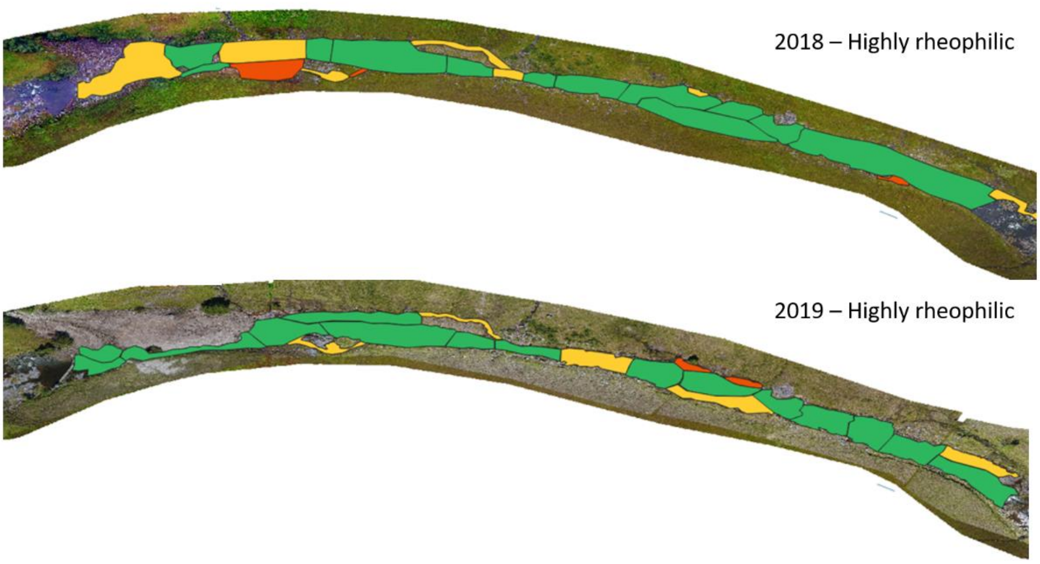


Figure 2.2.23c. Habitat suitability for highly rheophilic species

Figure 2.2.23d. Habitat suitability for generalist species

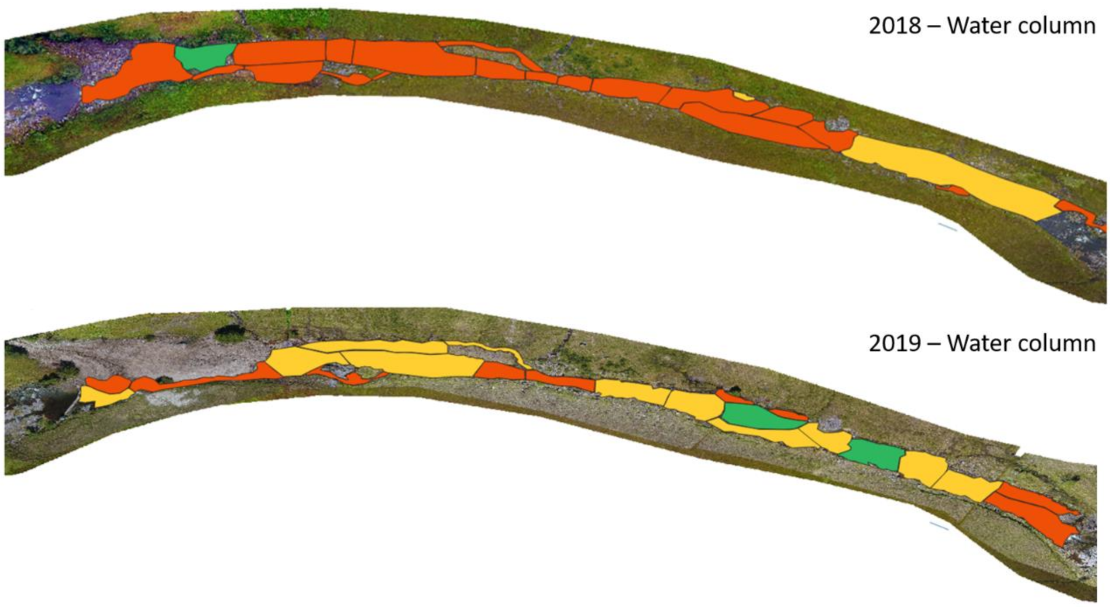


Figure 2.2.23e. Habitat suitability for water column species

A clear gain in habitat can be seen for generalist and water column species, and a shift in habitat for salmon. When modelling for salmon spawning habitat is performed, results suggest that the influx of sediment might have produced sediment that could be suitable for spawning (see **Figure 2.2.23f)**, although this will require further validation.

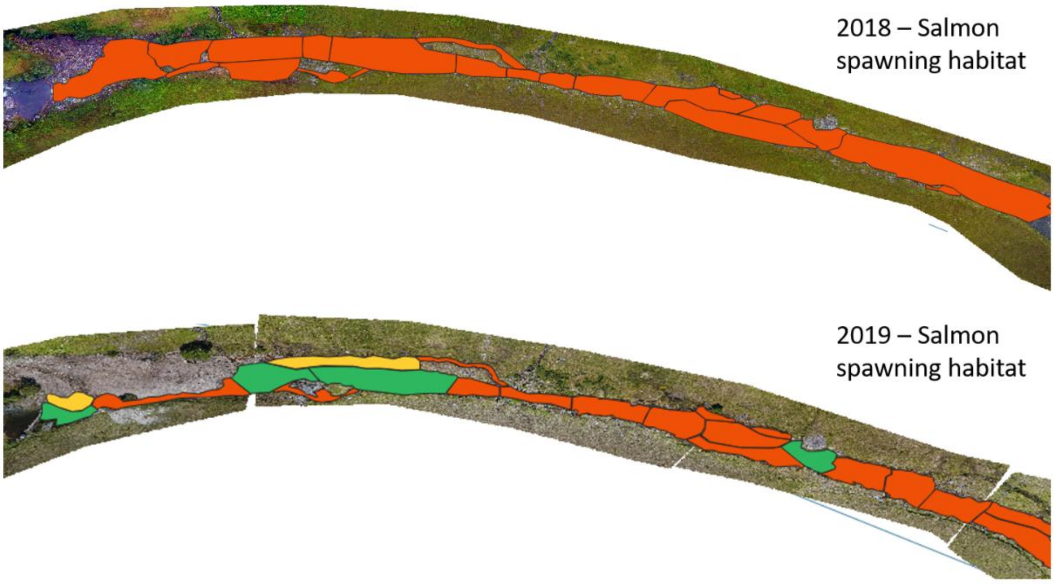


Figure 2.2.23f. Habitat suitability for water column species

Another potential advantage associated with the influx of sediment is the covering of significant amounts of periphyton present attached to much of the substrate downstream of Quoich Dam (see **Figure 2.2.23g**), which was likely to have resulted in a significant restriction in fish habitat.

Figure 2.2.23g. Presence of periphyton noticed in the 2018 survey

Although gravel has entered the system, there is a considerable amount of silt, which, as pointed out in the drone section, might provide hindrance to salmon spawning or for juveniles. This situation is unlikely to resolve very rapidly, given the regulated flow regime of the Gearr Garry, with limited capacity for sediment transport. Further experimental approaches are needed to establish whether this potential gain in spawning habitat will bear fruit, for example by placing salmon eggs in some of the units highlighted by the modelling, after further assessment in the field.

A 2.2.11 Caledonian Canal impact assessment - eDNA

Preliminary acoustic tagging findings from the Missing Salmon Project (cf. section A2.2.2) found that 50% of salmon in Scotland do not make it to sea, with the figure in the Ness system reaching an alarmingly high 91%. The Caledonian canal is suspected to account for approximately 25% of lost salmon, yet this figure is uncertain given that the placement of receivers did not account for salmon migrating via the canal. A second round of tagging specifically addressed whether salmon smolts enter the canals, and a complementary eDNA sampling time series was performed in the Caledonian canal during the period of smolt migration. Tagging data is due to be made available by June 2020, and after that a comparison between eDNA and telemetry results will be possible. The eDNA assay chosen for this experiment is a salmon-specific qPCR assay.

A2.2.11.1 Sampling and eDNA extraction

Samples were collected in the upper and lower parts of the Caledonian canal during the smolt migration during April and May 2019 (**Figure 2.2.24**). Due to the lentic nature of the canal, for each sampling site a bucket was used to collate 10x 1L subsamples at 3m intervals. The water in the bucket was then mixed and a 1L sample collected. The spacing between sampling locations within the canal was ~250m (**Figure 2.2.24b**). Bleaching (5% bleach) and rinsing (water) of equipment was carried out between each sampling location. For eDNA extraction method, please see Supplementary Materials S1.2.

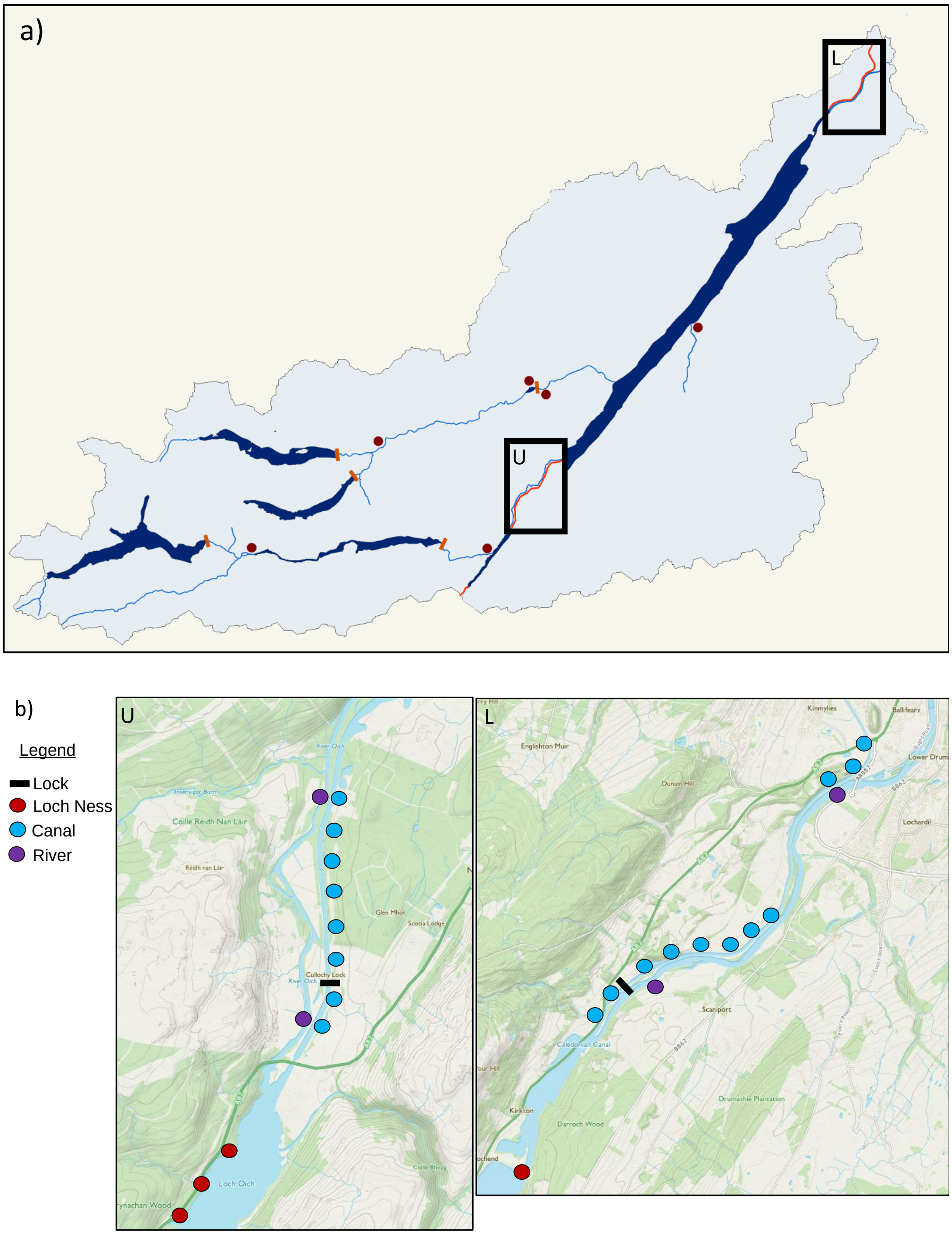


Figure 2.2.23. Spatial and temporal eDNA sampling on the Caledonian canal during smolt migration. a) Location of the Caledonian canal; b) spatial sampling of eDNA in the loch (red points), canal (blue points) and river (purple points), with canal samples taken above and below the sluice. Smolts began their migration ~30 April in the upper Ness system (U), and ~11 May in the lower Ness system (L). Temporal replicates overlapped with this migration, with sampling occurring on 25 April, 1 May and 9 May in U, and 9 May and 17 May in L.

A2.2.11.2 Salmon-specific qPCR assay

Before testing the eDNA samples collected, a salmon-specific qPCR assay needed to be validated. Two salmon-specific primers were tested: those developed by Parsons et al. (2005) and by Atkinson et al. (2018). They were tested on Scottish salmon and brown trout (*Salmo trutta*) samples to determine the accuracy of species-specific amplification, since brown trout is known to occur within the Ness system and is closely related to salmon. Preliminary results found that some brown trout amplified using both sets of primers. As such, investigation into the sequences of these brown trout samples are currently underway to determine whether they may in fact be hybrids, or whether primers need ot be re-designed to increase species specificity.

The lockdown has impacted also on this analysis and it is currently halted at the assay validation phase, awaiting the RLI laboratory being reopened.

A 2.2.12 Socioecological analysis of Garry catchment

One of the key factors in the success of any adaptive management approach is stakeholder engagement and participation, a prerequisite for development of a common vision and a comprehensive management plan at the catchment level.

In the current case study area, there are strong and effective ties between the main stakeholders operating for the management and preservation of freshwater resources, i.e. the Ness District Salmon Fishery Board, Scottish and Southern Energy and the Scottish Environmental Protection Agency. Additionally, the RLI has significant involvement in the management and restoration of the Upper Ness catchment through the Upper Garry Salmon Restoration Project. Clear advances are taking place through coordinated efforts of these stakeholders, as outlined in section A2.2.5.2.

The socioecological research described in this section engages with the above stakeholders, and seeks to identify and engage with additional stakeholders, with the local community in particular, by means of workshops and interviews.

A2.2.12.1 Objectives

Three key objectives of this research were to:

1. Identify additional stakeholders
2. Interview key professionals working in the freshwater and related land use sectors in the case study area
3. Interview members of the local community in a workshop setting

and thereby explore the following topics:

- Past and present management of freshwater resources in the Upper Garry Catchment, from a social and economic perspective.
- Social-ecological impact and perception of the GGHS over time
- Positive and negative economic implications of the GGHS, past and present.
- Social and cultural change in Glengarry before and after installation of the GGHS
- importance of the surrounding landscape and practices that shape community and river culture.

After a description of the methods used (A2.2.12.2), a broader overview of existing stakeholders is provided (A2.2.12.3), followed by an analysis of the themes emerging from interviews with professionals (A2.2.12.4), and by the themes emerging from the workshop at the Heritage Centre (A2.2.12.5). The outcome of this analysis is then discussed in section A2.2.12.6.

A2.2.12.2 Methodology

Interviews were fully transcribed into Nvivo and coded twice, once to identify the full array of codes and second to refine codes and organise the coding structure to produce dominant themes and sub-themes. With regard to the workshop with the local community, individual engagements and the group discussion with participants were recorded on a Dictaphone with their prior consent, then partially transcribed, coded and analysed for major themes.

A2.2.12.3 Stakeholder mapping

Water regulation and abstraction, and the management of the surrounding landscape sees the involvement of additional statutory bodies beyond NDSFB and SEPA, and these are listed below in **Table 2.2.2**. Among NGOs, and alongside SNH, the RSPB is heavily involved in monitoring the freshwater ecology in the catchment, given the presence of protected bird species and habitats around Loch Garry and Loch Loyne in particular. As mentioned in section A2.2.5, fish farming company MOWI is present in Loch Garry, and over time, the smolt-rearing facility has likely had an impact on the now dwindling wild salmon population through farm escapes. This is now being actively monitored by MOWI, with involvement of NDSFB and RLI.

An important link between renewable energy businesses and the local community, aside from direct employment, comes in the form of trusts and social enterprises such as the Glengarry Trust and the Beinneun Community Fund, who distribute community benefit funds for local initiatives, for example contributing to purchasing the land now managed by the Glengarry Community Woodlands project. SSE is also providing significant funds (~£80,000) every year to the NDSFB to mitigate for the impacts of the GGHS.

The Glengarry Heritage Centre is a charity run from the Glengarry Community Hall; it started as a visitor centre and now works to promote local history for the benefit of both residents and tourists. It has been instrumental in allowing the RLI to get in touch with the local community. Furthermore, the AMBER project has brought together various academic partners (see Table 2) and this resulted in ongoing collaborations, which are likely to continue beyond the lifespan of the project.

Table 2.2.2: stakeholders in the River Garry catchment

Organisation	Acronym	Description
Statutory		
Ness District Salmon Fishery board and trust	NDSFB	Responsible for the managing Ness Catchment
Scottish Environmental Protection Agency	SEPA	Hydropower and water management regulators
Marine Scotland Science	MSS	Overseeing freshwater fish ecology; provided temperature sensors for the Rivers Gearr Garry and Kingie.
Scottish Water	SW	Responsible for water quality, treatment and distribution
Scottish Canals	SC	Responsible for management of canal systems and navigation
Scottish Natural Heritage (Scottish Nature)	SNH	Responsible for conservation areas in the catchment
Forestry Commission (Scottish Forestry)	FC	Responsible for management of forest resources and regulation
Non-Governmental Organisation (NGOs)		
Royal Society for the Protection of Birds	RSPB	Charity advocating protection and conservation of bird species and habitats
Trees for Life	TL	Estate owner in catchment restoring native woodland
Atlantic Salmon Trust	AST	Leading the Missing Salmon Project (smolt escapement from the River Garry)
Businesses		
Scottish and Southern Electric	SSE	Hydro and other renewables development – energy provider
MOWI	MOWI	Fish farming company
Community organisations		
Glengarry Heritage Centre	GHC	Centre for communication of local history and gathering place for local community
Glengarry Community Woodlands	GCW	Responsible for management and use of community owned woodland
Academic		
Rivers and Lochs Institute, University of the Highlands and Islands	RLI UHI	AMBER case study lead
Samhal Mòr Ostaig, University of the Highlands and Islands	SMO UHI	Specialist in Gaelic language and history
Archaeology Institute, University of the Highlands and Islands	AI UHI	Providing research support and supervision for Mres on pre-hydropower river culture
Environmental Research Institute, University of the Highlands and Islands	ERI UHI	Water quality analysis to completement eDNA data.
Durham University	DU	Drone image mapping and analysis (AMBER partner)
Instytut Rybactwa Sródlądowego Poland	IRS	MesoHABSIM habitat mapping (AMBER partner)

A2.2.12.4 Interviews with professionals – emergent socioecological themes

During 2018 and 2019, a range of interviews were organised with people associated with the catchment, each representing a different professional and at times personal perspective. A topic guide was used to guide the interviews to capture comparable perspectives as well as individual experience and knowledge (see objectives); Interviews were conducted with:

- Environmental Advisor for SSEN (Scottish and Southern Electricity Networks), locally involved in renewable projects
- Two members of staff working for the NDSFB
- NGO estate manager in the catchment
- Estate stalker near Loch Quoich
- Former hydro engineer

Seven dominant themes were identified during the interviews, and these follow below. The implications of these themes are discussed in section A2.2.12.7.

1. Normalisation of impacts: Historical catchment management decisions have caused long-lasting impacts, but these have been normalised, giving rise to a culture of acceptance. River fragmentation is considered normal.

2. Environment vs development trade-offs: Many respondents mention the difficult task of balancing the range of objectives in the catchment, and the associated decisions, between development, economics, ecosystem health and resource use.

3. Understanding the significance of river ecosystem health: important in discussions about rivers, aquatic species and the role of dams was the connectivity, function, provision of services and health of the rivers and lochs, which was considered a key indicator of health for other land uses and communities in the catchment. This understanding was by many still found to be lacking, with an important role for education and multistakeholder initiatives.

4. Ownership and group interests constrain management operations: while there was found to be cohesion between policy and management, in shared concern for threatened species and habitats as the central focus, several issues were found to limit the scope of policy / management actions.

- communication and coordination at the catchment level: river fragmentation manifests not only as physical barriers but also as fragmented ownership of fishing rights, creating a mindset that focusses on the assessment and management of short river stretches rather than entire ecosystems, parcelling up the catchment into closed areas.
- Funding for enforcement of fishing regulations is limited and this could be ameliorated by introduction of a rod tax for anglers (present in England but not in Scotland); such tax was proposed but then dropped for political reasons.
- Management of deer populations and forested land is focused on the services provided to the hunting and shooting “industry”, which limits the scope for optimising land use to mitigate for floods (natural flood management) and other impacts on rivers.

5. Angling as a force for both exploitation and conservation: not all anglers always act responsibly when it comes to fishing sustainably and not releasing bait, and this can affect the health of the rivers, however some of the revenue from the fishing permits paid to proprietors feeds into the funds that allow the Fishery board to operate and ensure that conservation measures are implemented and improved over time.

6. Land use impacts on rivers require monitoring: although hydropower is considered to have more significant environmental impact associated with catchment fragmentation, depending on their location, wind farms can also potentially alter the balance, for example by causing more flash floods due to the reduction in tree cover in the area where they are installed. Recently, FC has seen to the planting of river-appropriate species, so there is an awareness of the importance of forestry management to offset land use changes, but more needs to be done to monitor these.

7. Need for changes to river management: several participants highlighted the need to change the approach and focus of current river management; quoting a participant: “A better way forward would be to accept that managing fish is not the same as managing rivers”. This is an important point, highlighting how fish are the economic driver for river management, and thus, while they enable river conservation, this is often more limited in scope, when it comes to catchment-wide initiatives looking at whole ecosystems.

A2.2.12.5 Workshop with local community – emergent themes

A day-long event was held at the Glengarry Heritage centre on 18 April 2018, starting with a presentation providing an overview of the AMBER project and the AMBER case study, followed by a discussion/interview with local residents. Ten attended the entire event, while an additional six joined part of the workshop to share their local and historical knowledge and perspectives on the area, with a specific focus on the past and present of hydropower in Glengarry and related land use changes. Many of the participants had lived and worked in the area for decades.

The participant list included:

- Garry Heritage centre manager
- Garry Heritage centre volunteer
- Estate Ghillie (x2)
- Estate workers (x2) and sister
- Marine worker
- Local resident (x6)
- Local forester

Two dominant themes (and their subthemes) are described below, relating to the importance of hydropower and of fishing culture to the local community. The implications of these themes are discussed in section A2.2.12.7, together with those arising from one-to-one interviews.

1. Dam renaissance: prosperity and change: dams had a positive impact on the community and have ushered in an era of employment, economic prosperity and population change. There is clearly limited living memory of Glengarry prior to hydropower, as very few residents were born at the time the dams were put in place, so there is also a limited sense of loss of an intact ecosystem. Wind energy was perceived much more critically by some, with the aesthetic impact of wind farms being considered far greater than that of dams, and for less return for the local community.

2. Fishing culture:
a) impact of predation on salmon: most participants remember and look upon dams as a very positive influence and place blame of dwindling fish stocks squarely on predation by birds (goosander and merganser) and pike. Goosander and merganser are indeed protected by the Wildlife and Countryside Act, and limited shooting licenses are available to control numbers, under instruction by SNH. It must be pointed out that the Act entered into force in 1981, so the salmon stock decline prior to the 1980s cannot be fully ascribed to said birds.
b) anglers vs kayakers: many anglers who pay for their fishing permit feel animosity toward kayakers who take advantage of the artificial spates released by Invergarry Dam to use their kayak, interfering with fishing (which is also more successful during a spate) and not contributing to the maintenance of the river as they are not required to pay to kayak.
c) poaching still a threat: limited monitoring of the rivers due to limited resources being available still offers opportunity for poachers. Although poaching is not as lucrative as in the past (prior to the arrival of fish farms), when salmon could be sold to local restaurants for good money (now the price of salmon does not provide the same incentive), the impact of even limited poaching can be as severe given that the number of salmon have dropped so dramatically.
d) salmon population changes: the present generation remembers that, aside from their greater numbers than at present, in the past Garry salmon stood out from other populations as shorter but with more girth; now they are smaller and not as broad. This could reflect both changed conditions at sea and a change in the local salmon population due to stocking of salmon from the River Esk and potential introgression with farmed salmon.
e) loss of prominence: fishing on the Garry attracted rich and influential people as tourists, and this indirectly benefited the local community, so there is an element of nostalgia for the times where the privileged visited the area, and a subsequent loss of identity and status for fishing in the area.

A2.2.12.6 Emergent conclusions and implications for catchment management

The social-ecological research conducted within the Ness catchment indicates that rivers, lochs and their associated uses are the life blood of the surrounding communities, social-ecological arteries of the landscape that shape ecosystems, human communities and surrounding industry. The services supplied by rivers, including hydropower, can be responsible for transformative change of both the surrounding riverine environment and the human communities. The arrival of hydropower, especially in the Highlands, was a key moment for many locals of the older generation, allowing access to electricity in remote and isolated parts of the Highlands, along with years of inflated and changing population dynamics in the area due to the influx of workers, development of infrastructure and presence of new settlers in the region. Hydropower brought what was seen as prosperity in the region, strengthening the community for decades to come. The development mainly brought a boom of jobs during construction, then a source of sustainable jobs connected to the operation and management of dams, and access to community funds and apprenticeship schemes set up by renewable energy companies (first hydropower and now also wind).

Along with the prosperity generated by hydropower development came the loss/transformation of local community identity, which changed from a close-knit community of smallholders made mostly of Gaelic speakers, to that of a ‘hydro community’, with the dam providing a back-drop of energy generation and income. In parallel to economic growth sustained by hydropower, the local fishing stocks and associated economy declined, with Glengarry going from being a famed destination with many visitors, large fish and plentifyul fishing, to a much smaller and more local angling community, with more limited scope for tourism, now primarily focussed around the Caledonian Canal and Loch Ness.

Hydropower (and renewable energy in general) are clearly part of the fabric of the local economy and thus are considered community assets, but the impression is that the community has so far been at the receiving end, rather than being a driving force of these developments, and a few participants welcomed the AMBER workshop as a much-needed opportunity to express their views, which, for good or for bad, they felt hadn't been given much consideration so far. Initiatives such as the Glengarry Community Woodlands (the purchasing of local woodlands) have provided opportunities for the community to reclaim some greater connection with their surroundings, but more could be done to ensure wider access to and fruition of the River Garry, for the community and as a tourist attraction, and for the ecosystem services it offers, albeit in its impounded state.

Furthermore, the themes identified during interviews with professionals suggest the need for a more integrated form of catchment management, with greater interaction between stakeholders, allowing river management to be a part of wider area management plans, with land use impacts on rivers being carefully considered, and research and monitoring efforts put in place to provide evidence and guidance on best practice for adaptation and mitigation. More comprehensive plans could help bridge the gap between local interests and wider ecosystem dynamics. Multi-stakeholder involvement and best use of resources requires development and promotion of River Culture based on an understanding of overall ecosystem health. This in turn can promote recreational and tourist opportunities and ensure greater community involvement.

Given the economic implications of such a change in management, change needs to be effected at the highest level, with a clear assessment of the financial shortcomings that limit Fishery Boards from operating successfully. The Scottish government commissioned a Wild Fisheries Review in 2014, which led to the drafting of a Wild Fisheries Bill in 2016, to develop and promote evidence-based management and the sustainability of fisheries, but what was considered by freshwater professionals a progressive piece of legislation was shelved for political reasons, so there is still some way to go before national policy aligns with management needs.

A2.2.13 Case study conclusions and reflection

The Upper River Garry AMBER case study was designed to build a bespoke adaptive management framework for the management of barriers in the River Ness catchment starting with the application of specific tools that might provide new insights into the social and ecological impacts of barriers and other freshwater uses. While this broad aim has not been fully achieved as yet, new research has been conducted and new tools implemented, and the case study has enabled capacity building and scientific exchange to integrate knowledge and skills across many partners with a long-term aim of developing a more holistic approach to assessing the impact of barriers within a catchment management perspective.

Several academic and industrial partners contributed to this work and collaborations have strengthened, leading to further multidisciplinary research. It has not been possible to fully integrate all the tools used, due to a combination of challenges including:

- establishing reproducible laboratory and field protocols associated with eDNA analysis, requiring trial and error (our lab was recently setup, so expertise had to be developed over time)

- the steep learning curve involved in developing expertise that crossed between different tools, requiring an understanding of what could be delivered by each tool

- the remote case study location, which posed logistical issues with sample collection and drone analysis and constrained the feasibility of any in-depth habitat assessment

- the unforeseen landslide affecting the area downstream of Quoich dam, which affected the temperature sensor located just below the dam, causing significant influx of sediment into the system.

- Balancing effectively the gathering of existing historical, social and ecological data with the development of fieldwork and experimental plans and schedules

As a chapter in the development of an adaptive management framework for the Ness catchment, this case study has opened new avenues for further exploration and collaboration and some lessons can be shared for the implementation of future case studies:

- ensure that sufficient development time is envisaged to establish new tools and test them effectively

- Scope the specific requirements of each tool to see how easily applicable it might be to the specific case study, to avoid trying to fit a tool that does not suit, or that requires significant modification.

- ensure that ancillary environmental parameters are available and if not that they can be gathered directly as part of the study.

- factor in extra time for multidisciplinary learning so that each expert in one tool is exposed to and understands any other relevant tool for the case study

Within any adaptive management approach there are time constraints and resource constraints to consider and it is well known that adaptive management is resource-intensive given that it is based on the acquisition of new data and on regular monitoring, both of which are expensive. Investing into adaptive management as a strategy comes with a commitment to develop understanding of a catchment over time, and this requires that balance between research and management is continuously sought and negotiated, to combine short- and long-term priorities. Fortunately, in the case of the Ness catchment, a long-term commitment exists among stakeholders to understand and improve the ecological state of the rivers and lochs affected by hydropower.

The next phase in this process is to integrate the data acquired by AMBER into management actions and the tools developed by AMBER into regular monitoring if that was deemed appropriate. Ideally, had data acquisition (namely eDNA) been completed earlier on in the project, there would have been scope for integration of results into management. However, this is still the intention, and a workshop will be held with all relevant stakeholders to present the AMBER results and devise follow up studies.

eDNA results have shown that collecting freshwater samples above and below barriers provides a snapshot of the species present along the water course and that clustering of lochs with rivers downstream might be more significant than the clustering of rivers versus lochs. No significant water quality issues were found downstream or upstream of barriers in the catchment, which suggests that the differences between the unimpacted Kingie River and the Gearr Garry might be due to subtler habitat effects. With that in mind it would be interesting to investigate invertebrate species composition in the sediment especially after the impact of the landslide to characterise habitat differences in terms of the species embedded at each site.

Looking to the future, the following research avenues could be considered:

- more detailed eDNA assessment with a time course of samples taken from a more limited set of locations, to develop a metric to assess the impact of barriers with eDNA, accounting for seasonal variation (comparing water and sediment)

- Developing a detailed habitat map based on both the drone images and the MesoHABSIM data to inform the choice of further eDNA sampling locations

- Integrating the work conducted as part of AMBER with the Upper Garry Salmon Restoration Project looking at introducing salmon eggs both on the Kingie and the Gearr Garry in a controlled experiment using the habitat map and existing eDNA data to inform sampling regime.

A2.3 CASE STUDY 5: Włocławek Dam, River Vistula

A2.3.1 Background and current status of Włocławek Dam and Vistula River fisheries

The River Vistula is the longest Baltic river (1,020km) and is second only to the River Neva in the size of its basin (194,000km2) and average streamflow (1,046m3/s) (**Figure 2.3.1**). The River Vistula is one of the last large European rives with substantial stretches of its lower and middle course preserved in close to natural or slightly modified morphological conditions (**Figure 2.3.2**). It was historically a main migration path in Poland for several diadromous fish species: sea trout (*Salmo trutta m. trutta* L.), Atlantic salmon (*Salmo salar* L.), Atlantic sturgeon (*Acipenser oxyrinchus* Mitchill 1815), and migratory populations vimba bream (*Vimba vimba* (L.), as well as river lamprey (*Lampetra fluviatilis* L.). In the past, these species reached the tributaries of the upper Vistula - Dunajec, Raba, Soła, Skawa, Wisłok, San and the tributaries of lower and middle Vistula River: Drwęca, Brda, Wierzyca, Bug and Narew, where spawning took place (**Figure 2.3.3**).

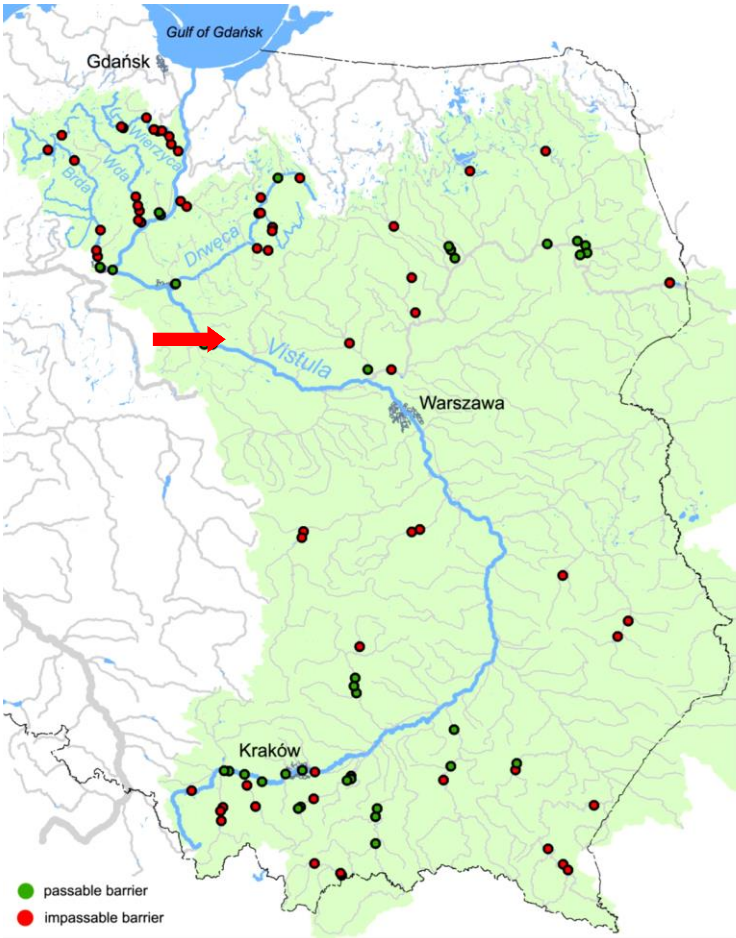


Figure 2.3.1. Map of the River Vistula and its main tributaries. Włocławek Dam is marked (red arrow), as well as other barrages (impassable – red dots, passable – green dots).

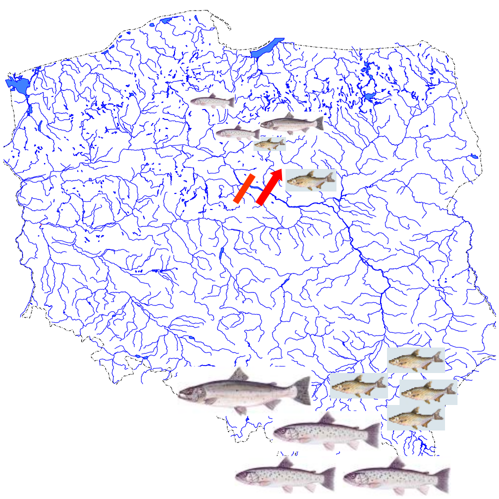


Figure 2.3.3. Historical migration routes of diadromous fish species in the Vistula system (Wiśniewolski, 2020). Włocławek Dam is marked by red arrow.

Some differences in species distribution in particular rivers were distinct, most often related to the existence of adequate spawning grounds for a given species. Historically, there was intensive commercial fishery concentrated mainly on migratory fish: sea trout, Atlantic salmon, vimba bream and, till the end of 19th century – Atlantic sturgeon (Morawska 1968, Backiel 1985, Wiśniewolski 1987, Bartel 2002, Bartel et al. 2007). This fishery was gradually decreasing over the 20th century due to water pollution, river regulation and damming, especially after erecting the Rożnów dam in 1940 on the main sea trout spawning tributary the River Dunajec (Kołder 1958, Żarnecki 1960). Nevertheless, in the 1950s commercial catches of sea trout in the River Vistula still exceeded 50 tons (Bartel 1993) and catches of vimba bream exceeded 300 tons (Wiśniewolski 1985).

A decisive moment was the construction of a dam across the River Vistula in Włocławek, 266km from its estuary and 754km from its source (**Figure 2.3.4**). It was completed in 1969 and created a reservoir of approximately 70.4km^2 surface area and 408 million m^3 of volume. One year later, a pool fishway was put into operation with a flow rate of 0.935m^3/s and located in the pillar between the weir and the hydroelectric plant (Biegała 1972) (**Figure 2.3.5**). The fish pass was initially not fully efficient - studies on the functioning of the pass at Włocławek Dam in 1972-74 indicated that 19 fish species passed through it, but only an average of half of them were able to negotiate it, and among these fish were only single specimens of sea trout (Bontemps 1977).

Through the following decades, bottom erosion below the impoundment caused water level lowering (Szupryczyński 1986) and further deterioration of fishpass functioning (Linnik et al. 1998, Woźniewski et al. 1999). Further deterioration led to the construction of an auxiliary stone ramp in 1998 downstream of the main dam (Dębowski 2016, Dębowski 2017) (**Figure 2.3.4**). New studies of the functionality of the fishway were conducted in the 1998-2004 period (Bartel et al. 2007). It was found that many eels, white breams, roaches, breams, bleaks as well as individuals of 11 other species, including sea trout and vimba, entered the fishway, but only 3.5% of them were able to climb the fishway. The estimated number of sea trout navigating the structure was barely 100 individuals annually (Bartel et al. 2007).

The Włocławek dam had crucial impact on migratory fish species in the Vistula river system (Backiel 1985, Bartel 1993, Bartel 2002, Wiśniewolski et al. 2004, Wisniewolski and Engel 2006, Dębowski 2018c). Populations of sea trout, vimba and potamodromous species, like asp and barbell, declined seriously after dam construction, while sturgeon and Atlantic salmon were extinct in the Vistula river catchment a few decades earlier due to overfishing and water pollution. Since then, a large reintroduction programmes have attempted to rehabilitate the extinct and endangered diadromous species, with some success so far.

Figure 2.3.2. the River Vistula – seminatural stretch at Bógpomóż Stary – 14km below the Włocławek Dam.

Figure 2.3.4. The Włocławek Dam on the River Vistula. The new fishpass marked with an arrow and the auxiliary dam.

The fishpass at Włocławek dam was reconstructed in 2014 into vertical slot type of better passability parameters and the entrance window was reconstructed and lowered below actual water level. Now, this is the vertical slot fishway with slot's width of 0.3m and 60 chambers 2.4 x 2.8m (**Figure 2.3.6**). Its length is 195m, slope 7.46 % and flow 0.59m^3/s. Attracting water in amount of 3m^3/s is supplied by a pipe to the lowest chamber. The entrance is located at the left side of the pillar, below the outflow from the turbines, and the exit at the right side of the pillar, opposite to the water intake.

Concurrently, a new dam is being planned downstream, aimed to hydraulically support the existing one and to stop bottom erosion. The ecological effects of Włocławek dam opening to fish migration and a possible new-build barrier impact were studied and modelled within this case study of the AMBER project. Tools developed by AMBER were applied as decision support for management of the middle River Vistula stretch, as crucial for migratory fish restoration in whole catchment. Specifically, this study aimed at:

1) Fish habitat availability studies conducted below and upstream of the Włocławek dam and coupled with measurements of physical conditions, including aerial mapping of habitats (using drones and satellite imagery). The results of these studies are used for modelling of environment changes and habitat loss in case of building a new dam reservoir below Włocławek.
2) Study the effect of fish migration through the Włocławek Dam newly reconstructed fish passage.
3) Within the AMBER framework, model the ecological effects of Włocławek dam opening to fish migration and effects of probable new-build barrier.
4) Using Tools developed by AMBER (aerial imaging, habitat maps, habitat suitability models, e–DNA study) as decision support for management of the middle Vistula River stretch and for migratory fish restoration in whole catchment.

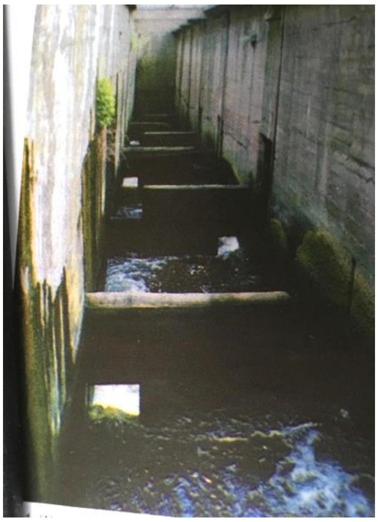


Figure 2.3.5. An old fishway and location of entrance windows.

Figure 2.3.6. The fishway after modernization.

A2.3.2 Włocławek Dam fishpass efficiency

An automatic fish counter (Riverwatcher, Vaki Aquaculture Systems Ltd.) ws installed in the 49th chamber (**Figure 2.3.7**). It uses infrared scanning and records passing objects together with direction and speed of movement, height and silhouette of an object and a short film (**Figure 2.3.8**). These records are examined one by one for elimination of non-fish and identification of fish species. The procedure results in the number of fish of separate species passing the counter over time. Because of a big difference between the river and the fishway flow and localisation of the exit, it is assumed that downmigrating fish are unable to find the exit and all fish recorded as swimming down, previously swam upstream then returned not attaining the exit. So, given numbers of fish are net amounts: fish passed upstream minus fish passed downstream.

Fish ability to pass the entire fishway and their speed were studied with RFID (radio frequency identification) technology (Prentice et al. 1990, Castro-Santos et al. 1996). Four loop antennae were installed in slots between 5 and 6, 18 and 19, 49 and 50, 56 and 57 chambers (upstream numeration) (**Figure 2.3.9**). Each antenna was connected to Oregon HDX reader, equipped with a test PIT (passive integrated transponder) tag and powered from mains power supply.

Fish for PIT tagging were caught in a trap in the uppermost chamber. PIT tags were injected into the body cavity of fish using a tagging gun (**Figure 2.3.10**). OREGON HDX PIT tags 12.0 x 2.12mm, 23.0 x 3.65mm or 32.0 x 3.65mm were used depending on fish size. Tagged fish were released directly below the dam on the opposite to the turbine outflow and the fishway entrance, right side of the pillar. In tatal 880 fish of 12 species were tagged.

Temperature data were obtained from fish counter's sensor and river flow data were provided by Regional Water Management Board.

The results recapitulates four years of the counter work (2015 – 2018) and five years of PIT tagging experiments 2015 – 2019.

Figure 2.3.7. An infrared fish counter (VAKI Riverwatcher).

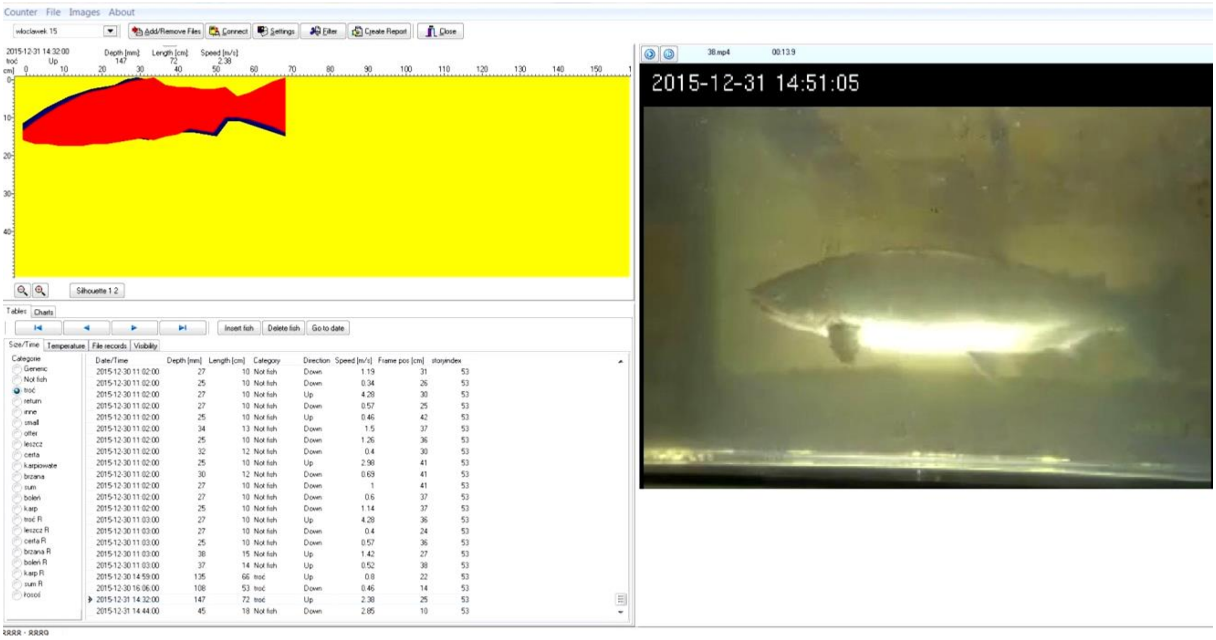


Figure 2.3.8. Record from the counter.

Figure 2.3.9. RFID antenna.

Figure 2.3.10. Tagging with PIT.

A2.3.3 Results

Hydrological and thermal conditions of the River Vistula 2015-2018

Analysed years were very different from a hydrological point of view (**Figure 2.3.11**). In 2015 spring flow was rather moderate and stable, at the beginning of June increased rapidly for a few days and stayed low and stable during summer and autumn. In 2016 flow was more variable, without June's rise but with higher water in autumn. Flow in 2017 was distinguished by very low-level early spring, two very high peaks in March and May, and high and variable water in autumn. In 2018 instead of typical March rise there were peaks in early January, early February and early April, separated by low water in early March; there was also fierce and short rise in the middle of summer, and low and stable flow in autumn.

Water level difference at the auxiliary dam below the main dam depends inversely on river flow (**Figure 2.3.12**) and the dam is fully covered by water at flow above 640m3/s (Dębowski 2017). This difference oscillates around 1m in spring and decreases to or below 0.5m during water rises, then increases above 1.5m in summer with slight decrease in autumn. Year 2018 differed from the others (**Figure 2.3.13**).

Water temperature followed generally similar annual course with 20°C attained usually at the second half of May and remained above until the end of August. Maximum annual temperature varied around 25 °C. Year 2018 was generally warmer than the others (**Figure 2.3.14**).

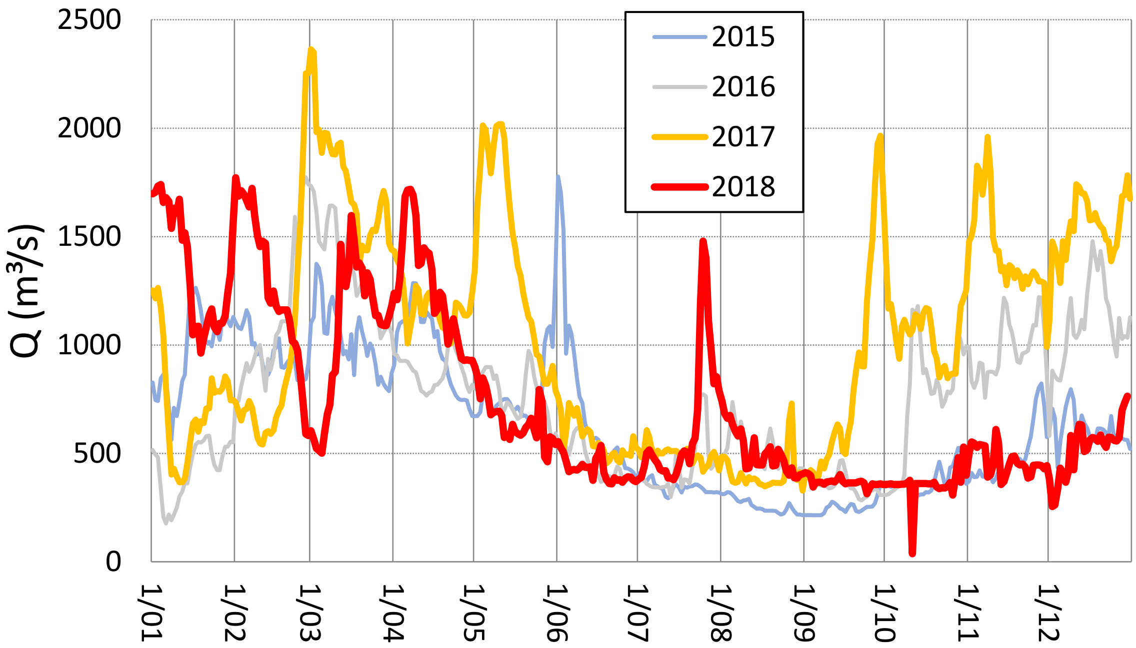


Figure 2.3.11. River flow in the River Vistula at Włocławek Dam.

Figure 2.3.12. The auxiliary dam: right (A) and left (B) side, Jan 2017, flow 1,264m^3/s; right (C) and left (D) side, Sept 2016, flow 407m^3/s.

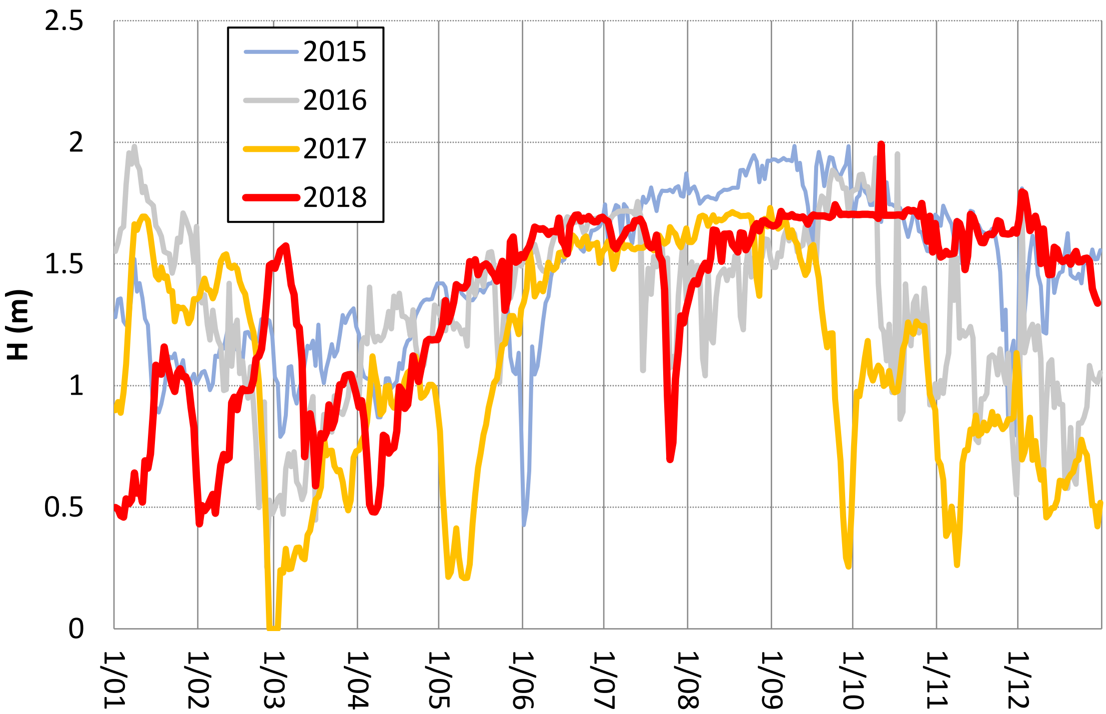


Figure 2.3.13. Water level difference on the auxiliary dam.

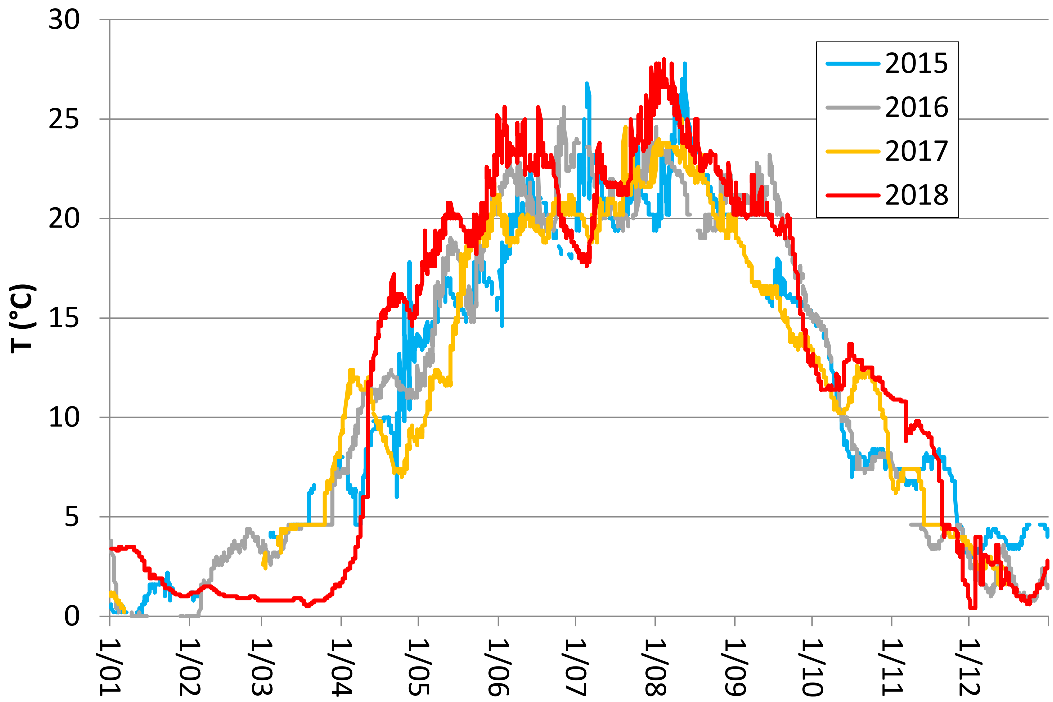


Figure 2.3.14. Water temperature in the River Vistula.

The VAKI Riverwatcher fish counter results

Amounts of observed migrating fish varied a lot between the years: from 3882 fish in 2015 to 23028 in 2017 (**Table 2.3.1**). There were also big differences in species compositions. Anadromous fish, sea trout and vimba, evidently dominated in 2015 and constituted together 81% of migrants. Sea trout in following years declined substantially to only 173 fish in 2017 and vimba increased sevenfold to over 11,000 also in 2017. Bream, rare in 2015, migrated in amounts of few thousands in the other years. Intense migration of white bream was recorded only in 2017. Catfish in 2015 constituted almost 8% of migrants, but around 1% in the other years.

Table 2.3.1. Number of fish recorded by the fish scanner (net amounts).

		Years			
Species		2015	2016	2017	2018
vimba	*Vimba vimba*	1575	1123	11091	2876
bream	*Abramis brama*	234	4909	5968	3036
white bream	*Blicca bjoerkna*			3372	276
sea trout	*Salmo trutta*	1566	811	173	388
asp	*Aspius aspius*	53	624	1468	385
barbel	*Barbus barbus*	59	221	686	219
catfish	*Silurus glanis*	295	76	189	89
carp	*Cyprinus carpio*	41	32	36	15
roach	*Rutilus rutilus*		1	1	124
ide	*Leuciscus idus*	1	6	20	11
chub	*Leuciscus cephalus*		1	9	2
salmon	*Salmo salar*	2	1		8
white-eye bream	*Abramis sapa*				7
perch	*Perca fluviatilis*		4		
eel	*Anguilla anguilla*				3
pikeperch	*Sander lucioperca*		2		
grass carp	*Ctenopharyngodon idella*		1		1
burbot	*Lota lota*		1		
pike	*Esox lucius*				1
river lamprey	*Lapetra fluviatilis*				1
unidentified		56	5	15	3
Total		**3882**	**7818**	**23028**	**7445**

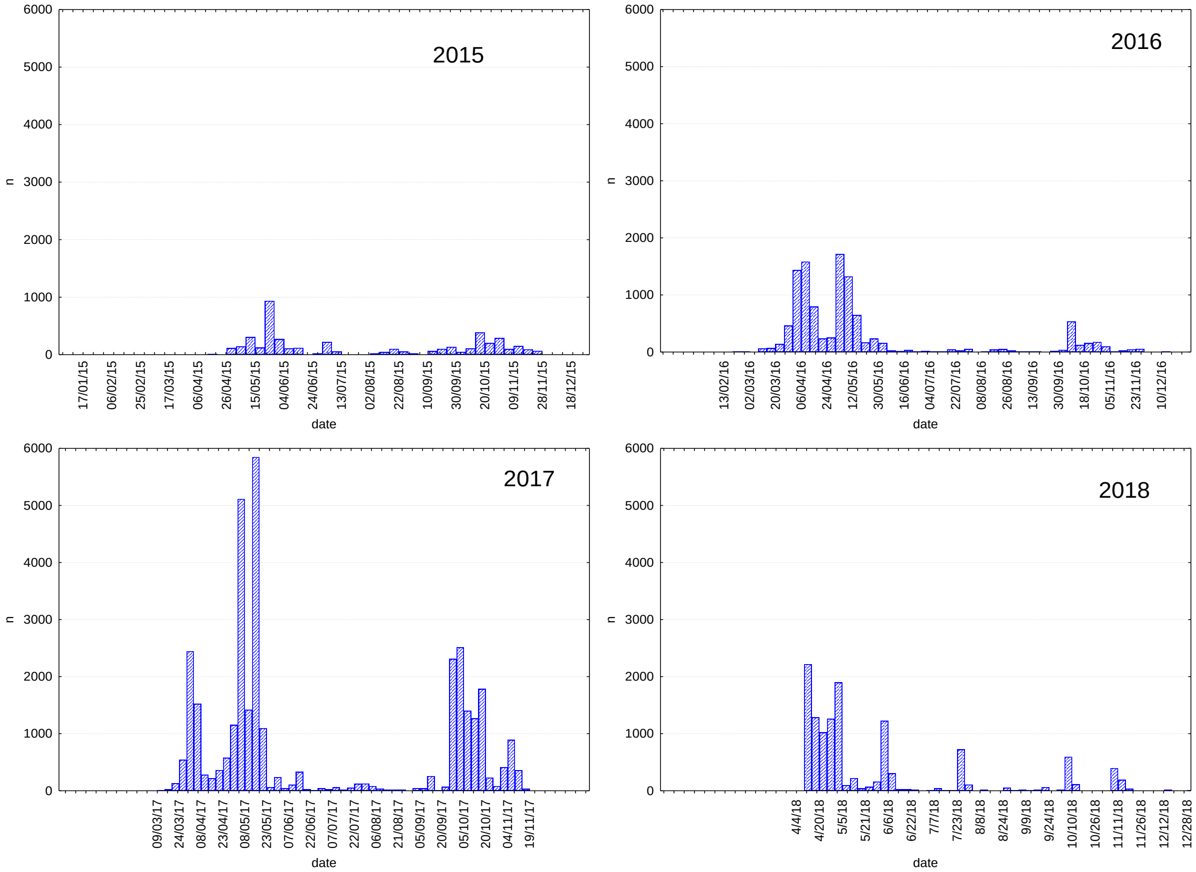
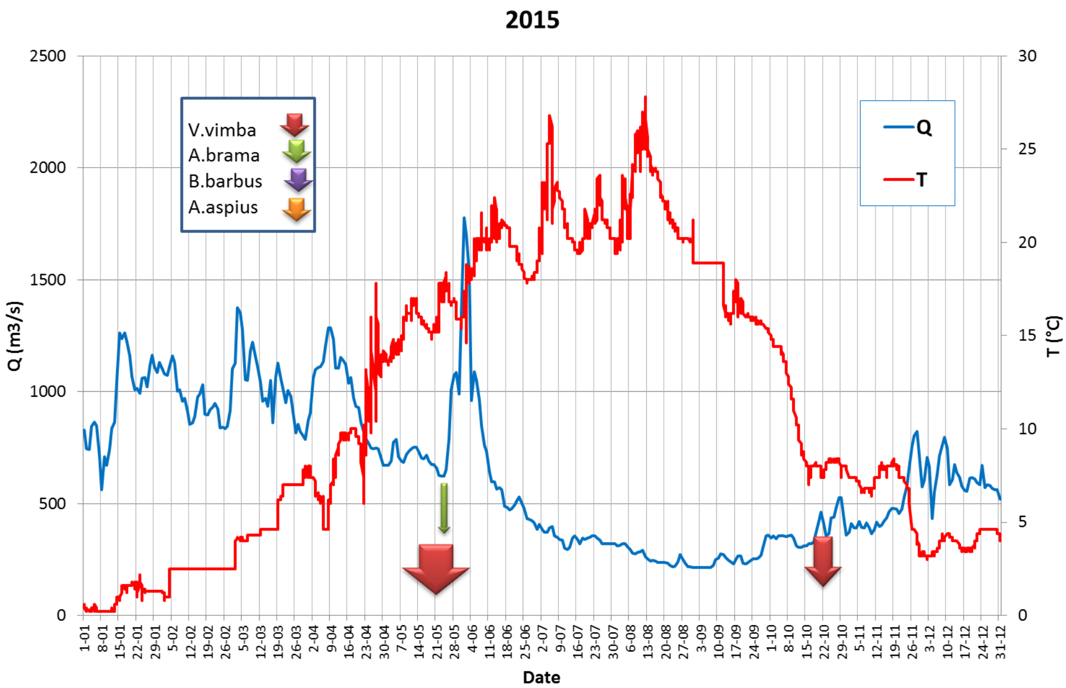


Figure 2.3.15. Fish migration trough the fishway (number of fish per day).

There were two migration seasons: spring and autumn. The first one, between March and May, in some years had two peaks – in March/April and May (**Figure 2.3.15**). The earliest were usually the first run of vimba and bream sometimes accompanied by asp then the second run of bream and vimba, barbel, alternatively white bream. Autumn migration consisted mainly of vimba, barbel and sea trout. Main spring runs often followed water temperature increase and/or decrease of flow (**Figure 2.3.16a** and **b**).

Runs of separate species were very often very short and intensive: 96% of migrating in 2017 white breams passed in 6 days with 644 fish/day in average, number per day of vimba and bream in peaks of run often exceeded 500.



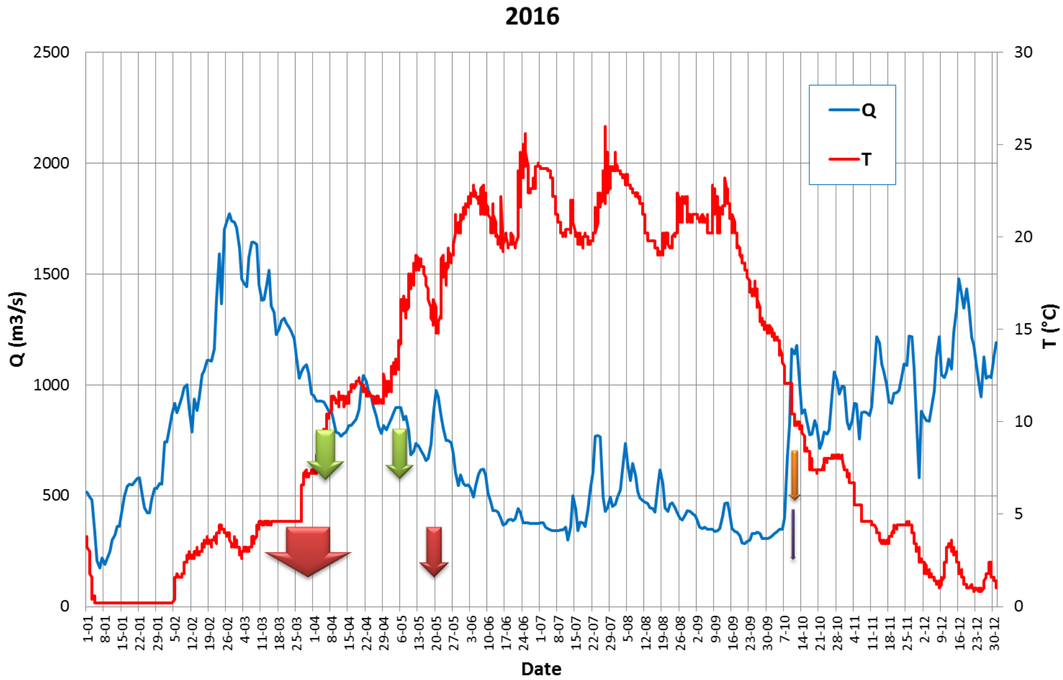
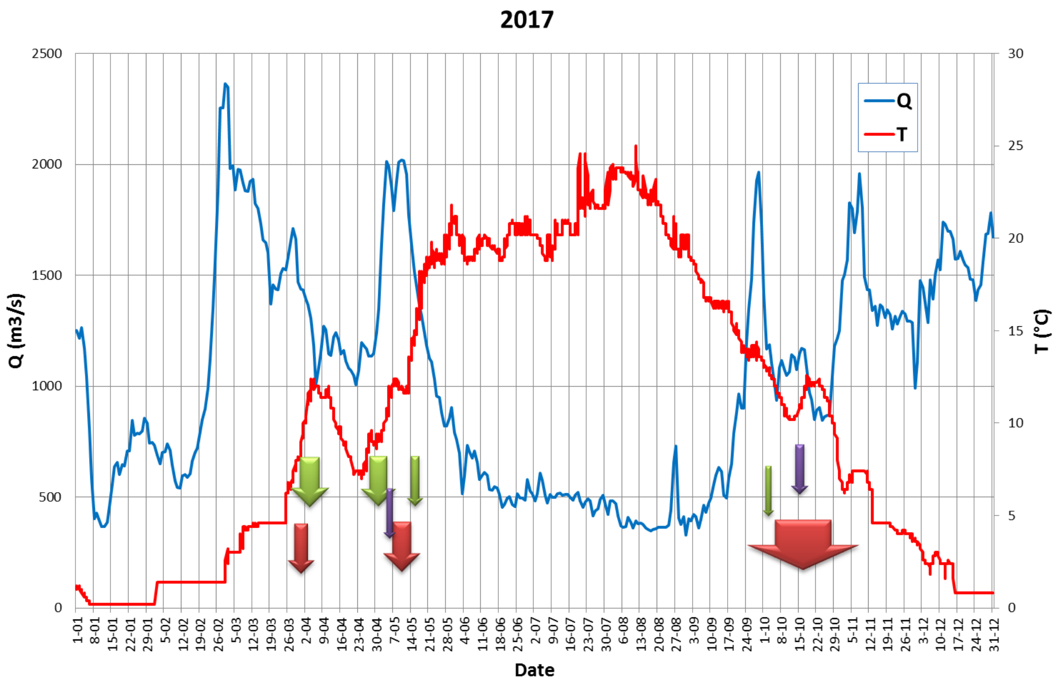


Figure 2.3.16a: Main runs of main species on the background of flow and temperature (2015-2018).



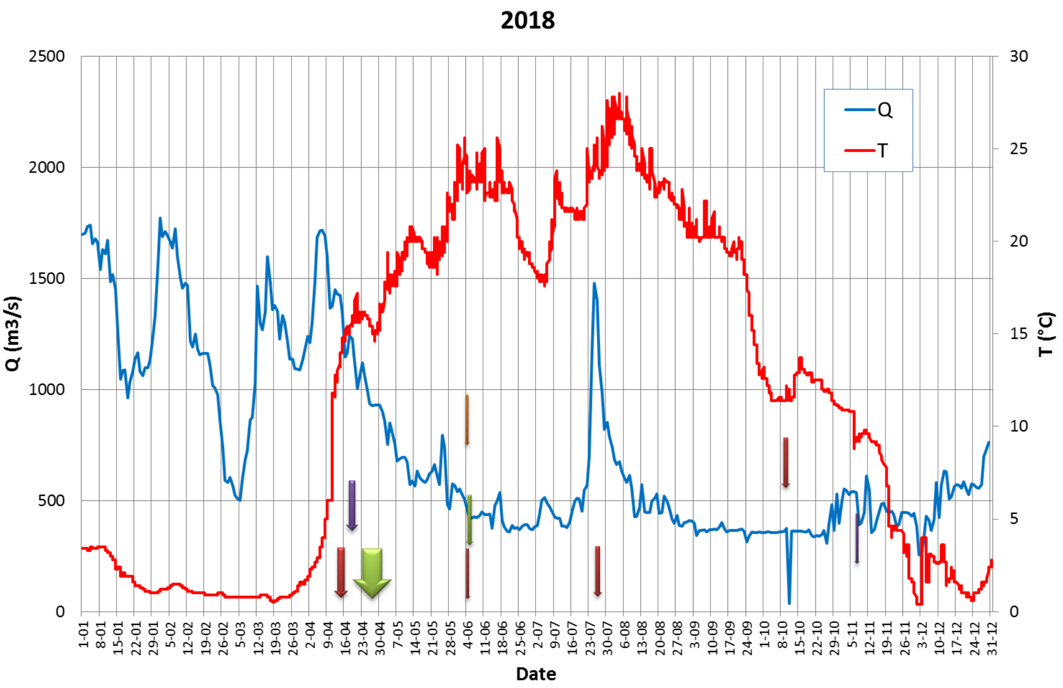


Figure 2.3.16b: Main runs of main species on the background of flow and temperature (2015-2018).

The RFID system (radio frequency identification) results

Eleven percent (98 ind.) from 881 tagged fish were recorded by RFID antennae in the fishway (**Table 2.3.2**). The fastest fish (vimba) entered the fishway after 2 h and 18 min and the slowest (bream) after 3 years and 1 month. Total average was 51 days but most of the two main species vimba and bream entered during 5 days and between 9 and 13 from the releasing, respectively (**Figure 2.3.17**).

Thirty three percent (32 ind.) of fish which entered the fishway didn't attain the uppermost antennae (57th chamber) and turned back (**Table 2.3.3**). It was half of breams and one-third of vimba counts.

Time of passing the entire fishway (precisely: distance between 18th and 57th chambers) ranged from 1.5 hour to almost 16 days (**Figure 2.3.18**). Total average was 14 hours but there were big differences between species: barbel and vimba were the fastest with 2:53 and 6:01 in average, respectively, but most of vimba passed in 4 hours. Sea trout was the slowest 106:17.

Table 2.3.2. Dates of experiment and number of tagged fish.

Date	Number of tagged fish	Number of returning fish
11-15 May 2015	72	12
2 Nov 2016	9	4
18 Sep 2017	111	22
24 Apr 2018	41	4
24 May 2019	648	56
Total	**881**	**98**

Table 2.3.3. Fish tagged, returned, turned back, negotiated the fishpass and time of passing (measured between 18th and 57th chambers).

Species		Number of tagged fish	Range of length	Number of fish entered the pass	Percent of fish entered the pass	Number of fish turned back in the fishpass	Percent of fish turned back in the fishpass	Number of fish negotiated the fishpass	Percent of fish negotiated the fishpass	Average time of passing the fishpass (h:mm)
vimba	*Vimba vimba*	648	12.5-41.5	61	9	18	30	43	70	6:01
bream	*Abramis brama*	95	24.5-57.0	23	24	12	52	11	48	8:48
bleak	*Alburnus alburnus*	36	12.5-17.0	2	6	0	0	2	100	
sea trout	*Salmo trutta*	21	54.0-92.0	4	19	0	0	4	100	106:17
barbel	*Barbus barbus*	20	24.0-37.0	3	15	1	33	2	67	2:53
roach	*Rutilus rutilus*	18	19.5-28.5	0						
white-eye bream	*Abramis sapa*	15	23.0-31.0	3	20	0	0	3	100	24:54
white bream	*Blicca bjoerkna*	12	20.0-35.0	0						
asp	*Aspius aspius*	8	55.0-65.0	2	25	1	50	1	50	8:06
ide	*Leuciscus idus*	5	13.0-46.0	0						
nase	*Chondrostoma nasus*	2	20.5-27.5	0						
dace	*Leuciscus leuciscus*	1	20.0	0						
Total		**881**		**98**	**11**	**32**	**33**	**66**	**67**	**14:09**

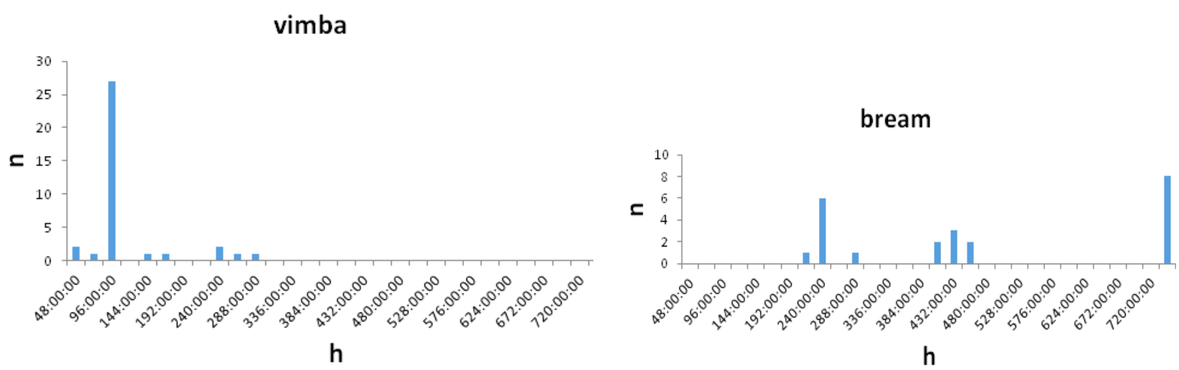


Figure 2.3.17. Time in hours between releasing and return to the fishway.

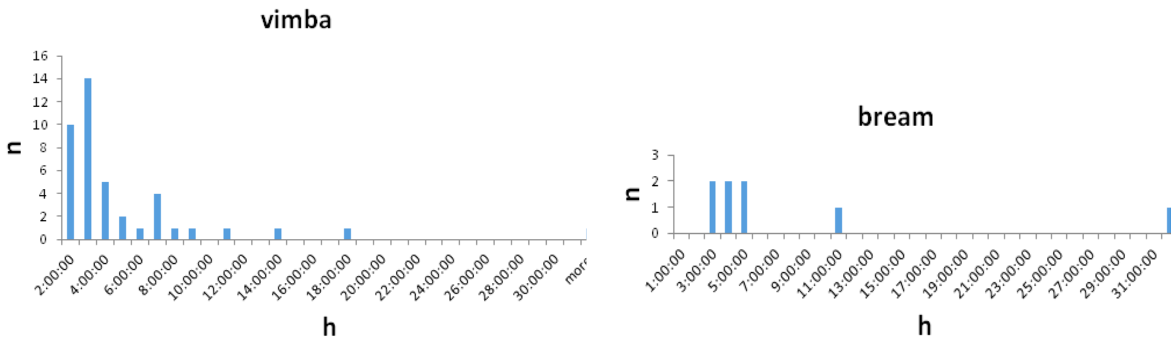


Figure 2.3.18. Time of passing the entire fishway.

A2.3.4 Discussion

There are three groups of species passing the fishway. The first one includes obligatory migrants – anadromous fish: sea trout and vimba. They are good and determined swimmers and variation intheir numbers most likely reflects changes in population status (Dębowski 2018a, Dębowski 2018c). The second group are not obligatory migrants, but show clear migration tendency and their success depends on hydrologic conditions. When they meet favourable conditions, they use it and can migrate even in a few short runs during a year. Still, the interannual variability in passing the fishway is surprisingly high. This suggests that the ability of passing the auxiliary dam by these weaker swimmers limits their access to the fishway. These are: bream, barbel and asp. And in the third group are fish which don't migrate every year but, if they meet favourable condition in a particular period of a year, they do it. Good examples are catfish in June/July 2015 or white bream in May 2017 (Dębowski 2016, Dębowski 2018b). Recorded numbers of fish of the two last groups don't reflect status of their populations at least in short periods.

Number of tagged fish returned to the fishway reflects not only ability to find the entrance but also level of stress of trapping, tagging and releasing, and species' specific reaction on it. Percentage of fish negotiating all the fishway was rather high taking into consideration length and the not optimal parameters of the fishway. This and time of passing also reflects determination of migrants. An interesting exception is sea trout, which probably finds in the fishway a well aerated and shadowed place to stay.

The modified fishway has improved possibilities of passing the Włocławek dam. Fish of many species can find the entrance and negotiate the entire fishway and some of them do it very quickly. The main limitation is the auxiliary dam which in low water condition constitutes a real barrier for migrating fish. Correspondence between flow, temperature and migration runs suggests that the auxiliary dam is passable only under certain flow conditions and the large upstream pool serves as holding tank for fish waiting for the right conditions to migrate upstream.

A2.3.5 River Vistula Habitat Study

Study site

For the purpose of the study of the dam's impact on fish habitat, the investigated area of the River Vistula is divided into three sections:

1. The Włocławek dam impoundment of 54km;
2. Morphologically altered single channel reaches located downstream of Włocławek Dam, estimated to cover about 25km and represented by mapped2 km long site in Włocławek;
3. Reference braided reaches based on the representative site in Bógpomóż, estimated to cover 30km of river length.

The river segment downstream of the dam is a dispersed mix of section 2 and 3.

The impoundment is a relatively homogenous reservoir habitat with depth ranging down to 13m. The majority of the deep area is located in first 20km upstream of the dam. The remaining portion shows depths lower than 5m (**Figure 2.3.19**).

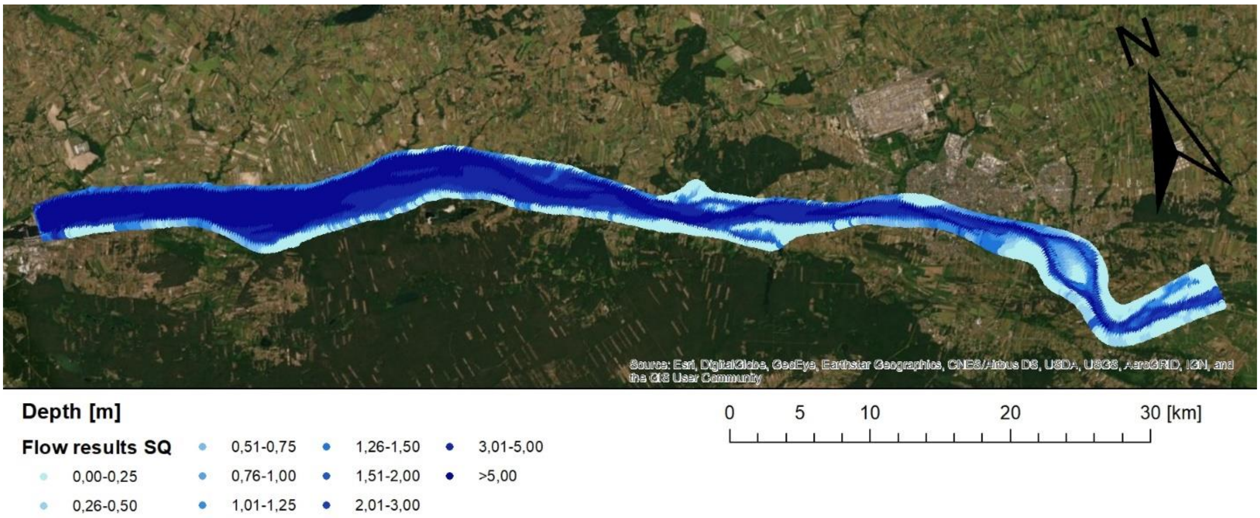


Figure 2.3.19. Depths distribution in the impoundment section.

Figure 2.3.20 shows the proportions of hydromorphologic unit (HMU) area. The section of Włocławek is located downstream of the dam and is affected by some channel modification and riverbed degradation. With partially riprap modified embankments, which are spaced quite widely, it is dominated by run hydromorphology. The Bógpomóż section consists of multiple sidearms and islands, with diversified main channel, presence of woody debris, boulders and undercut banks. It is not as extensively diversified as the 40km long portion of the river upstream of the impoundment (**Figure 2.3.21**, Wyszogród). Therefore, it cannot be considered natural, but represents a pragmatic minimum of optimal target conditions for the River Vistula in the study area.

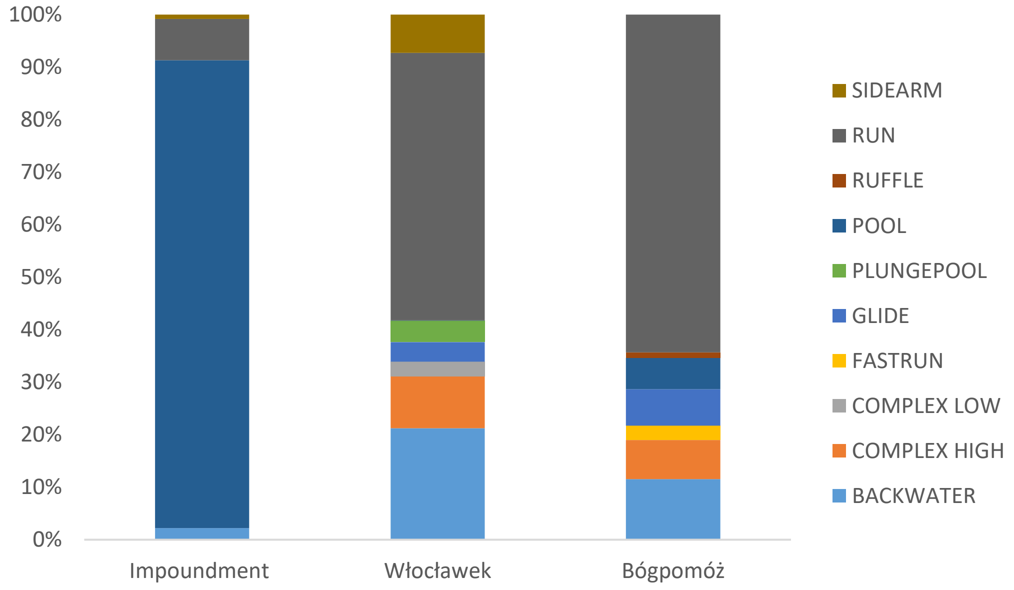


Figure 2.3.20. Distribution of hydromorphologic units (HMU) in study sites.

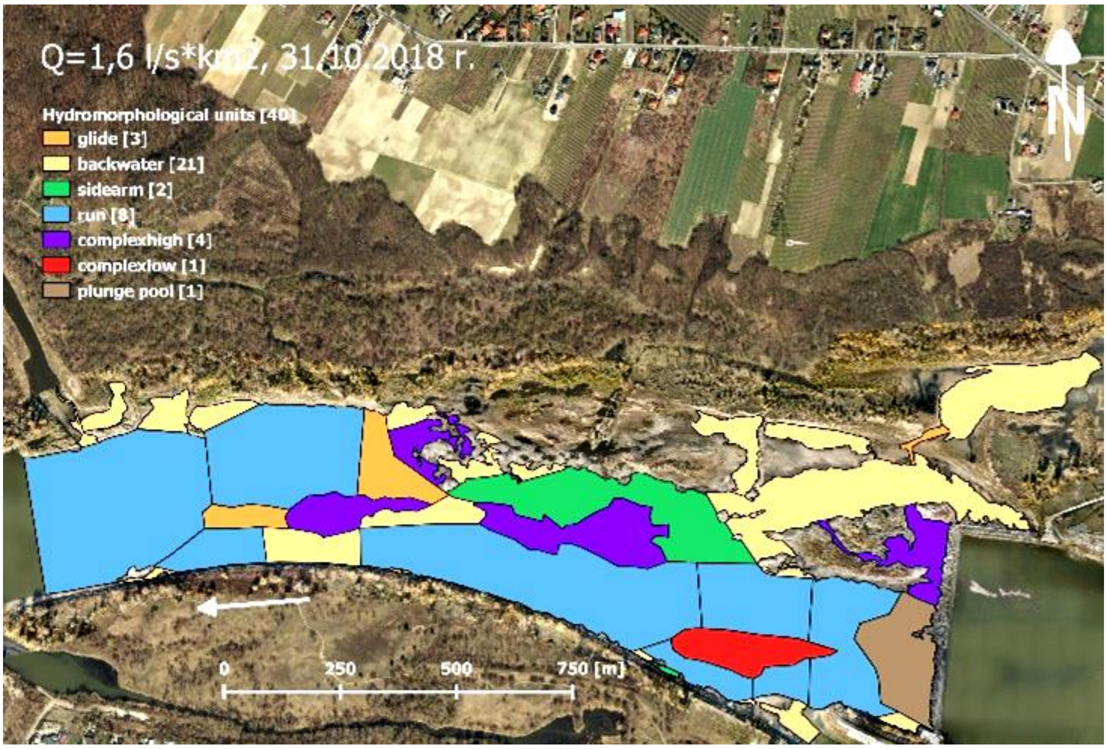
Figure 2.3.21. Fully braided section of the River Vistula upstream of Włocławek Reservoir near Wyszogród.

A2.3.6 Materials and Methods

Field data collection

Three representative sites were selected to collect habitat data in the river: the Włocławek Impoundment, 2km section directly downstream of the dam representing Section 2 and another of the same length further downstream representing close to natural river morphology of Section 3. Spatial distribution of fish habitat was mapped at 3 low flow conditions equivalent to specific flows of 1.6, 2.3 and 3.8l/s/km^2 (lskm). We used lightweight unmanned aerial vehicles (Phantom 3 Advanced and the Phantom 4 Professional) for habitat data collection (Woodget et al. 2017). Combination of nadir and oblique aerial pictures allowed for identification of hydromorphologic units, bottom substrate in shallow areas, submerged vegetation, branches, debris and other cover source for fish. The aerial imagery was associated with hydraulic data (depth and flow velocity) measured concurrently with help Side Scan Sonar and Acoustic Doppler Profiler or dipping bar of Jense (in shallow areas). Android t-Map software was also used for image annotation in the field.

The habitat mapping is conducted in post processing on GIS platform. We apply the MesoHABSIM method (Parasiewicz 2008ab, Parasiewicz and Adamczyk 2014) to identify hydromorphological units, as an example we put **Figure 2.3.22**. The distribution of bottom substrate was calculated with help of SubDisMo approach (see below).



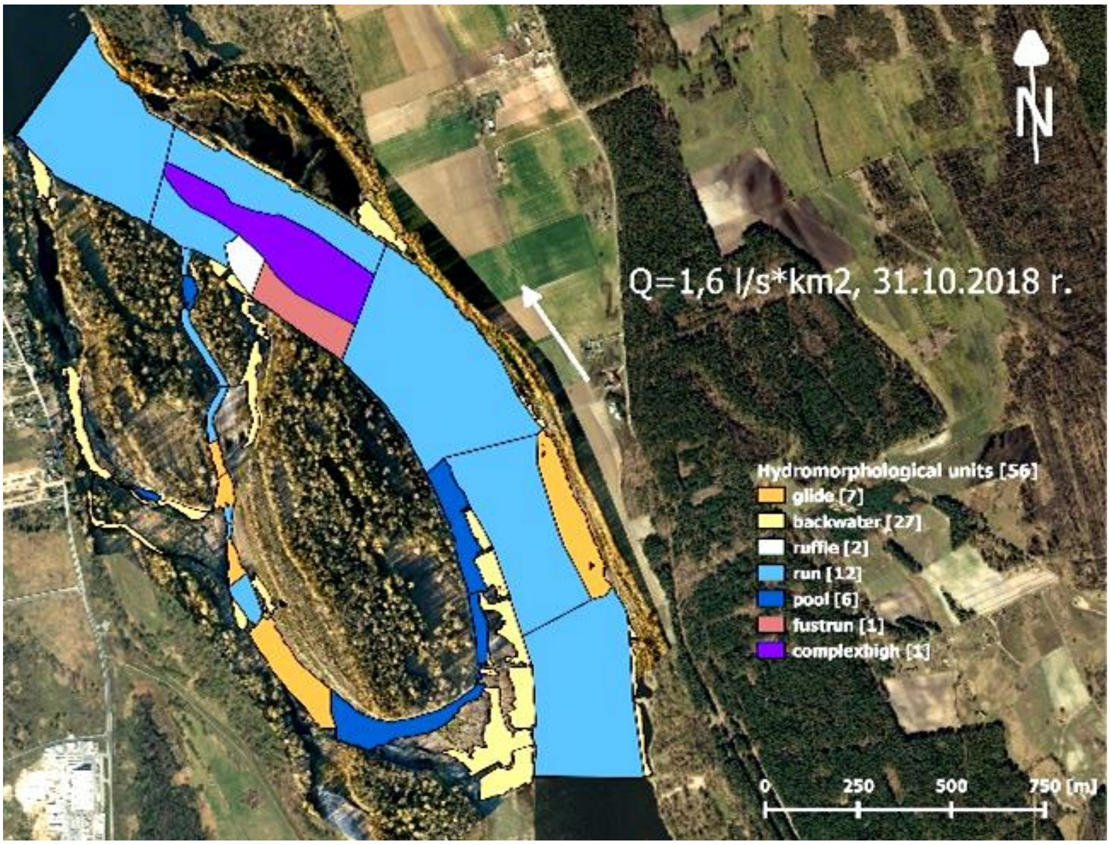


Figure 2.3.22. Hydromorphological units on the River Vistula at lowest water flow conditions: below the Wloclawek Dam (upper) and in Bógpomóż (lower).

Fish sampling
Astandard electrofishing technique has been applied to sample habitats for fish in both of the sites. We used backpack electroshockers following the AMBER field techniques manual. Due to the size of the river and gear selectivity the deep fast flowing areas were sampled only around shore areas. Fish samples were processed at the location, measuring length and weight of each individual.

Substrate
Building upon a rich data set available from earlier studies of the Rushing Rivers Institute, a model was developed to predict the substrate distribution from adjacent hydromorphic features. Input attributes of the model are gradient type of the river (low, medium, high), hydromorphologic unit type as well as water depth and velocity distribution in a unit. On the basis of these attributes, proportions of individual substrates in the studied area are modeled. A multilayer neural network that retrieve the data set characterizing the unit and return a standardized vector representing the contribution of individual substrate types has been constructed. This network was trained, refined and tested on the basis of 37 rivers, divided into total of about 11,000 hydromorphologic units, sampled at total over 123,000 points. The measure of the discrepancy between the actual and predicted composition vectors was the length of the Root mean Square Error vector. Alternatively, an analogous measure, but in a non-orthogonal base representing the lack of independence between variables corresponding to fractions of physically similar substrate types, was also tried.

The model has been tested on a separate test set. The accuracy of the prediction varies between different types of substrate as a consequence of uneven representation of the classes in the data set. The sandy fraction is most accurately predicted. Mud and largest rocks are predicted well also.

The model was employed to work on new data from five rivers in Poland and the obtained results for the substrate were used to simulate habitats under the MesoHABSIM model. The obtained habitats practically did not differ from those simulated using the experimentally confirmed substrate. It was eventually applied on the Vistula Case study to predict substrate distribution as input for MesoHABSIM model.

Expected fish community habitat distribution for the River Vistula in the study area was estimated from Fish Community Macrohabitat Types (FCMacHT) map created in the AMBER project (Parasiewicz et al., *in prep*). It corresponded with the FCMacHT of Central European Lowland, Medium Sediment Rivers, which provided target proportions of habitat for Habitat Use Guilds in expected natural fish community (**Figure 2.3.23**). In preparation of the model, we considered also the fact that large European Rivers are underrepresented in the fish observation data used for development FCMacHT. To verify model predictions and potentially adjust the model, additional fish data collection has been conducted in the reference section of the study area. Based on the observations of fish presence and on expert assessment of the ranking of the Habitat Use Guilds in the community, expected habitat proportions are adjusted by applying Target Fish Community model to recalculate expected habitat proportions (Bain and Meixler 2008).

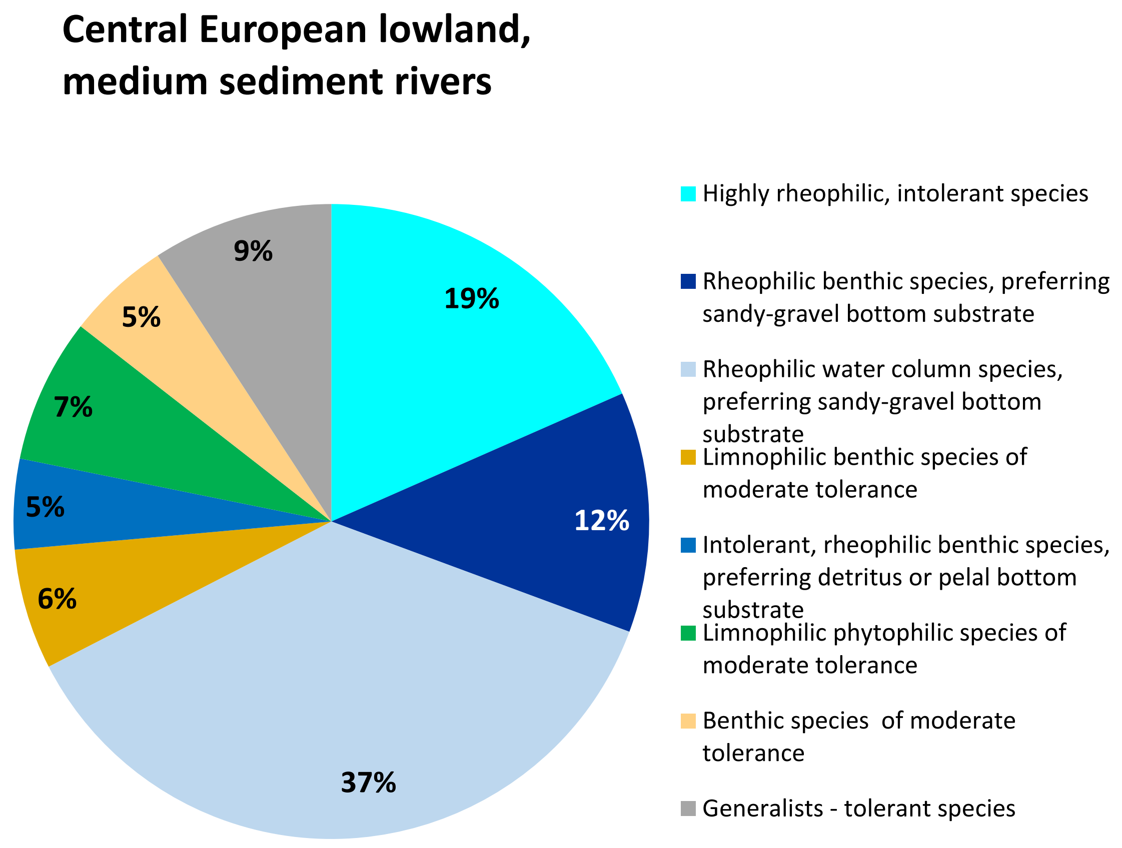


Figure 2.3.23. Expected proportions of macrohabitats in the FCMacHT of Central European Lowland, Medium Sediment Rivers.

For determination of habitat suitability for fish communities, suitability criteria are established from literature information. Using the Conditional Suitability Criteria Approach of MesoHABSIM the preferable ranges of substrate, depth, velocity cover and hydromorphologic units are specified. Upon analysis of created habitat maps, these criteria have been further calibrated. We have also considered that the highly rheophilic, intolerant species use the River Vistula for migration purposes only. Hence, a special set of criteria that corresponds with their migratory habitat needs was established for this guild.

Fish samples

A total of 36 hydromorphologic units of different types are sampled. To take into account the unit sampling bias, the proportion of captured guilds are weighted with the proportion of the area of each unit type represented in the study sites. For determination of the proportion of the guilds in existing fish community (XFC) the guilds were ranked according to their abundance. Then the proportions of the reciprocal rank values are used to calculate existing fish community structure. Such processed data could be compared with the structure of the expected fish community.

The data was also used for model validation purposes and each sample compared with predicted habitat suitability. The sampled habitat units were classified into unsuitable, suitable and optimal habitats and these classes compared with the abundance of fish in a sample. If less than a 25-quantile of individuals observed in all samples for one guild was captured at one location, the fish was considered to be present only. Otherwise it was either absent or abundant. The proportions of unsuitable, suitable and optimal habitat are plotted for each of the abundance classes for all fish guilds together, expecting higher share of suitable habitat in areas where fish were captured.

Sim Stream
Sim-Stream Software from the Rushing Rivers Institute is applied to organize collected habitat data and to calculate the amounts of suitable habitat area for each guild presented on habitat suitability maps. Every mapped unit is colour coded as unsuitable, suitable and optimal habitats. The proportions of channel area serving as effectively suitable habitats (weighted sum of 25% suitable and 75% optimal) available for each guild across investigated flows are presented in form of habitat rating curves. The habitat structure (i.e. proportions of effectively suitable habitat for each guild) was calculated at the four commonly occurring low flow conditions (1, 2, 3 and 4 lskm). It was compared with expected habitat proportions of FCMacHT using affinity index model (Novak and Bode 1992). Subsequently flow habitat rating curve for fish community is developed by weighting habitat of each guild by its proportions in adjusted FCMacHT. This curve is applied to calculate habitat time series for past and future scenarios.

Habitat time series analysis
One of the most important underlying characteristics of any riverine environment is its continuous change over time due to the fluctuations of flowing water. Since flow rates during different seasons create various habitat conditions, habitat availability is also in flux. Consequently, fauna are shaped by varying environments rather than by static conditions. To investigate the habitat availability and the flows that create them, we must analyze the temporal patterns that occur in the time series.

The habitat time series is based on the amount of flow in the river recorded on any given day. With help of the community rating, curve flows are evaluated for how much habitat they provide, and this value is plotted into habitograph instead of flow value for every day in the record (**Figure 2.3.24**). The habitograph depicts fluctuation patterns of habitat occurring in the river over time. The adequacy of the occurring habitograph for the survival of the fauna needs to be analyzed with a habitograph for reference (close to natural) conditions. The assumption here is that the aquatic community is adapted to natural flow patterns. Following the theory of habitat templates, we also assume that this adaptation is oriented on the predictability of the events (Parasiewicz 2007ab, Poff and Ward 1990) hence, conditions that occur rarely in nature create stress to aquatic fauna. For this reason, we observe frequency of habitat level occurrenceforms the basis for determining **habitat thresholds**, which specify a boundary of conditions necessary to support native fish community structure.

Continuous Under-Threshold Analysis: A General Description of the Method
The purpose of this analysis is to investigate flow duration patterns, and to identify conditions that could create pulse and press disturbances as described by Niemi et al. (1990). A pulse stressor is an instantaneous alteration in fish densities, while a press disturbance causes a sustained alteration of species composition. In the habitat analysis, they can be caused either by extreme habitat deficiencies regardless of duration or by catastrophically long duration of events with habitat availability critically low. The press disturbance can be caused by frequent occurrences of persistent-duration events with habitat availability critically low. Therefore, the analysis of habitat magnitude, as well as duration and frequency of non-exceedance events serves in identifying Habitat Stressor Thresholds (HST).

To identify HST, a habitat time series is developed, and the resulting habitat duration curves were analyzed. Next, Uniform Continuous Under-Threshold habitat duration curves (UCUT curves) are created (Parasiewicz 2007ab). As documented by Capra et al. (1995), the curves are good predictors of biological conditions. The curves evaluate the continuous duration and frequency of continuous non-exceedance events for different habitat magnitudes. Rapid changes in frequency pattern are used to identify transitions between typical and unusual events and classify them as extreme, rare, critical, and common HST for the low-flow conditions. Rare habitat events happen infrequently or for only a short period of time, characterized by sharp habitat deficits. The critical level defines a more frequent event than rare and has the purpose of specifying management "warning" rather than indicating biological response. Common habitat levels are the highest defined and should demarcate the beginning of normal circumstances from less common events.

A habitat event is defined as a continuous period in which the quantity of habitat (relative habitat area) stays under a predefined threshold. The UCUT curves describe the duration and frequency of habitat events for a given bioperiod; therefore, the first step is to extract bioperiod data for each year from the habitographs (**Figure 2.3.24**).

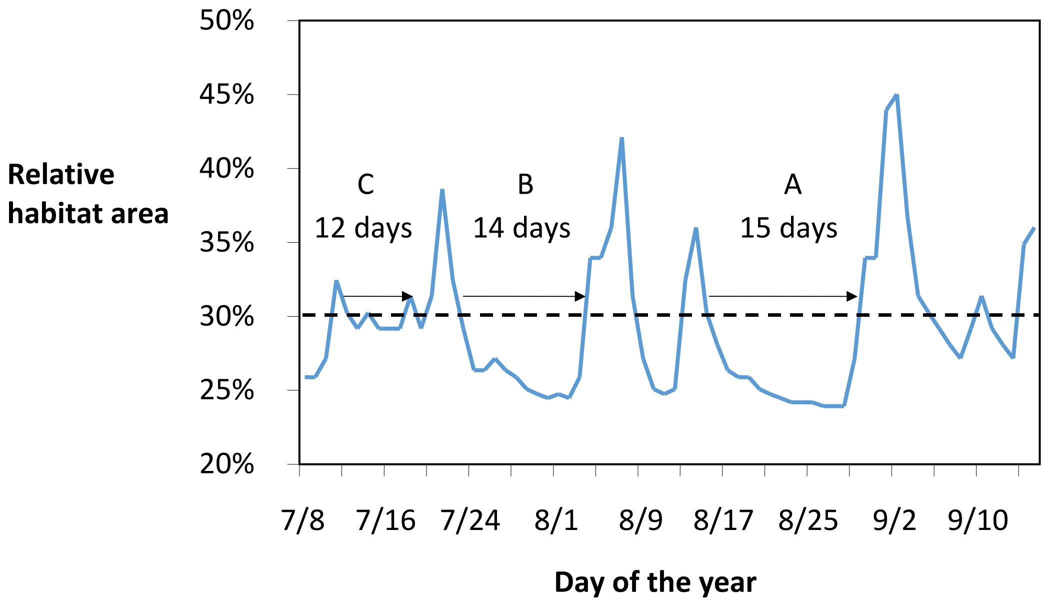


Figure 2.3.24. Schematic of UCUT curve computation for hypothetical suitable habitat time series selecting the periods when habitat falls below a threshold.

In the second step, the sum of all events of the same duration within each bioperiod is expressed as a ratio of the total duration of all bioperiods in the record (on the x-axis of the graph). The proportions are plotted as a cumulative frequency (i.e., the proportion of shorter periods is added to the proportions of all longer periods) (**Figure 2.3.25**).

The UCUT curves diagram captures the duration and frequency of events for a given bioperiod (**Figure 2.3.24**). The y-axis represents event durations in days. The x-axis represents the cumulative percent duration of events within a bioperiod aggregated by increasing duration; the sum length of all events of the same duration within a bioperiod is computed as a percentage of the total duration of all years of the bioperiod in the record.

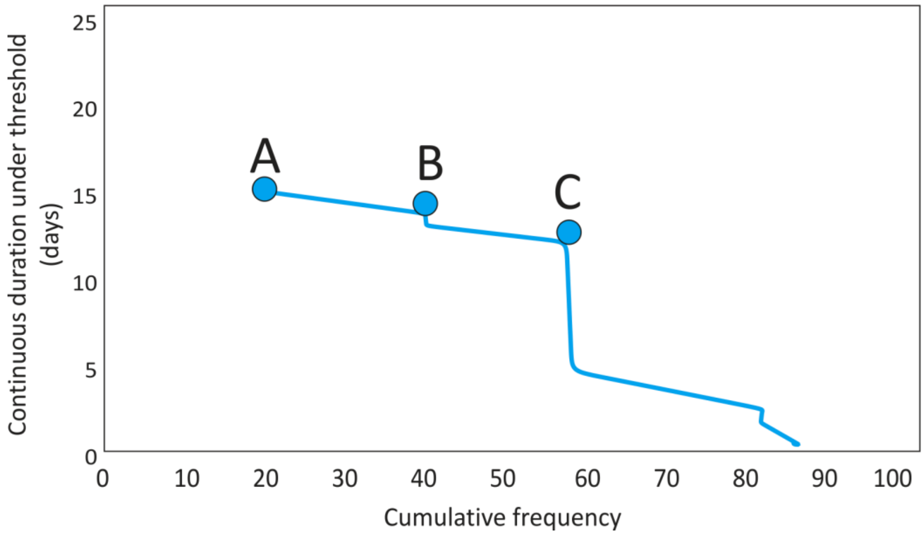


Figure 2.3.25. Construction of UCUT curve.

This procedure is repeated for the entire set of thresholds with constant increments. The magnitude of the habitat increments between the thresholds is selected on an iterative basis, for example, changing the increments until a clear pattern can be recognized. We look here for specific regions with a higher or lower concentration of the curves on the plot that would correspond with rare and common events. When many curves are plotted, these two regions are easily identifiable.

Common and less common habitat events can be identified based on the cumulative durations, the shape, and distances between the curves. The procedure has two steps: 1) determination of habitat threshold levels by selecting curves on the graphs, and 2) identification of persistent durations by locating inflection points. Interpretation of these patterns is based on the following observations:

- The curves in the lower left portion of the graph depict rare events (i.e., with low cumulative durations).
- The horizontal distance between curves indicates the change in the frequency of events associated with habitat increase to the next level (i.e., the larger the distance between two curves at the same continuous duration, the larger the change in the frequency of the events).
- Steep curves represent low change in event frequency.
- Critical points of the curve reflect rapid change in frequency of continuous durations.

The curves in **Figure 2.3.25** indicate selected habitat thresholds in increments of 1% of channel area. Based on the density of the curves, three have been selected as significant thresholds for rare (red), critical (yellow), and common (green) events. The circles at the critical points demarcate transition to persistent (yellow) and catastrophic (red) durations.

Typically, the UCUTs for rare habitat are located in the lower left corner, are steep and are very close to each other. In this range, small increases in habitat level have barely any effect on cumulative duration. As the habitat level increases, this pattern rapidly changes. We selected the highest in this lower-habitat group (before the rapid change of cumulative duration) of curves as a *rare* habitat level threshold. In our framework, the *rare* habitat should be exceeded most of the time and corresponds with subsistence flow conditions. We identified the next highest UCUT line (the first that stands out) as a *critical* level. The distance between the lines after exceeding the *critical* level are usually greater than in the previous group but still close to each other. Critical habitat occurs at trigger flow level, which calls for management actions. The next outstanding curve demarcating rapid changes in the frequency of events is assumed to mark the stage at which more *common* habitat levels begin. This threshold occurs at flows called habitat base flows.

Once the threshold levels are identified, we search for the shortest persistent durations indicated by the lowest, convex critical point on the UCUT curves. Above these points the curves are steep, which show a low frequency of long events. The shortest of the long durations, appearing only on the decadal scale, are defined as catastrophic durations along with their frequency of occurrence. In this way, we identified three categories of habitat event durations: typical, persistent and catastrophic (**Figure 2.3.26**) associated with each HST.

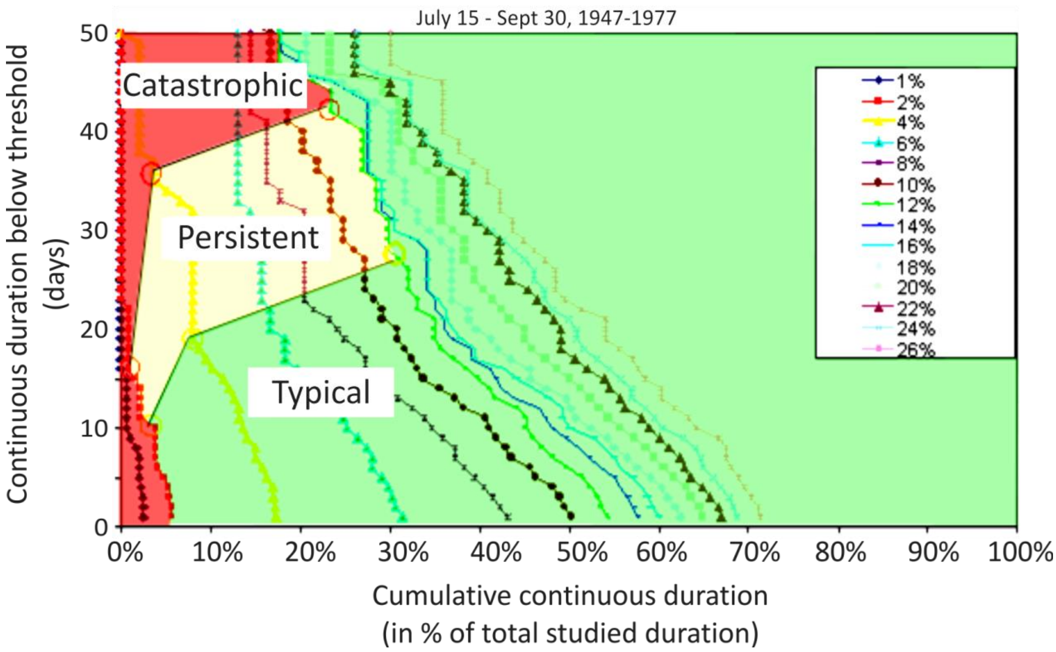


Figure 2.3.26. Schematic of frequency and duration zones on UCUT curves. Each curve represents events below habitat area of less than indicated % of channel area.

As visible on the above diagram (**Figure 2.3.26**), most of the UCUTs display the rapid change in a gradient demarcating the beginning of persistent or catastrophic conditions. The border line between zones can be drawn by connecting the inflection points. From an active management perspective, it would not be feasible to recommend a large number of thresholds; therefore, the prescription was simplified by identifying only the most outstanding curves in the diagram.

Time Series Analysis of the River Vistula

To develop the reference habitat time series of the River Vistula, the Community Habitat rating curve representing the reference habitat configuration is applied to the flow time series simulated for the River Vistula with climate change models (see below). The study focused on a Rearing and Growth bioperiod (July-September) due to the fact that it is the period with the lowest flows and therefore critical events may occur in this season. Hence, during the summer or Rearing and Growth season, the habitat time series may reflect habitat for Community. However, it needs to be considered that different habitat conditions may be required during spawning and overwintering seasons.

The reference habitat time series have been analyzed with help of the UCUT technique to select HST. Each HST consists of habitat magnitude, continuous duration and frequency of allowable and catastrophic events. To define the current status of habitat we also created the habitat time series representing the current habitat configuration including all 3 sections and determined the change in frequency of habitat events violating the HST. It is represented as a percent increase in frequency of habitat stress days (i.e. habitat deficits of persistent duration) as compared to the reference conditions. Alteration of Habitat Stress Days can be measured at the diagram as a shift of persistent duration point along the x-axis for each HST. An average of the three habitat stress days alterations is used as a metric for scenario comparison.

A2.3.7 Adaptive management scenarios

To evaluate the consequences for fish habitat of adaptive management options for Włocławek dam we developed 7 scenarios:

Scenario 0 – reference conditions; it represent the river without the dam, impoundment and channel alterations i.e. equivalent to the Bógpomóż site
Scenario 1 – current conditions
Scenario 2 – current hydromorphology but introduction of dynamic flow augmentation, which asks for releasing flows corresponding with common habitat stressor threshold for two days, at the time when flows were lower than those corresponding with rare threshold for persistent period of time.
Scenario 3 – lowering of the dam such that the Impoundment will be 20 km long and restoring the river downstream to the conditions resembling Bógpomóż site
Scenario 4 – lowering of the dam such that the Impoundment will be 10 km long and restoring the river downstream to the conditions resembling Bógpomóż site
Scenario 5 and 6 are combinations of **scenario 3 and 4 with scenario 2** i.e. lowering the dam and introducing flow augmentation.

For each scenario we calculated the amount of occurring fish community habitat stress days (i.e. days of habitat deficits). The change in the number of stress days, as well as alteration of habitat structure at the subsistence flow level were then used as a metric for scenario comparison. The results are presented in River Restoration Analysis diagram (Parasiewicz et al. 2012), where alteration of habitat stress, structure and habitat area available for fish community are compared.

Climate change
Simulations of daily discharges for historical period of 1971-2000 and for near future (period of 2021-2050) grid-cell based global hydrological models, which spatially cover the whole globe at a resolution of 0.5°×0.5°, were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, https://www.isimip.org/). ISIMIP offers simulating data, which can be used for studying the impacts of climate change across affected sectors and spatial scales. It is an international network of climate-impact modellers and contributes to a comprehensive and consistent view of the world under different climate-change scenarios.

Simulations of daily discharges, obtained from ISIMIP, were derived by six hydrological models (**Table 2.3.4**). Each model was driven by five Earth System Models (GCMs; **Table 2.3.5**), which were developed in order to study long-term response of the climate system to natural and anthropogenic forcings as a part of the 5th Phase of the Coupled Model Intercomparison Project (CMIP5). Hydrological models have generated future hydrological projections for the whole globe under Representative Concentration Pathways RCP4.5 Wm^{-2} for decades: 2021-2030, 2031-2040 and 2041-2050. According to AR5 (IPCC, 2013) the global mean surface temperature change for the period 2046–2065 relative to 1986–2005 under RCP4.5 will likely be in the range between 0.9°C and 2.0°C (mean: 1.4°C).

Projections of daily discharges (in m^3s^{-1}) were calculated for Vistula River Włocławek site (the grid-cell with centre at 19.25 longitude E and 52.75 latitude N) for two periods: historical 1971-2000 and near future 2021-2050 under RCP4.5:

Table 2.3.4. List of used hydrological models. Each model was available for the historical period (1971–2000) and future periods (2021–2050) under RCP4.5, driven with five Earth System Models (Table 2), which creates 10 different combinations for every hydrological models (five for historical and five for future periods). Spatial resolution of daily simulations was 0.5 degree.

Hydrological model		References
CLM	Community Land Model it is a collaborative project between scientists in the Terrestrial Sciences Section (TSS) and the Climate and Global Dynamics Division (CGD) at the National Center for Atmospheric Research (NCAR) and the CESM Land Model Working Group.	Oleson et al. (2004)
H08	Hydrological model developed by National Institute of Environmental Studies and University of Tokyo, Japan.	Hanasaki et al. (2008)
LPJmL	Lund–Potsdam–Jena managed Land developed by Potsdam Institute for Climate Impact Research (PIK), Germany.	Gerten et al. (2004)
MPI-HM	Max Planck Institute – Hydrology Model developed by Max Planck Institute for Meteorology, Germany	Hagemann and Dümenil (2001)
PCR-GLOBWB	PCRaster GLOBal Water Balance model developed by Utrecht University, The Netherlands.	Van Beek and Bierkens (2008)
WBM	Water Balance Model developed by Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA, Department of Environmental, Earth and Ocean Sciences, University of Massachusetts-Boston, Massachusetts, USA, Department of Civil Engineering and NOAA-CREST, City College of New York, City University of New York, USA.	Vörösmarty et al. (1998)

Table 2.3.5. List of used GCM-run in hydrological models. Spatial resolution of GCM simulations was 0.5 degree.

GCM		Institute
GFDL-ESM2M	Earth System Model developed by Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration	NOAA
HadGEM2-ES	Earth System Model developed by the Met Office Hadley Centre ESM	Met Office Hadley Centre
IPSL-CM5A-LR	Earth System Model developed by Institut Pierre-Simon Laplace	IPSL Climate Modelling Centre
MIROC5	Model for Interdisciplinary Research On Climate developed by the University of Tokyo, Center for Climate System Research, National Institute for Environmental Studies, Japan, Japan Agency for Marine-Earth Science and Technology, Frontier Research Center for Global Change	University of Tokyo, CCSR, NIES, JAMSTEC, Frontier Research Center for Global Change
NorESM1-M	The Norwegian Climate Center's Earth System Model is a nationally coordinated effort, developed by the Bjerknes Centre for Climate Research in Bergen, Norwegian Meteorological Institute and in Oslo, University of Oslo. NorESM is based on the CCSM operated at the National Center for Atmospheric Research.	Bjerknes Centre for Climate Research, Bergen, Norwegian Meteorological Institute, Oslo, University of Oslo

The flow time series calculated for the historical period are compared with flow records for selection of the model combination that offered the best performance metrics as follows:

1) Percent bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate overestimation bias, whereas negative values indicate model underestimation bias.

Table 2.3.6. General performance ratings for recommended statistics for a monthly time step for streamflow (Moriasi et al. 2007).

Performance Rating	PBIAS (%)
Very good	PBIAS < ±10
Good	±10 < PBIAS < ±15
Satisfactory	±15 < PBIAS < ±25
Unsatisfactory	PBIAS > ±25

2) rSD Ratio of Standard Deviations, rSD = sd(sim) / sd(obs). The optimal value of rSD is 1.0
3) q-q plot

After selecting the best performing model combination of flow time series simulated or near future conditions are incorporated into habitat models representing all above scenarios. The alteration metrics are recalculated and presented in RAA diagram (Parasiewicz 2012).

Fish Communities of the River Vistula

Fish data
Table 2.3.7 demonstrates proportions of Habitat Use Guilds captured in 16 HMUs at the Bógpomóż site and 20 at Włocławek site. A total of 6535 individuals were captured in shallow and shore areas of the river in 7 types of hydromorphologic units (backwater, complexhigh, fastrun, glide, pool, run and sidearm). Relative abundance of captured guilds observed in each HMU type was weighted by proportions of HMU type areas occurring during the sampling time (16%, 4%, 7%, 4%, 5%, 59%, 5% respectively). These values are ranked to calculate the existing fish community model (XFC).

Table 2.3.7. Relative abundance of captured guilds observed.

Habitat Use Guild	Fish proportions weighted by HMU area	rank	reciproke	XFC
Rheophilic benthic sand_gravel	0.81%	6	0.16	6%
Rheophilic water column sand_gravel	1.77%	5	0.20	8%
Limnophilic benthic moderate tolerant	15.21%	3	0.33	13%
Limnophilic lithophilic moderate tolerant	0.45%	7	0.14	6%
Limnophilic phytophilic moderate tolerant	26.71%	2	0.50	19%
Benthic modrate tolerant	4.81%	4	0.25	10%
Generalist tolerant	50.24%	1	1	39%
		Sum	**2.592**	

Due to capturing a solid number of limnophylic lithophylic moderately tolerant species we decided to add habitat for this guild to FCMacHT. It received the lowest ranking and caused recalculation of habitat proportions to those presented in **Figure 2.3.27**, which demonstrates the expected macrohabitat distribution in Vistula River after taking into account recent fish observations.

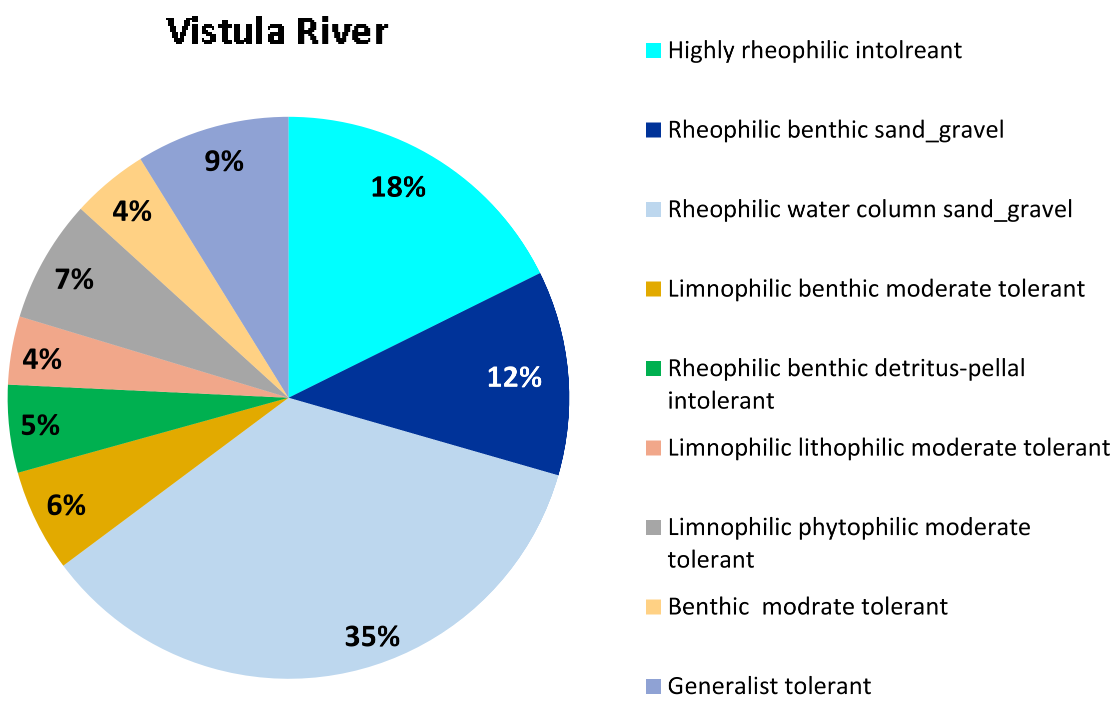


Figure 2.3.27. FCMacHT for the River Vistula (adjusted from Central European Lowland, Medium Sediment Rivers, see **Figure 2.3.23**).

The existing fish community (XFC) matches the fish community expected according to FCMacHT (Target Fish Community – TFC) to 44% only. It is indicating a strong overabundance of generalist and limnophylic species (**Figure 2.3.28**).

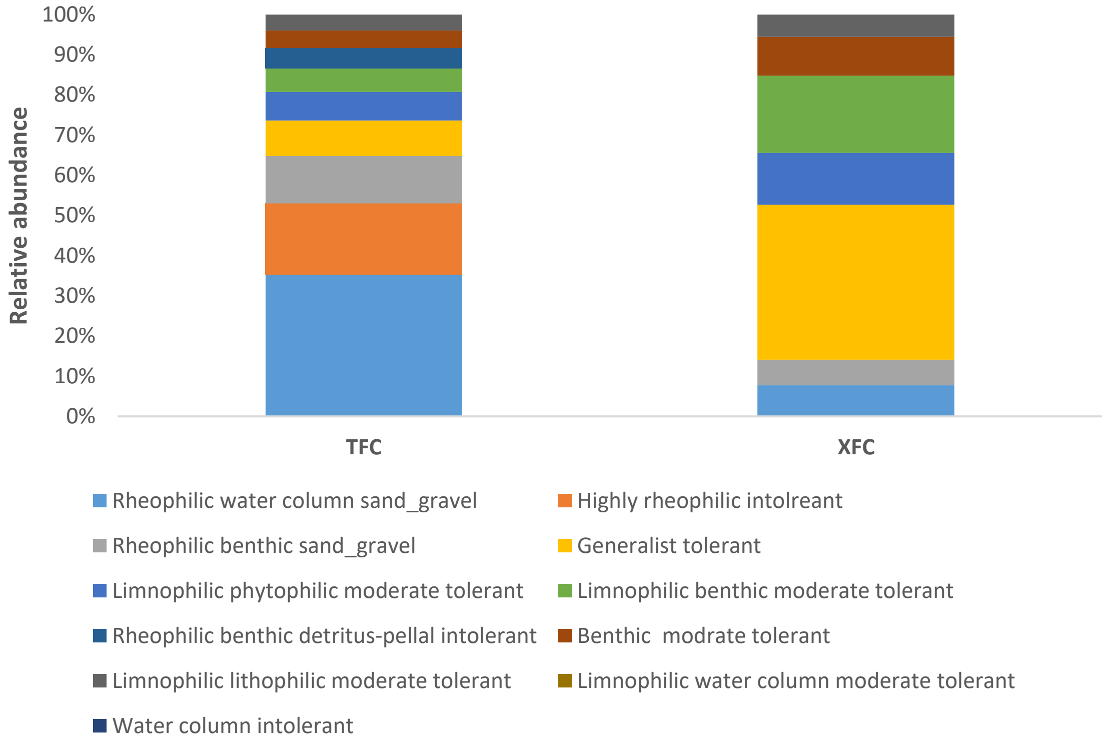


Figure 2.3.28. Comparison of Target Fish Community and Existing Fish Community Structure.

Habitat Use Criteria

Table 2.3.8 demonstrates Conditional Habitat Use Criteria for the guilds occurring in Vistula River. The substrate definition is according to the Austrian Norm M6232, because it corresponds with macrozoobenthos habitat types, hence reflects also food availability for fish.

Table 2.3.8. Conditional Habitat Use Criteria for the guilds occurring in Vistula River. The attributes in bold are critical for guild presence and those in red are reducing the area suitability.

No	Fish Guilds	Depth [m]	Velocity [m s^{-1}]	Choriotope	HMU Type	Covers
1	**Highly rheophilic, intolerant species**	0.50-1.5	0,3-1,2 (max. 2,0)	gigalithal megalithal >40 cm, makrolithal 20-40 cm, mesolithal6-20 cm, microlithal 2-6 cm, psammal, akal	riffle, ruffle, cascade, rapid, fast run, plunge-pool, pool, glide, sidearm	boulders, woody debris
2	**Rheophilic benthic species**, preferring sandy-gravel bottom substrate	0,3-2,0	0,3-0,1.5	megalithal >40 cm, makrolithal 20-40 cm, mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, xylal, pelal, sapropel	riffle, ruffle, cascade, rapid, fast run, run, glide, plunge-pool, pool,	boulders, undercut banks woody debris, submerged vegetation
3	**Rheophilic water column species**, preferring sandy-gravel bottom substrate	0,5-4,0	0,15-0,7	mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, xylal	run, fast run, pool, plunge-pool	undercut banks woody debris, canopy shading, submerged vegetation
4	**Limnophilic benthic species** of moderate tolerance	0,25-2,5	0,0-0,5	microlithal 2-6 cm psammal, pelal, akal, debris, xylal	run, pool, glide, sidearm	undercut banks woody debris, submerged vegetation, canopy shading
6	**Intolerant, rheophilic benthic species**, preferring detritus or pelal bottom substrate	0,20-0,50	0,15-0,5	detritus, pelal, psammal, sapropel	backwater, glide, pool, run	shallow margins, woody debries
8	**Limnophilic lithophilic species** of moderate tolerance	0,5-4,0	0,1-0,7	megalithal , macrolithal, mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, xylal	riffle, ruffle, run, glide, plunge-pool, pool, backwater, fast run	boulders, woody debris, submerged vegetation

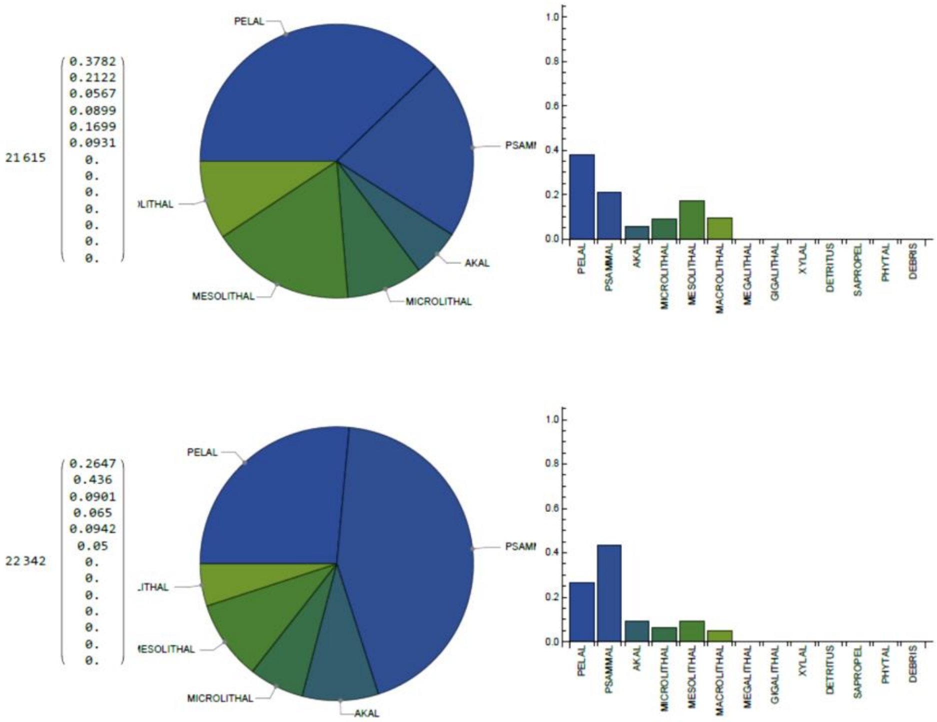
No	Fish Guilds	Depth [m]	Velocity [m s^{-1}]	Choriotope	HMU Type	Covers
9	**Limnophilic phytophilic species** of moderate tolerance	0,3-2,0	0,0-0,45	psammal, pelal, akal, debris, xylal	backwater, glide, pool, run, side-arm	submerged vegetation, woody debries, undercut banks, canopy shading
10	**Benthic species** of moderate tolerance	0,5-2,5	0,15-0,7	mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, xylal, pelal, detritus, phytal	run, glide, pool, backwater, side-arm	submerged vegetation, undercut baks, woody debries
11	**Generalists** - tolerant species	0,25-4,0	0,0-0,45	mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, pelal, sapropel, xylal	run, pool, glide, sidearm, backwater	woody debries, undercut banks, canopy shading

Substrate simulation
A total of 283 large hydromorphological units were delineated at three flow rates. These units were covered by approximately 96 000 hydraulic measurements and substrate composition calculated from hydraulic data.

The dominance of the mineral slit (PELAL) and sandy (PSAMMAL) fractions is noticeable. This agrees with expectations. Among the remaining minority substrates, mud (SAPROPEL) and stony fractions (AKAL-MEGALITHAL) in various proportions with a prevalence of gravel (AKAL) also have significant representations.

The substrate compositions calculated at three different flow rates were compared for selected units, demonstrating a large extent of overlap. Two examples of such a comparison are provided in **Figure 2.3.29.**

Example 1



Example 2

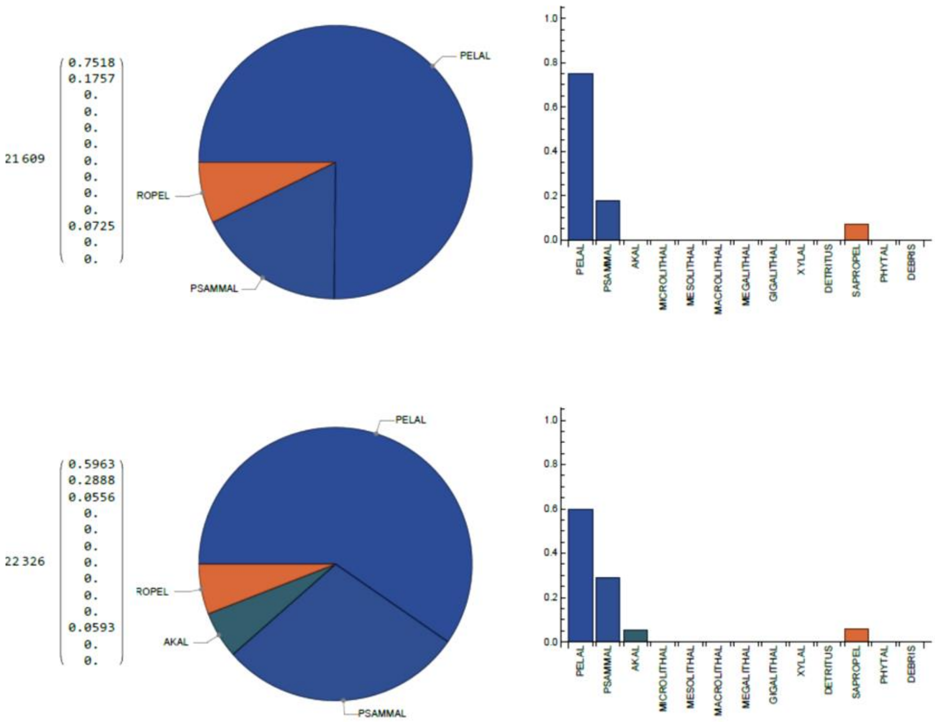


Figure 2.3.29. Two examples of substrate compositions in overlapping units modeled at different flow rates.

The composition of the substrate obtained at three different flows has been compared on all of such units that overlap to a large extent. The units were considered corresponding when they overlap at least in 80%. In some cases, unit unions had been taken, instead of individual units, as this resulted in better overlapping of the areas they cover at different flows. For example, one unit at high flow may correspond to the union of three units at low flow. In such cases, the weighted average of substrate compositions in the component units had been taken as the substrate composition representative for the whole area of the combined units; the weighting coefficients are the surface areas of these component units.

- Chart sets (pie and bar charts - to choose) had been generated for areas (units or their unions) corresponding to each other.
- The substrate composition for a given area had been calculated, averaged over three flows (or two, if only two were available).
- The average composition had been presented, similarly, as the compositions at individual flows are.
- The dispersion of results at individual flows around their average had been calculated.

The most natural measure of dispersion for one-dimensional variables is a standard deviation. Its generalization into multi-(here: 13)-dimensional variables runs as follows:

The usual standard deviation is the root of the mean square (RMS) of the deviations (E) of individual elements from the mean (or the root of the variance, defined as the mean square (MS) of deviations (E) - which comes to the same thing). In the multidimensional case, the deviations are, of course, the vectors $E = X - \mu$. Their external product $\Sigma^2 = E\,E^T$ is a covariance matrix, and the internal product (scalar product) $\sigma^2 = E^T E$ (or trace of the covariance matrix $\sigma^2 = \mathrm{Tr}\,\Sigma^2$ - which comes to the same thing) a scalar variance of a vector variable. Its root determines the representative (RMS) distance of elements from the mean in their multidimensional space - precisely like the usual standard deviation. In the case of our space of compositions $\sigma \epsilon \left[0, \sqrt{2}\right]$. For convenience, they had been normalized to $\sigma' \epsilon [0,1]$.

σ introduced above is a measure of the dispersion of results at different flows for the same (at least 80% the same) area. (They may differ due to natural dynamics of sediments and modeling imperfections, but in such a large river, a possible high dispersion should be attributed to model imperfections, as the bottom does not change too quickly.)

As a measure of dispersion for all analyzed areas, it is sufficient to take RMS of the σ obtained for individual areas.

$$\boldsymbol{\sigma} = \sqrt{\mathbb{E}(\sigma)^2} = \sqrt{\frac{1}{U}\sum_{u=1}^{U}(\sigma_u)^2} = \sqrt{\frac{1}{U}\sum_{u=1}^{U}\sigma_u^2} = \sqrt{\frac{1}{U}\sum_{u=1}^{U}E^T E} = \sqrt{\frac{1}{U}\sum_{u=1}^{U}(X-\mu)^T(X-\mu)}$$
$$= \sqrt{\frac{1}{U}\sum_{u=1}^{U}\sum_{i=1}^{I}(X_{i\,u}-\mu_{i\,u})^2}$$

$\boldsymbol{\sigma}' = 0{,}16$ has been obtained at the Włocławek site indicating a very good model performance.

Model Verification

In total 36 hydromorphologic units were sampled for fish in Włocławek and Bógpomóż sites. The **Figure 2.3.30** demonstrates the proportions of not suitable, suitable and optimal habitats occurring in the areas were fish were not captured, present or abundant. The increase of suitable and optimal habitat proportions with increase of fish abundance is clearly visible at the figure. As it can be expected about 40% of the samples was missing at least one guild and 70% of those within suitable and optimal habitats for missing guild. Only 6% had low fish abundance and half of it was in suitable habitats. From 56% of high abundance samples 60% is in optimal habitat and only 2% in not suitable habitats. This documents a high level of model performance.

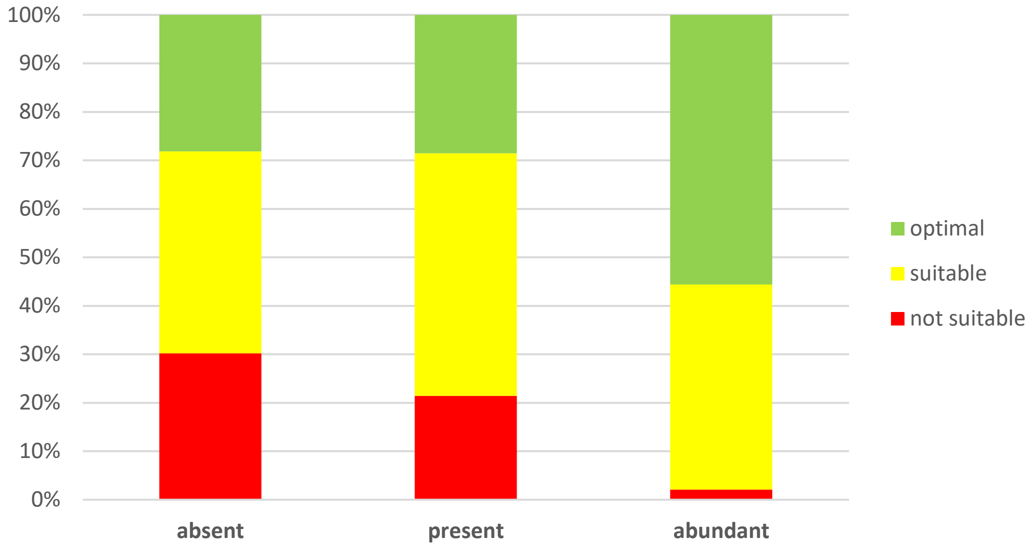


Figure 2.3.30. Verification of habitat model predictions by comparing abundance of captured guildswith habitat suitability classes.

Habitat Maps (highly rheophylic I generalist)

Hydromorphological units as mapped in Bógpomóż section and Włocławek sections: dam and reservoir are shown in **Figures 2.3.31abc**; **2.3.32abc** and **2.3.33**.

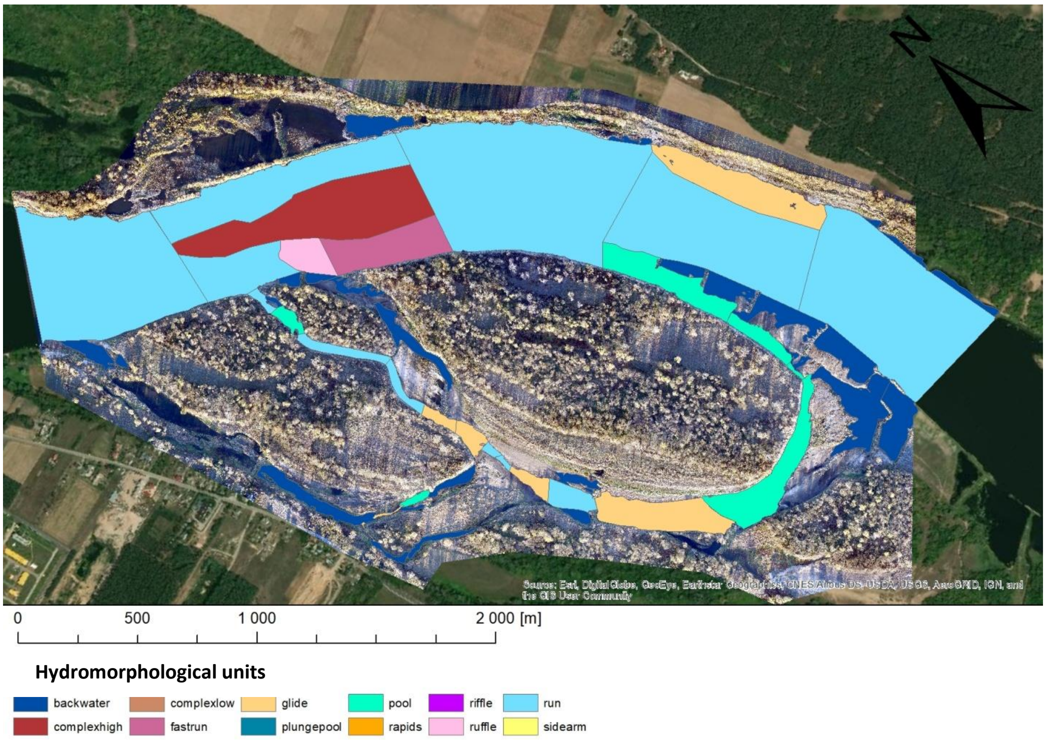


Figure 2.3.31a. Hydromorphological units in Bógpomóż section (1.6 l/sek/m^2).

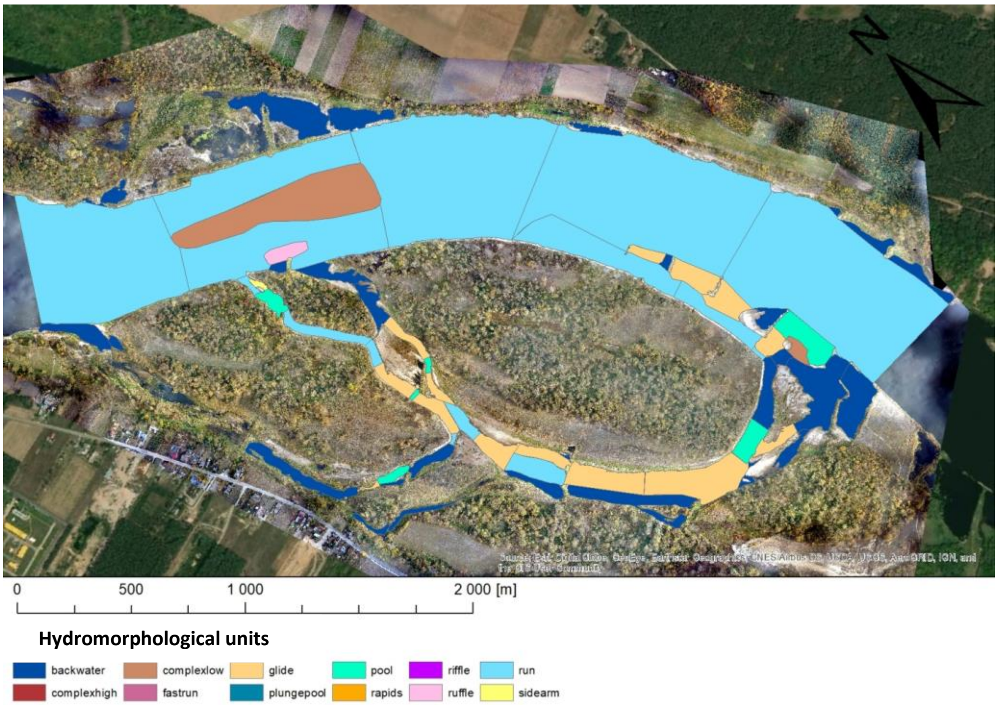


Figure 2.3.31b. Hydromorphological units in Bógpomóż section (2.3 l/sek/m^2).

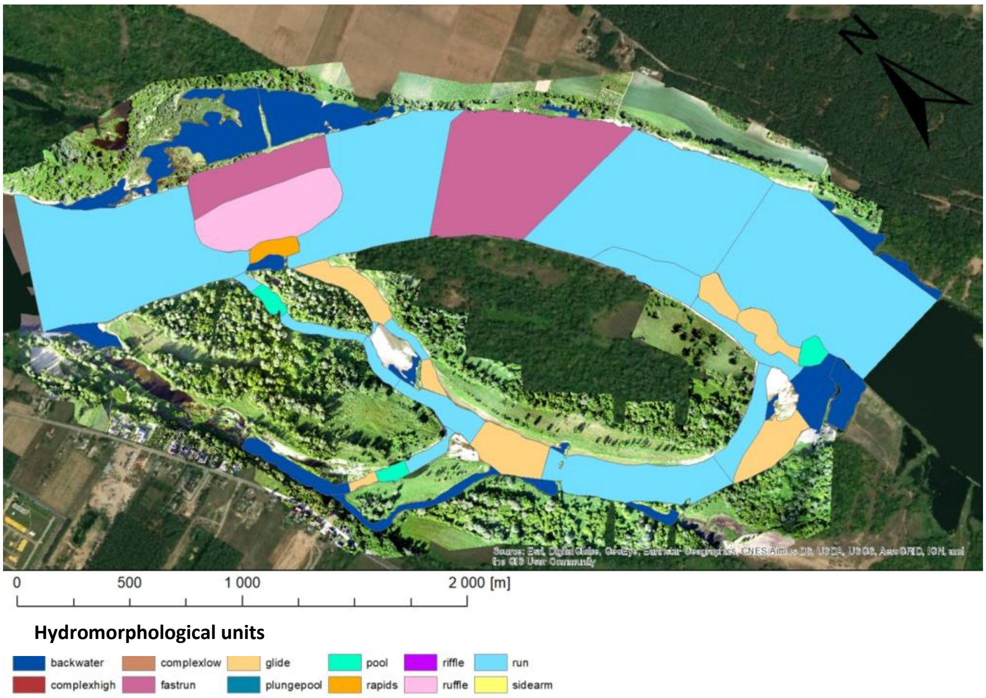


Figure 2.3.31c. Hydromorphological units in Bógpomóż section (3.8 l/sek/m^2).

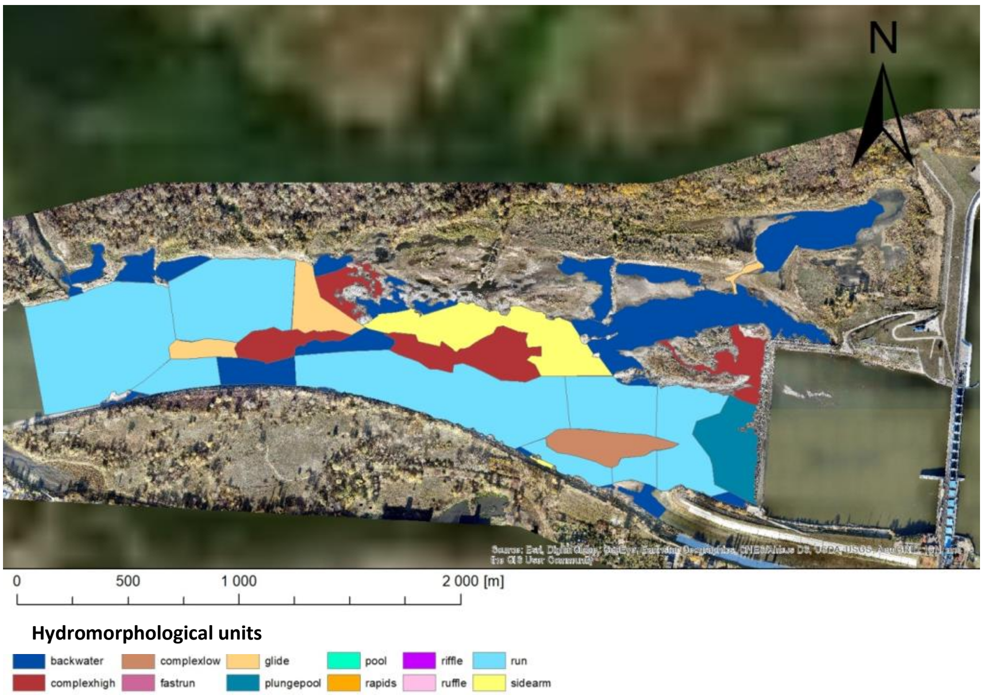


Figure 2.3.32a. Hydromorphological units in Włocławek Dam section (1.6 l/sek/m^2).

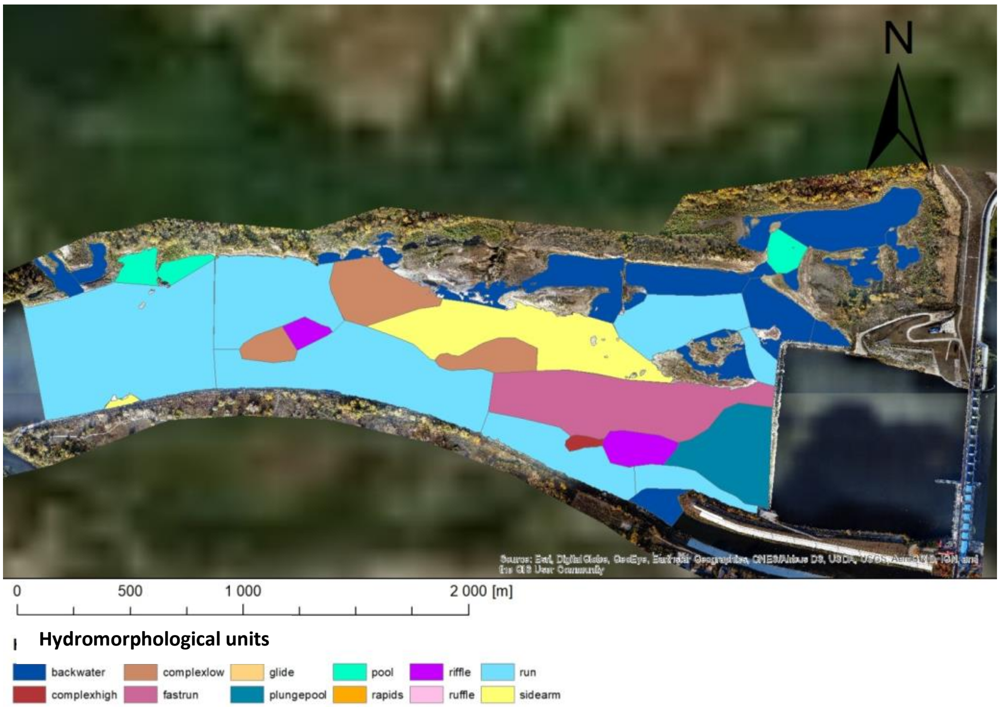


Figure 2.3.32b. Hydromorphological units in Włocławek Dam section (2.3l/sek/m^2).

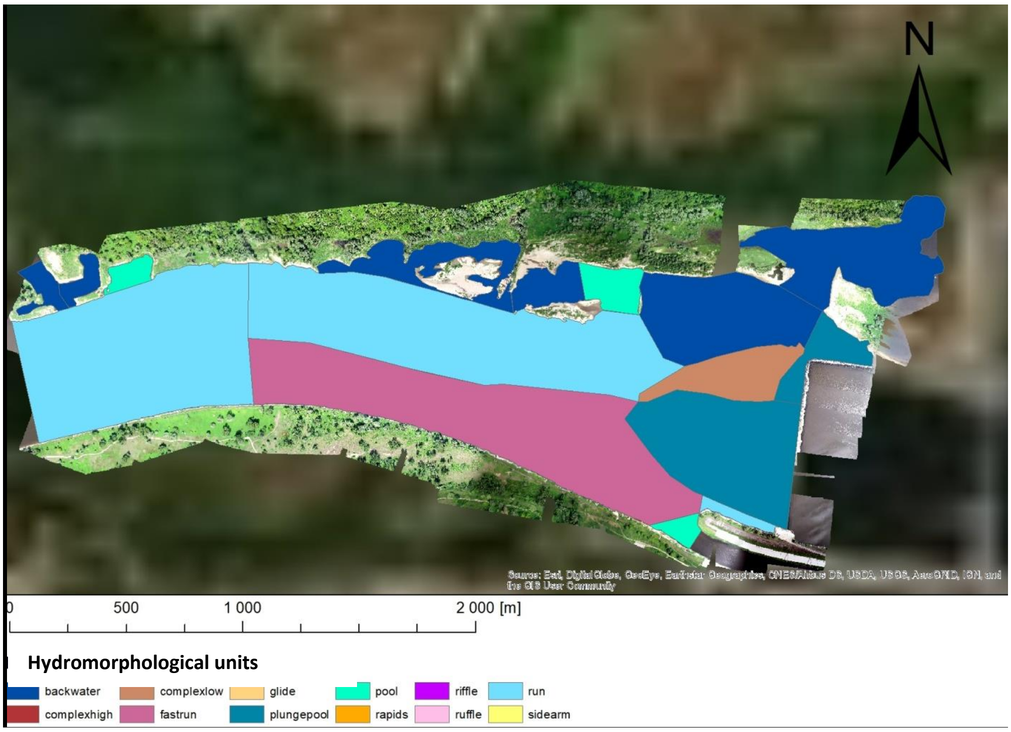


Figure 2.3.32c. Hydromorphological units in Włocławek Dam section (3.8 l/sek/m^2).

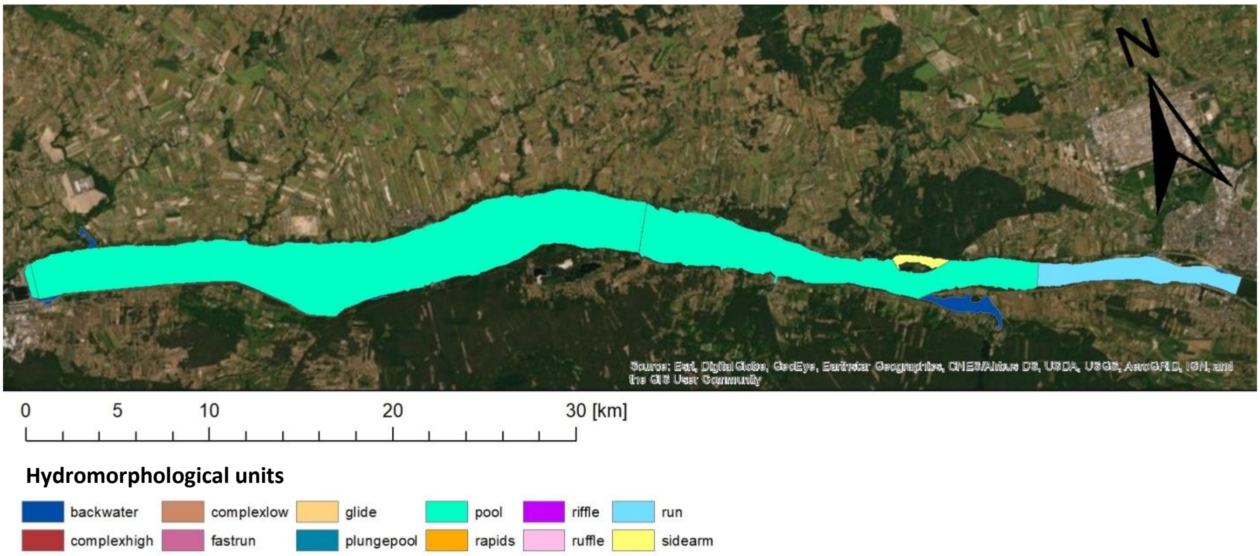


Figure 2.3.33. Hydromorphological units of Włocławek Reservoir.

Figures below represent habitat maps on example of two common guilds in Vistula River: Highly rheophilic intolerant (**Figure 2.3.34 a, b, c, d, e, f, g**) and Generalist tolerant guild (**Figure 2.3.35 a, b, c, d, e, f, g**) at sites Bógpomóż, Włocławek dam and Włocławek impoundment. Habitat maps for the remaining 7 guilds are in the supplementary material (**Figures 7.1.1 to 7.2.7**).

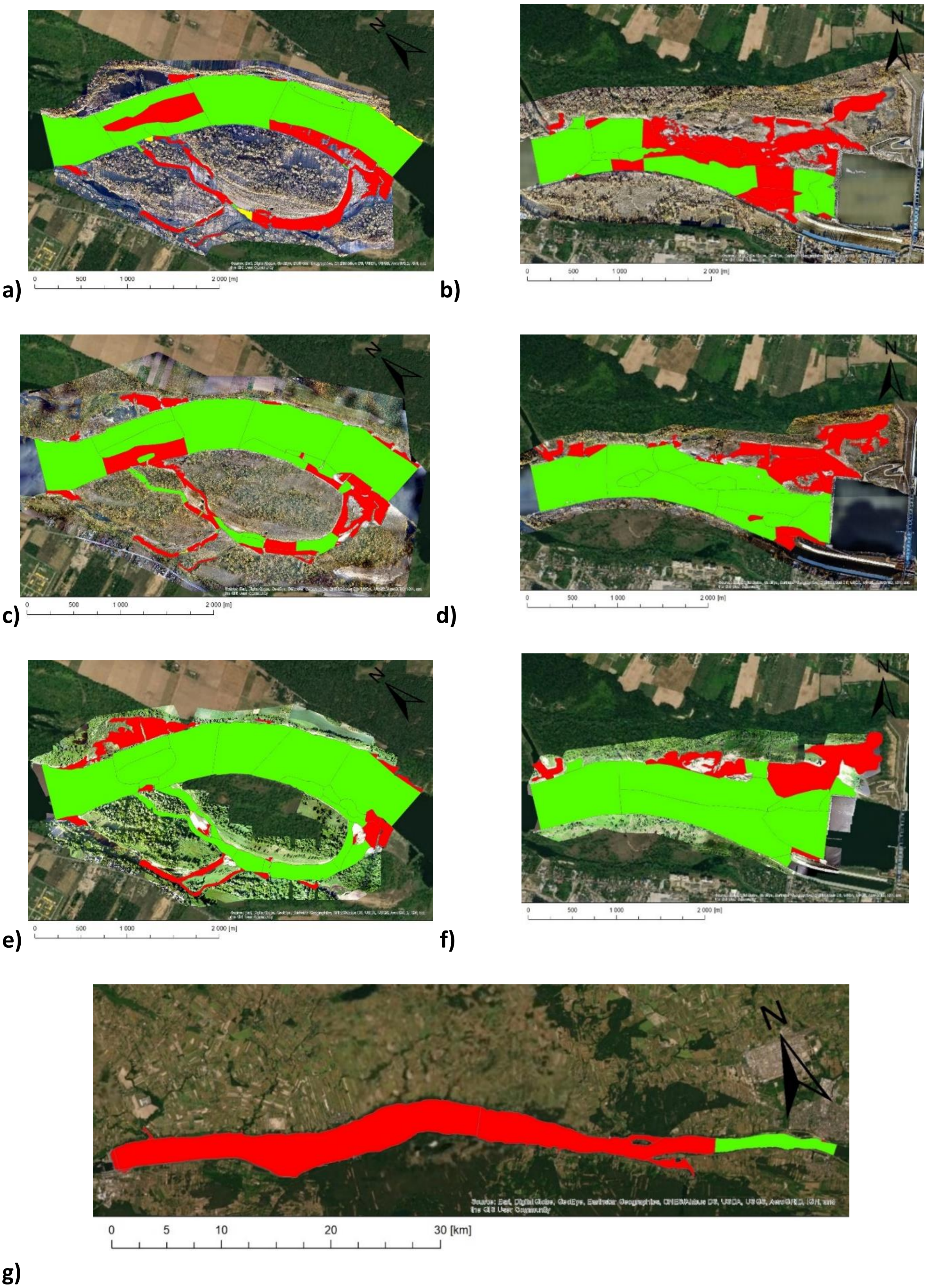


Figure 2.3.34.34 a, b, c, d, e, f, g. Highly rheophilic intolerant guild in the River Vistula: Bógpomóż a) Q=1.6 l/s·km^2, b) Q=2.3 l/s·km^2, c) Q=3.8 l/s·km^2; Wloclawek (below the dam) d) Q=1.6 l/s·km^2, e) Q=2.3 l/s·km^2, f) Q=3.8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

Highly rheophilic intolerant species in Vistula River at: Q=1.6 l/s·km^2 in Bógpomóż section (**Figure 2.3.34 a**) have 70% of the optimal, 29% of the unsuitable and only 1% of the suitable area; at Q=2.3 l/s·km^2 (**Figure 2.3.34 b**) have 76% of optimal and 24% of unsuitable area; at Q=3.8 l/s·km^2 (**Figure 2.3.34c**) have 86% of optimal and 14% of unsuitable area. This guild in Wloclawek section: at Q=1.6 l/s·km^2 (**Figure 2.3.34 d**) has 50% of optimal and 50% of unsuitable area; at Q=2.3 l/s·km^2 (**Figure 2.3.34 e**) has 71% of optimal and 29% of unsuitable area; at Q=3.8 l/s·km^2 (**Figure 2.3.34 f**) has 78% of optimal and 22% of unsuitable area. Optimal habitats are mainly in the main riverbed especially at low water flow. Highly rheophilic intolerant species in the River Vistula section above the Wloclawek Dam have 92% of unsuitable and only 8% of optimal area (far from the Dam, where water begins to flow).

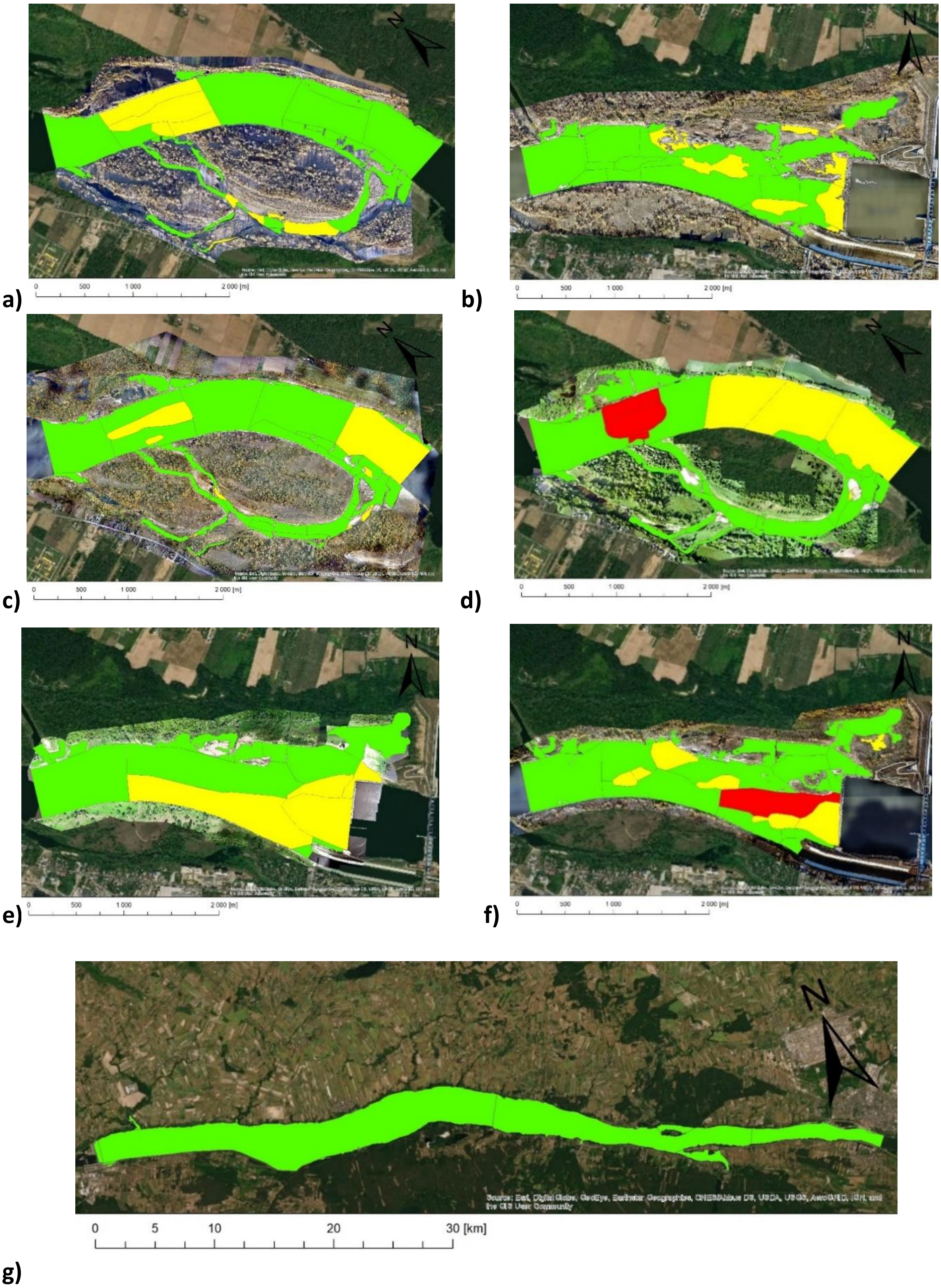


Figure 2.3.35 a, b, c, d, e, f, g. Generalist tolerant guild in the River Vistula: Bógpomóż a) Q=1.6 l/s·km^2, b) Q=2.3 l/s·km^2, c) Q=3.8 l/s·km^2; Wloclawek (below the dam) d) Q=1.6 l/s·km^2, e) Q=2.3 l/s·km^2, f) Q=3.8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

Generalist tolerant species in the River Vistulaat: Q=1.6 l/s·km^2 and Q=2.3 l/s·km^2 in section (**Figure 2.3.35 a,b**) have 79% of the optimal and 21% of the suitable area; at Q=3.8 l/s·km^2 (**Figure 2.3.35 c**) have 54% of optimal, 38% of suitable and 8% of unsuitable area. This guild in Wloclawek section: at Q=1.6 l/s·km^2 (**Figure 2.3.35 d**) has 83% of optimal and 17% of suitable area; at Q=2.3 l/s·km^2 (**Figure 2.3.35 e**) has 75% of optimal and 15% of suitable and 10% of unsuitable area; at Q=3.8 l/s·km^2 (**Figure 2.3.35 f**) has 65% of optimal and 35% of suitable area. Generalist tolerant species in the Wloclawek Dam Reservoir have only optimal area (100%). Most habitats in analyzed Vistula river sections meets the requirements of this guild.

Habitat availability

Bógpomóż section

Figure 2.3.36 demonstrates habitat rating curves for the Habitat Use Guilds of the River Vistula in conditions close to natural of reference site. Habitat for rheophylic species show continuous increase with flow increase, while habitat for many of limnophylic and benthic species plateaus at about 1.6 lskm and increases again about 2.5 lskm. Limnophylic phytophylic species have continuous habitat increase but the slope also declines above 2.5 lskm. In contrast the habitat for generalist raises until ca. 2.5 lskm and decline sharply above this value. Generic fish habitat representing sum of habitat area used by all species increases rapidly below 2 lskm to 60% channel area and continue growth up to 80% of river channel area at highest flow.

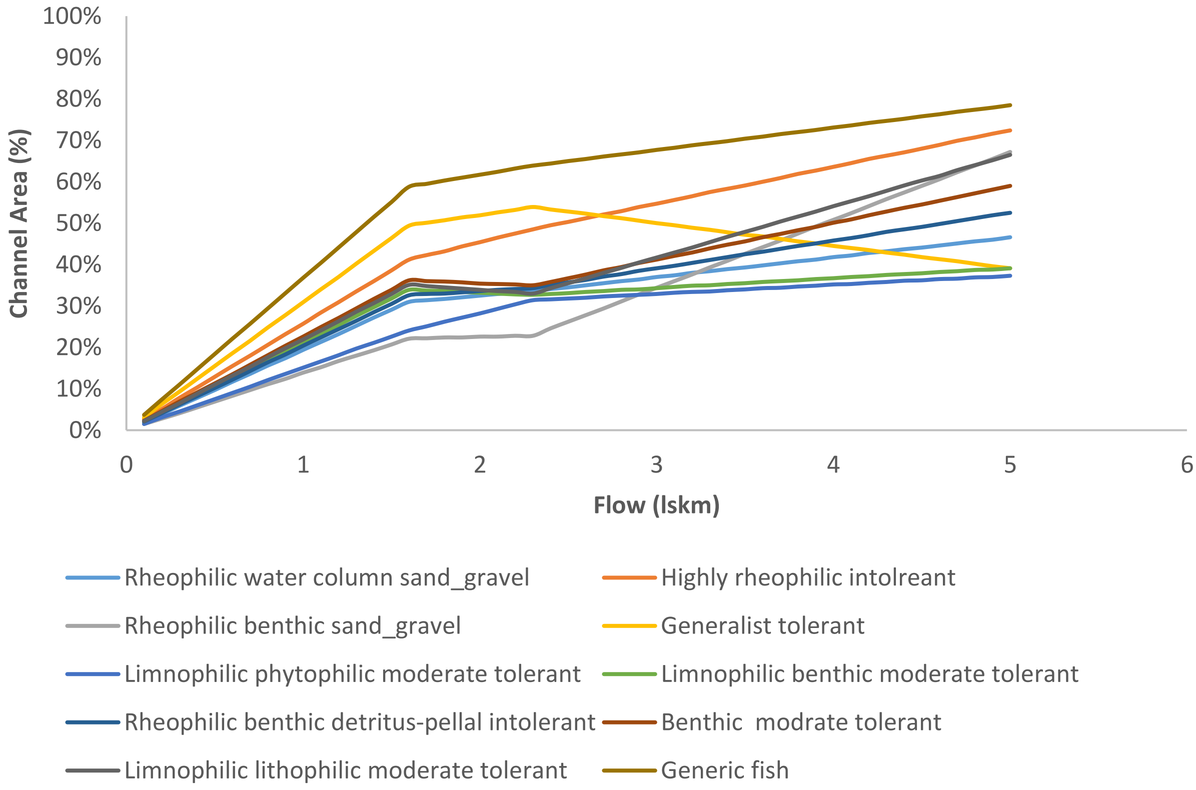


Figure 2.3.36. Rating curves for Habitat Use Guilds in Bógpomóż site.

Włocławek section

Figure 2.3.37 demonstrates habitat rating curves for the Habitat Use Guilds the River Vistula in conditions with modified channel as observed at Włocławek site. Habitat for most rheophylic species show increase only slowly below 1.6 lskm staying below 20% of channel area, to rapidly increase above this value. Some other species such as rheophylic water column sand and gravel, rheophylic benthic detritus-pellal, intolerant guild and limnophylic lithophylic moderate tolerant have habitat, which constantly increase with flow. For limnophylic phythophylic and benthic moderate tolerant guilds the increase slows down at 1.6 lskm and continues above 2.5 lskm. Habitat for Generalist and limnphylic benthic moderate tolerant reaches its peak at 1.6 lsm and 2.5 lskm respectively and remains almost constant. Generic fish habitat representing sum of habitat area used by all species increases rapidly until about continuously up to 68% of river channel area.

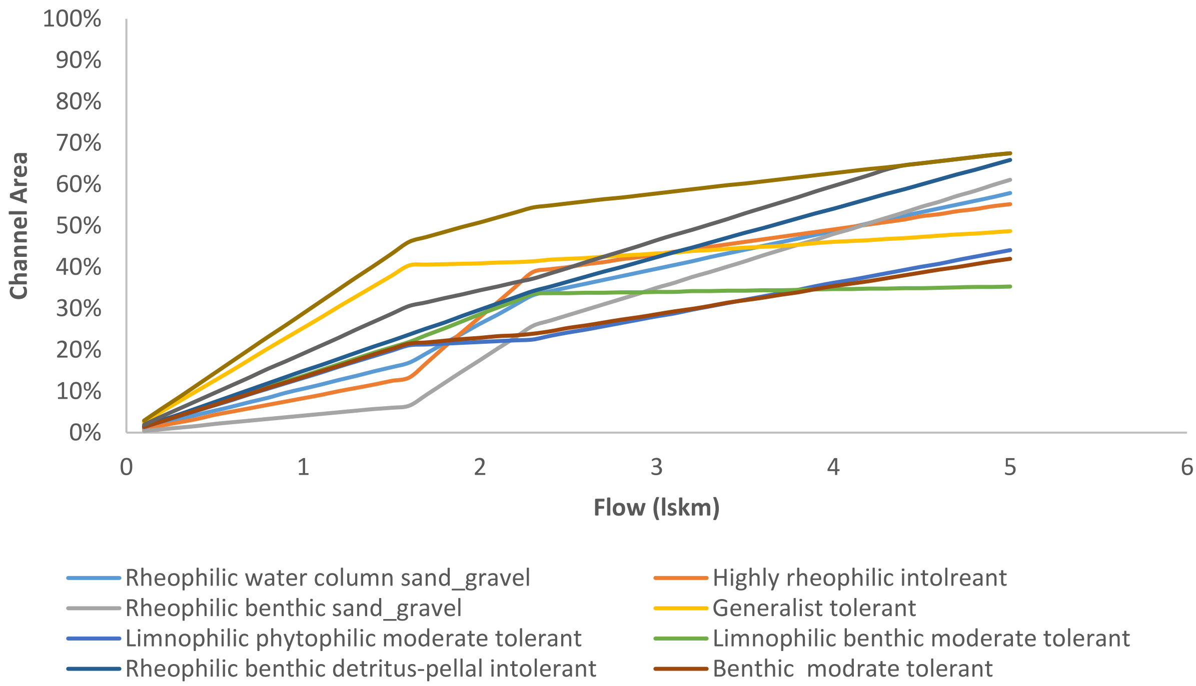


Figure 2.3.37. Rating curves for Habitat Use Guilds in Włocławek site.

For the Włocławek Impoundment, it was assumed that within assessed range of summer flow the habitat conditions remain constant.

To better compare the habitat structure with habitat expected under FCMacHT **Figures 2.3.38-2.3.40** demonstrate habitat structure for the study sites at 4 low flow conditions from 1 to 3 lskm. In the Bogpomóż site (**Figure 2.3.38**) the affinity between the FCMacHT habitat ranges from 66% at 1 lskm to 72% at 4 lskm. At very low flow condition it shows a deviation from what would be expected, but it is getting closer to the target at median low flow, which is 3 lskm. The most apparent deviation is low amount of suitable area from the species expected to be the most dominant i.e. rheophylic water column sand and gravel. The second largest discrepancy is overabundance of habitat for generalist, benthic moderate tolerant, limnophylic lithophylic species and lampreys.

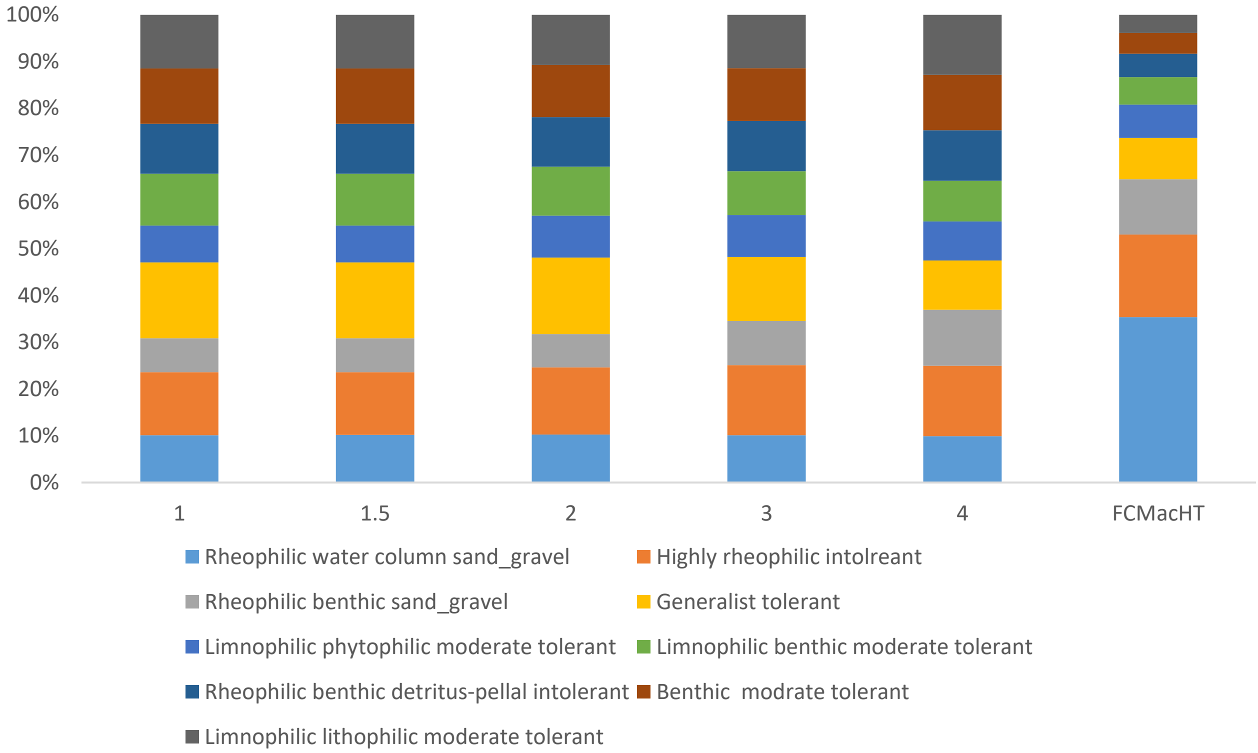


Figure 2.3.38. Habitat structure observed at Bógpmóż site as compared to FCMacHT target.

In the Włocławek dam site (**Figure 2.3.39**) the affinity between the FCMacHT habitat ranges from 53% at 1 lskm to 70% at 4 lskm. At very low flow condition it shows a deviation from what would be expected, but it is getting closer to the target at median low flow, which is 3 lskm. Still at the very low flows up to 1.5 lskm there is a strong dominance of limnophylic and, foremost, generalist habitat at the cost of highly rehophylic and rheophylic benthic sand and gravel habitat. The improvement begins at 2 lskm.

In the Włocławek Impoundment site (**Figure 2.3.40**) the affinity between the FCMacHT habitat is 38%. Limnophylic and generalist species have abundance of habitat at the cost of rheophylic species habitat. Due to dam management the habitat structure is considered to be unchangeable with the flow.

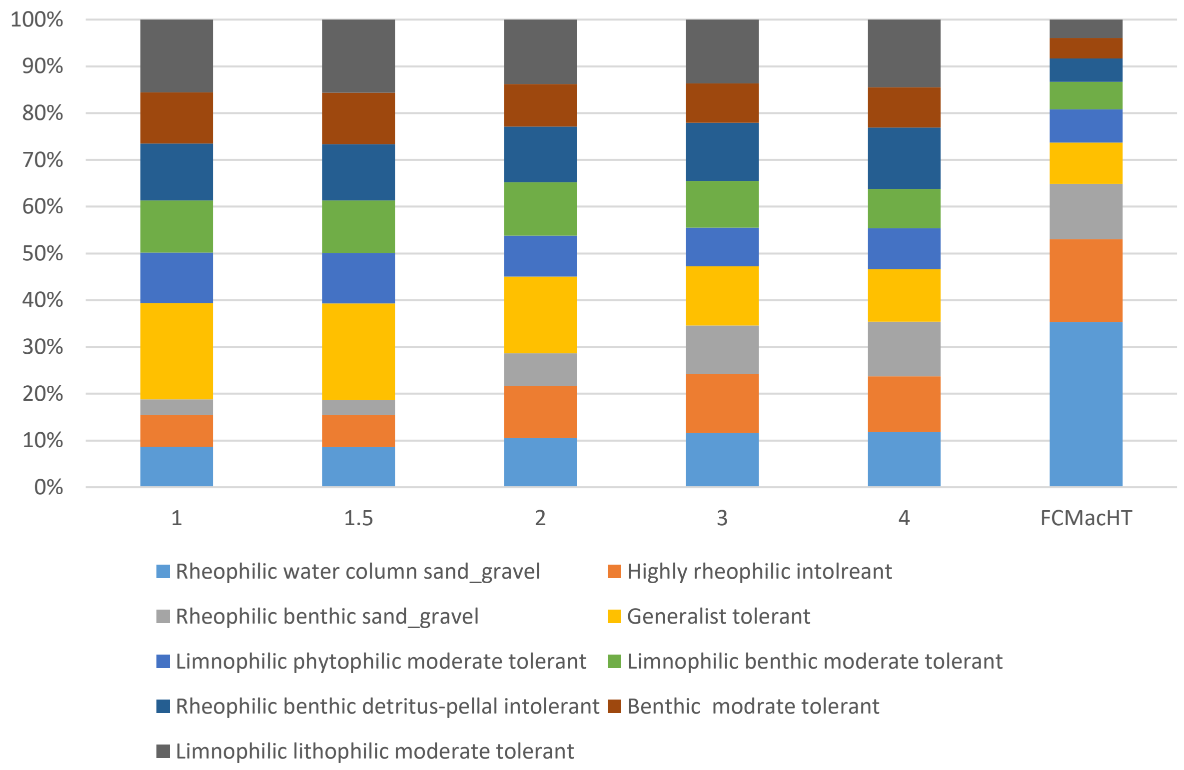


Figure 2.3.39. Habitat structure observed at Włocławek dam site as compared to FCMacHT target.

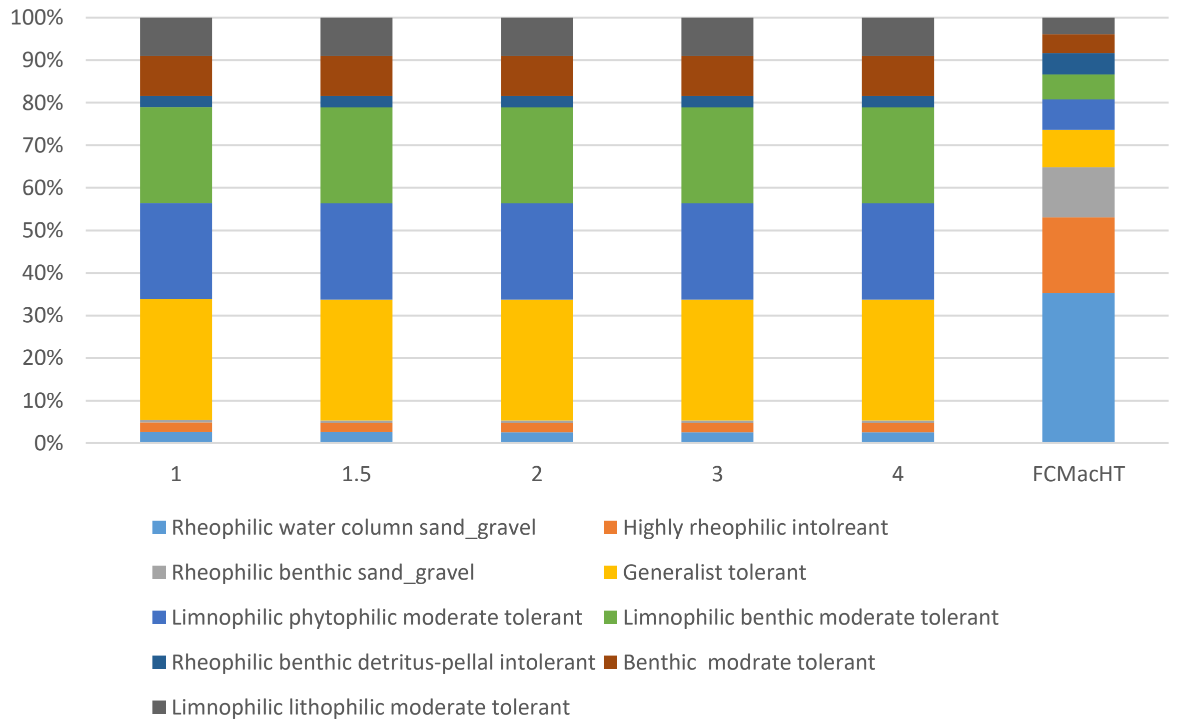


Figure 2.3.40. Habitat structure observed at Włocławek impoundment site as compared to FCMacHT target.

Figure 2.3.41 demonstrates community rating curves for all three sites. As mentioned before, it is calculated by weighting the habitat area for each guild with its expected proportion in FCMacHT. Therefore, we can expect that the greater the affinity of habitat structure to FCMacHT the higher the curve value. The reference curve has the steepest increase at the low flows and continues up to 50% channel area (CA). Since as presented before the habitat structure is not changing that dramatically between the flow, the increase is mostly due to expansion of habitat area. This stands in contrast to Włocławek site where the raise of the curve is influenced by improvement in habitat structure. Although almost all wetted area in impounded section is suitable for one or more guilds, poor habitat structure lowers its value to 25% of CA i.e. half of the reference value.

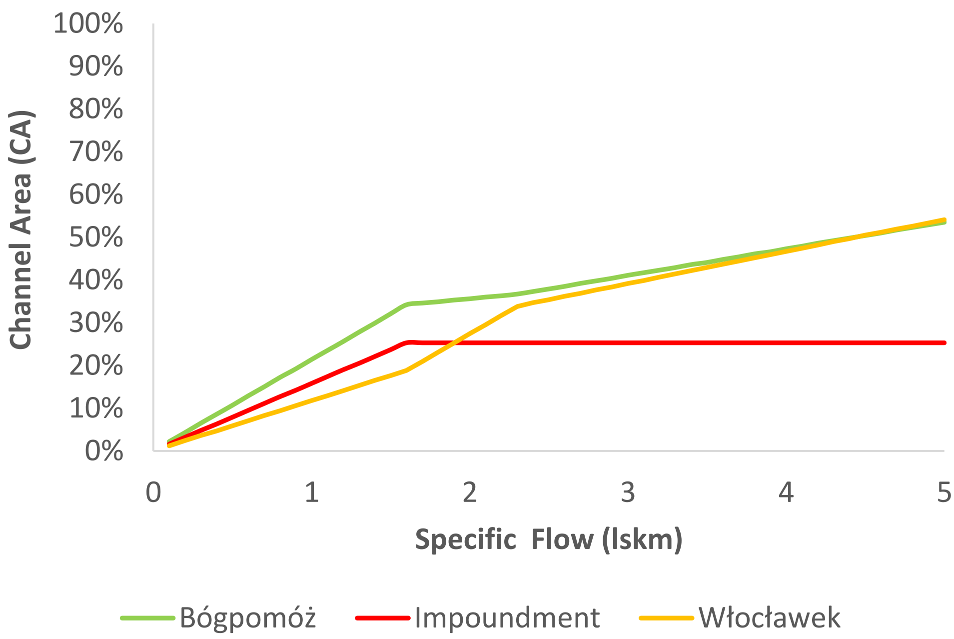


Figure 2.3.41. Habitat Rating Curves for Fish Community in surveyed sites.

Time series Analysis

Data of the Global Hydrological Models (GHMs)

The temperature is rising, what is observed in global as well as in regional scale. Depending on the development, mitigation and adaptation strategies, changes in land use or population increase, four Representative Concentration Pathways (RCPs) were prepared and used for climate modeling and research for the IPCC fifth Assessment Report (AR5) in 2014. The RCPs: RCP2.6, RCP4.5, RCP6, and RCP8.5 mean a possible ranges of radiative forcing values in the year 2100 (i.e. 2.6, 4.5, 6, and 8.5 W m^{-2}, respectively) (van Vuuren et al. 2011). Climate models developed based on these RCPs are compatible and predict for the future an increase in mean, and also in minimum and maximum temperatures. Changes in precipitation are more difficult to project because of spatial diversity, high natural variability, seasonality and the complexity of the phenomenon involving the sub-grid scale features such as topography or land use. Also, in order to quantify global water availability and usage in the past, present, and future, a number of global hydrological models (GHMs) have been developed, like H08, WaterGAP, LPJmL, PCR-GLOBWB, WBMplus, HiGWMAT and others (Hanasaki et al. 2018).

Global hydrological models cover the whole globe at a spatial resolution of 0.5 x 0.5 degree, and the calculation interval is 1 day. They are driven by climate models and any other models describing hydrological processess. One of the sources of GHMs is The Inter-Sectoral Impact Model Intercomparison Project ISIMIP (https://www.isimip.org/), which offers a framework for consistently projecting the impacts of climate change across affected sectors and spatial scales. This is an international network of climate-impact under different climate-change scenarios.

For this research the RCP4.5 and symulations of daily discharges for historical period: 1971-2000 and for near future 2021-2050 for six grid-cell based global hydrological models, namely: H08, LPJmL, CLM, PCR-GLOBWB, MPI-HM and WBM have been chosen. Each hydrological model implements climatological variables from five global climate models (GCM): IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5 and NorESM1-M.

The Representative Concentration Pathway RCP4.5 is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions (van Vuuren et al. 2011). Projection of global warming increase relative to average temperature for period 1986–2005, according to AR5 (IPCC, 2014), for this scenario is 1.4°C (0.9°C to 2.0°C; mean and likely range) for the period 2046–2065 and 1.8°C (1.1°C to 2.6°C) for the last twenty years of the 21st century (2081–2100).

Validation of the Global Hydrological Models (GHMs)
The results of the six different GHMs with the same set of climatic inputs choosen in first step for past period 1971-2000 were compared with daily data for hydrological station Włocławek on the River Vistula (Poland). Simulations for the models were obtained for grid embracing station with observed data (the centre of grid: lat=52.75°N and lon=19.25°E). Station is located in Włocławek by the Marszałka Rydza-Śmigłego Bridge (lat=52.66°N and lon=19.07°E). In the research period: 1971-2000 the minimum discharge observed in the River Vistula on Włocławek station was 160 $m^3 s^{-1}$ (during year with severe drought in 1992); the Q_1 was estimated on 524 $m^3 s^{-1}$; median = 741 $m^3 s^{-1}$, Q_3 = 1100 $m^3 s^{-1}$ and the maximum discharge was 6080 $m^3 s^{-1}$ (rainfall-melt flood in 1979).

The method used in validation was a comparison of the q-q plots of discharges for Włocławek and hydrological model simulations from the grid. Based on these q-q plots for daily discharges model H08 with the five climatic inputs has been preselected as the best one (**Figure 2.3.42**).

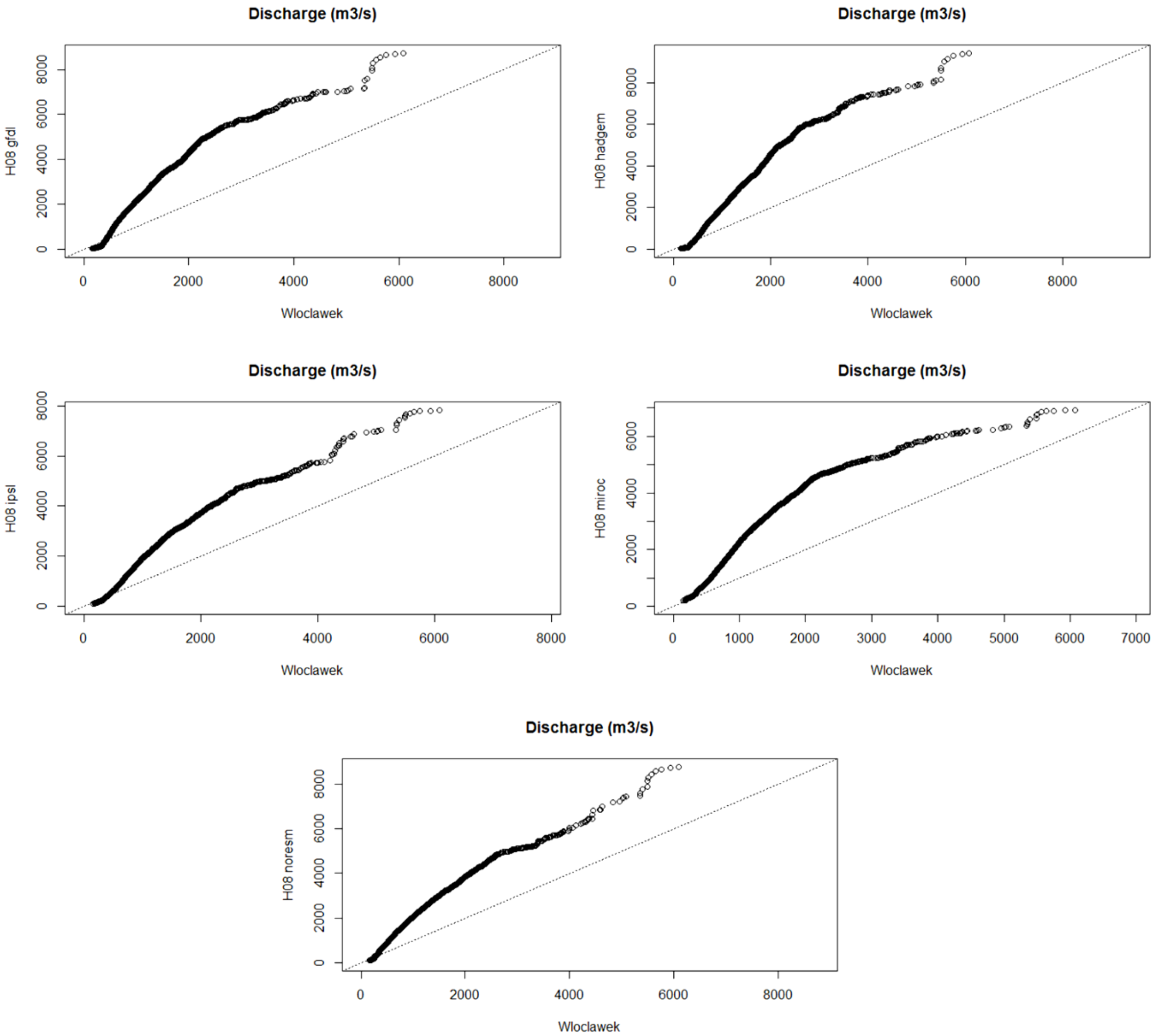


Figure 2.3.42. The q-q plots of daily discharges for Włocławek and hydrological model simulation and five climatic inputs: GFDL-ESM2M (gfdl); HadGEM2-ES (hadgem); IPSL-CM5A-LR (ipsl), MIROC5 (miroc) and NorESM1-M (noresm). Dotted line means perfect match, i.e. the Włocławek-Włocławek percentile values.

Next the q-q- plots have been limited to the value of discharge in Vistula River at the Włocławek station 524 $m^3 s^{-1}$, which corresponds Q_1 (25^{th} percentile of discharge) to check the fitting to the lowest values (**Figure 2.3.43**).

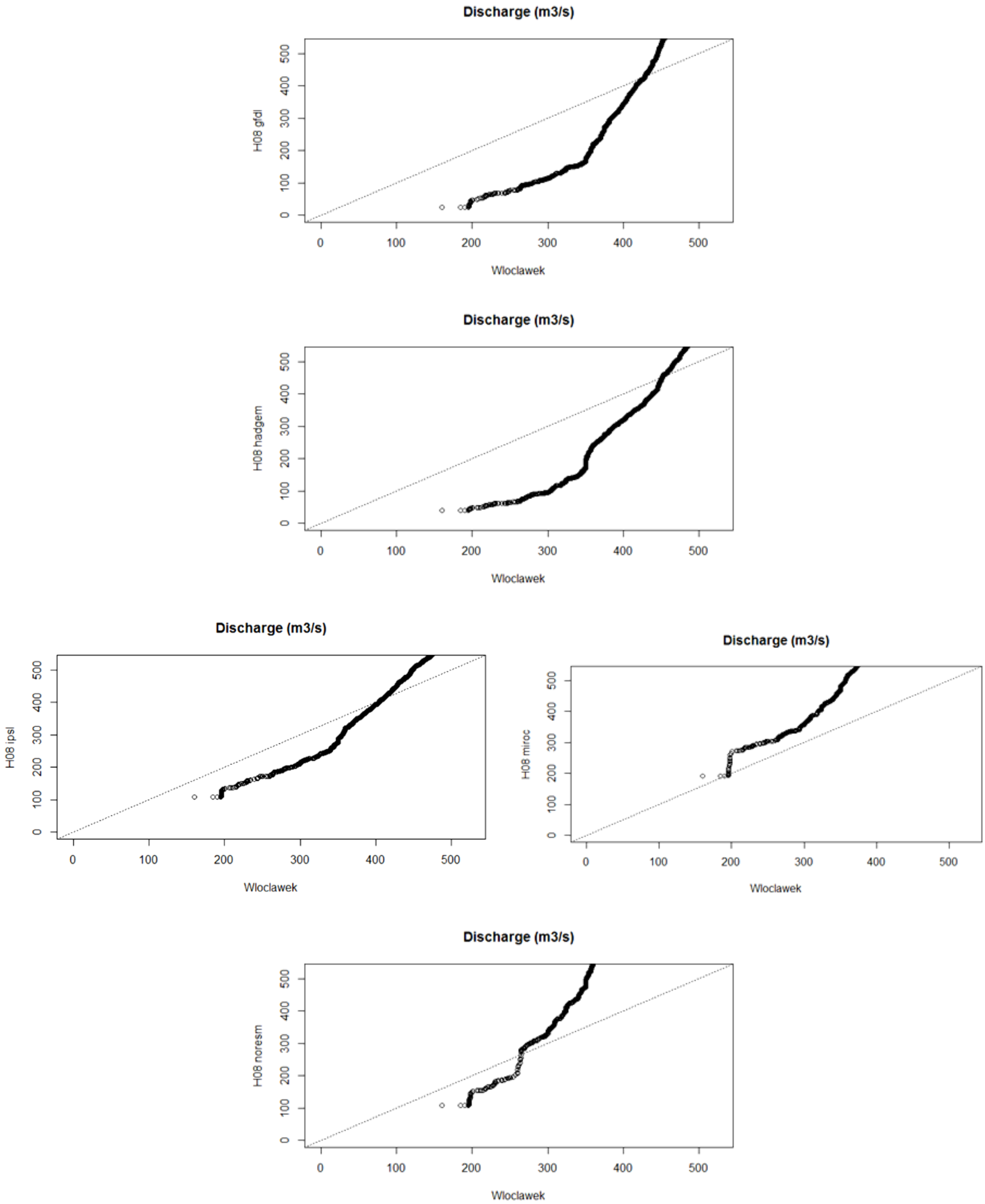


Figure 2.3.43. The same as in **Figure 2.3.42**, but for the values up to Q_1 (25^{th} perecentile).

Based on these q-q plots, the model H08 with the IPSL-CM5A-LR climatological variables was choosen. **Figure 2.3.44** presented regression line for this model and the lowest values of discharges. Adjusted R-squared was 0.9646.

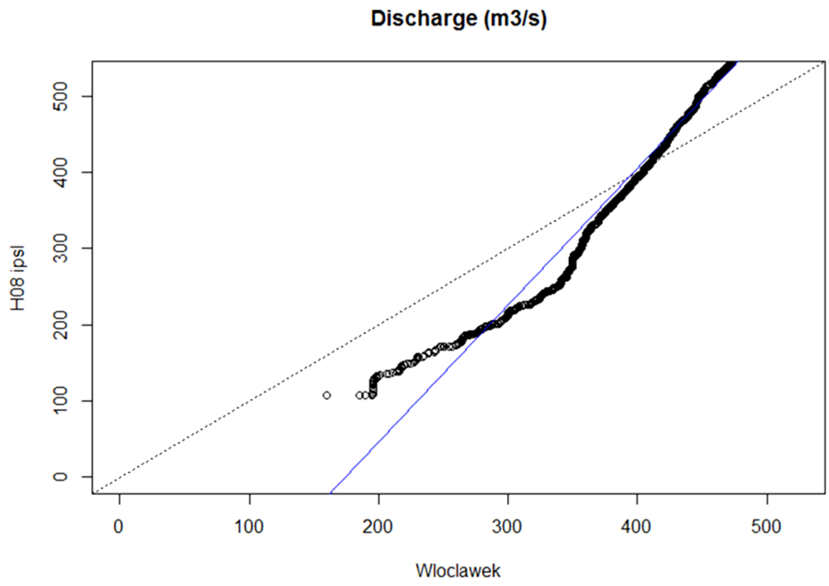


Figure 2.3.44. The q-q plot and regression line (blue) for model H08 IPSL-CM5A-LR for the lowest values of discharges.

Habitat time series analysis
Flow vs. fish community habitat rating curve was applied to develop habitograph for reference conditions and computed UCUT diagram built for 1 % of CA interval is presented in **Figure 2.3.45**. The curve for 34% of CA clearly stands out as threshold to rare conditions and 0.35% CA was chosen as critical value. The corresponding subsistence and trigger flows are 1.6 and 1.8 lskm respectively. The curve of 46% CA demarcates transition to common condition and corresponds with habitat base flow of 3.8 lskm. The critical points describing shortest persistent duration are 7 days for subsistence flow, 16 for trigger flow and 44 for base flow (**Table 2.3.8**). The lowest measured flow on record is 0.62 lskm.

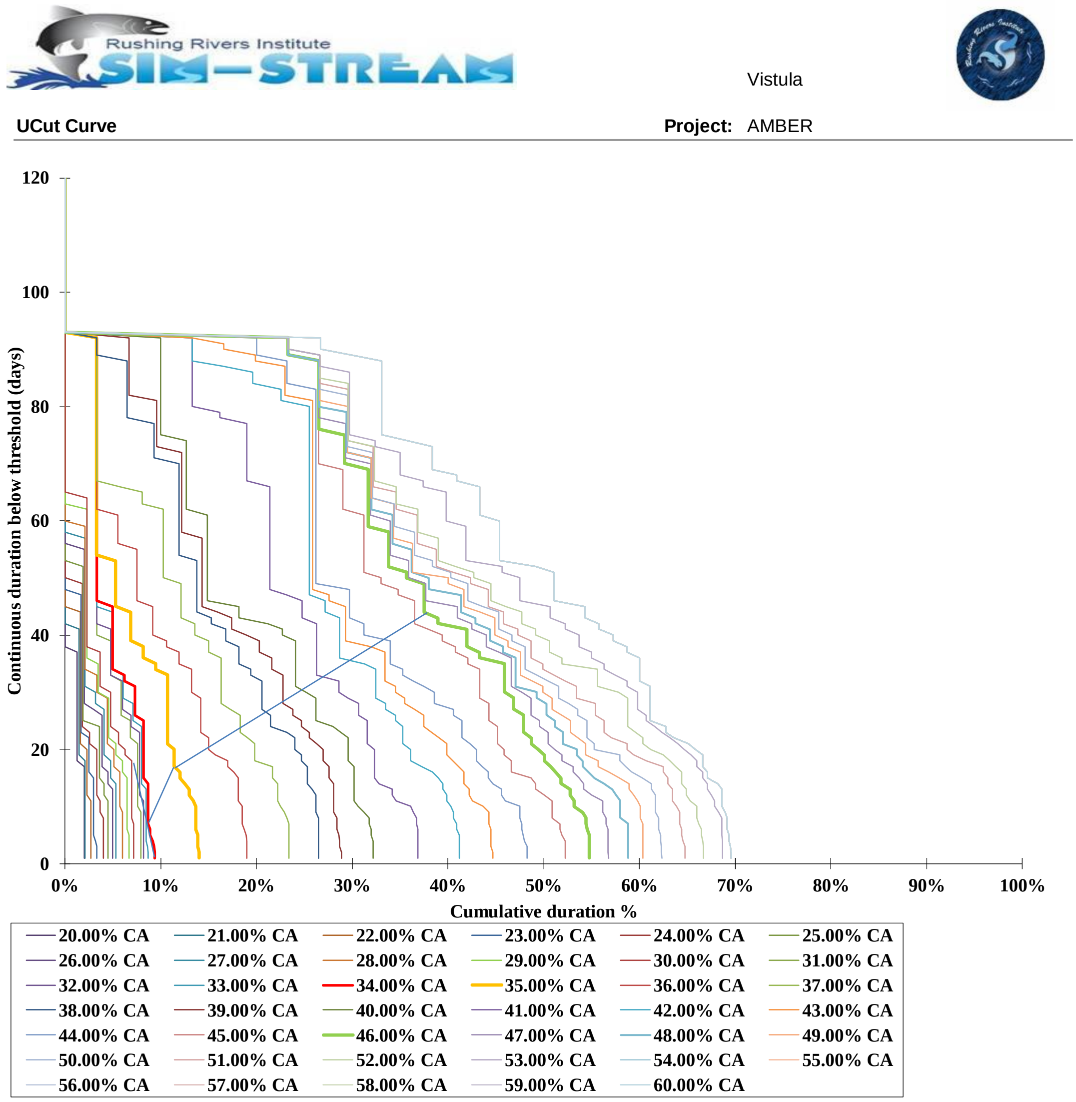


Figure 2.3.45. Habitograph for reference conditions and computed UCUT diagram built for 1 % of CA interval.

Table 2.3.8. Critical points describing shortest persistent duration are 7 days for subsistence flow, 16 for trigger flow and 44 for base flow

River	Vistula
Rearing and growth	VII-IX
Gaging station	Włocławek
watershed area (km2)	172000
Common habitat (%CA)	**46**
Allowable duration under (days)	44
Catastrophic duration (days)	92
Habitat base flow (lskm)	3.80
Habitat base flow (m3s-1)	653.60
Critical habitat	**35**
Allowable duration under (days)	16
Catastrophic duration (days)	31
Trigger flow (lskm)	1.80
Trigger flow (m3s-1)	309.60
Rare habitat (%CA)	**34**
Allowable duration under (days)	7
Catastrophic duration (days)	31
Subsistence flow (lskm)	1.58
Subsistence flow (m3s-1)	271.76
Abs. Minimum (lskm)	**0.62**

Scenarios

Figure 2.3.46 demonstrates the change of habitat structure between the channel modification scenarios at flow of 1.5 lskm. The affinity indices increase from scenario 1 to 4 from 50% to 63%. Habitat structure in Scenario 4 is already very close to reference conditions. This is mostly due to increase of, at the cost of generalists, a rheophylic species habitat.

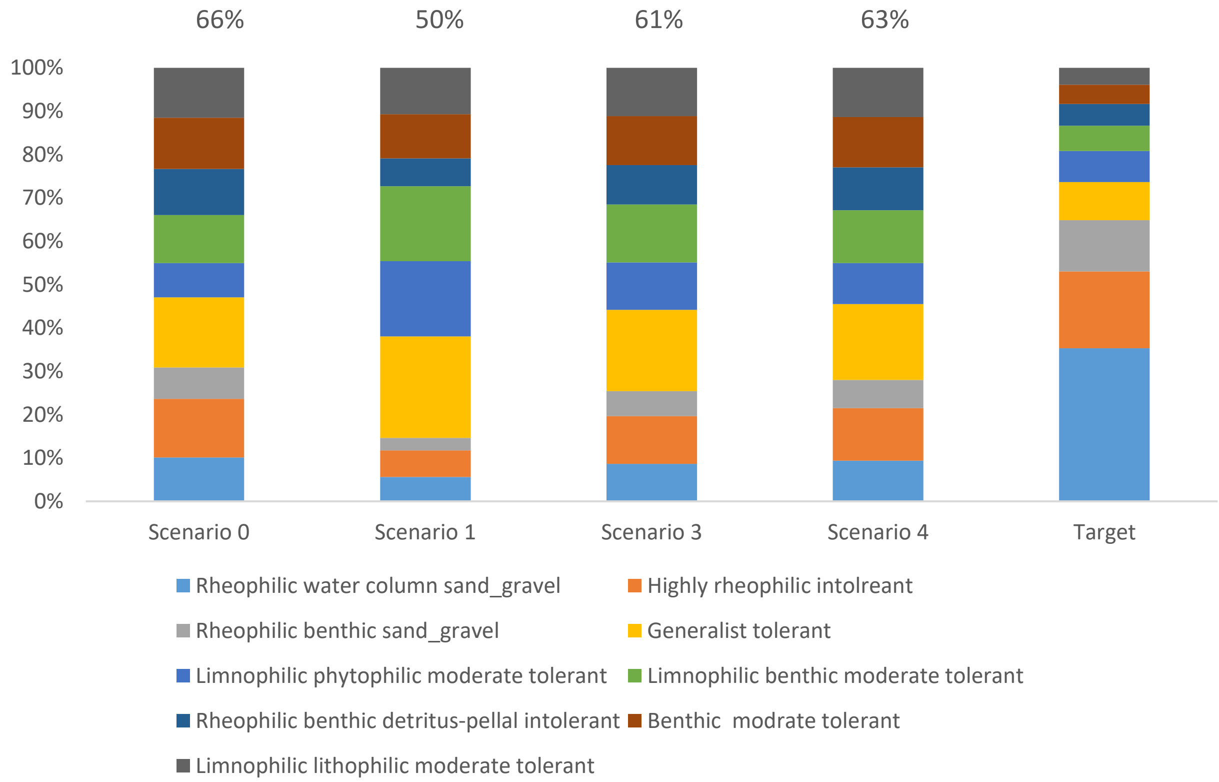


Figure 2.3.46. The change of habitat structure between the channel modification scenarios at flow of 1.5 lskm.

Calculation of Habitat Stress Days Alteration for tested scenarios

Figure 2.3.47 demonstrates the UCUT curves for rare and common habitat thresholds for each of of tested scenarios using historical flow time series. The shift of corresponding curves to the right indicates an increase of frequency of events when habitat is lower than the threshold. The arrows in the scenario 1 diagram indicate where the increase of stress days is measured (lowest persistent duration). The average of these and critical thresholds values is used as a metric for scenario comparison at RAA diagram. As visible on these figures in scenario 1, there is a sharp increase in frequency of habitat stress days for the rare conditions (over 500%) and to 145% for common level. Compared to current situation in scenario 2, the augmentation slightly lowers the number of events of persistent and catastrophic durations, but at the threshold level of persistent durations HSD frequency increased to 483%. At the common threshold the HSD frequency remains at similar level as in scenario 1. In scenario 3 shortening the impoundment to 20km still creates 230% more of stress days at the rare persistent threshold, but for the common level the differences are well within the error boundaries. In scenario 4, only small increases in stress days are observed. Similar can be mentioned for both scenarios of 6 and 7 where the number of stress days for persistent and catastrophic conditions actually declines.

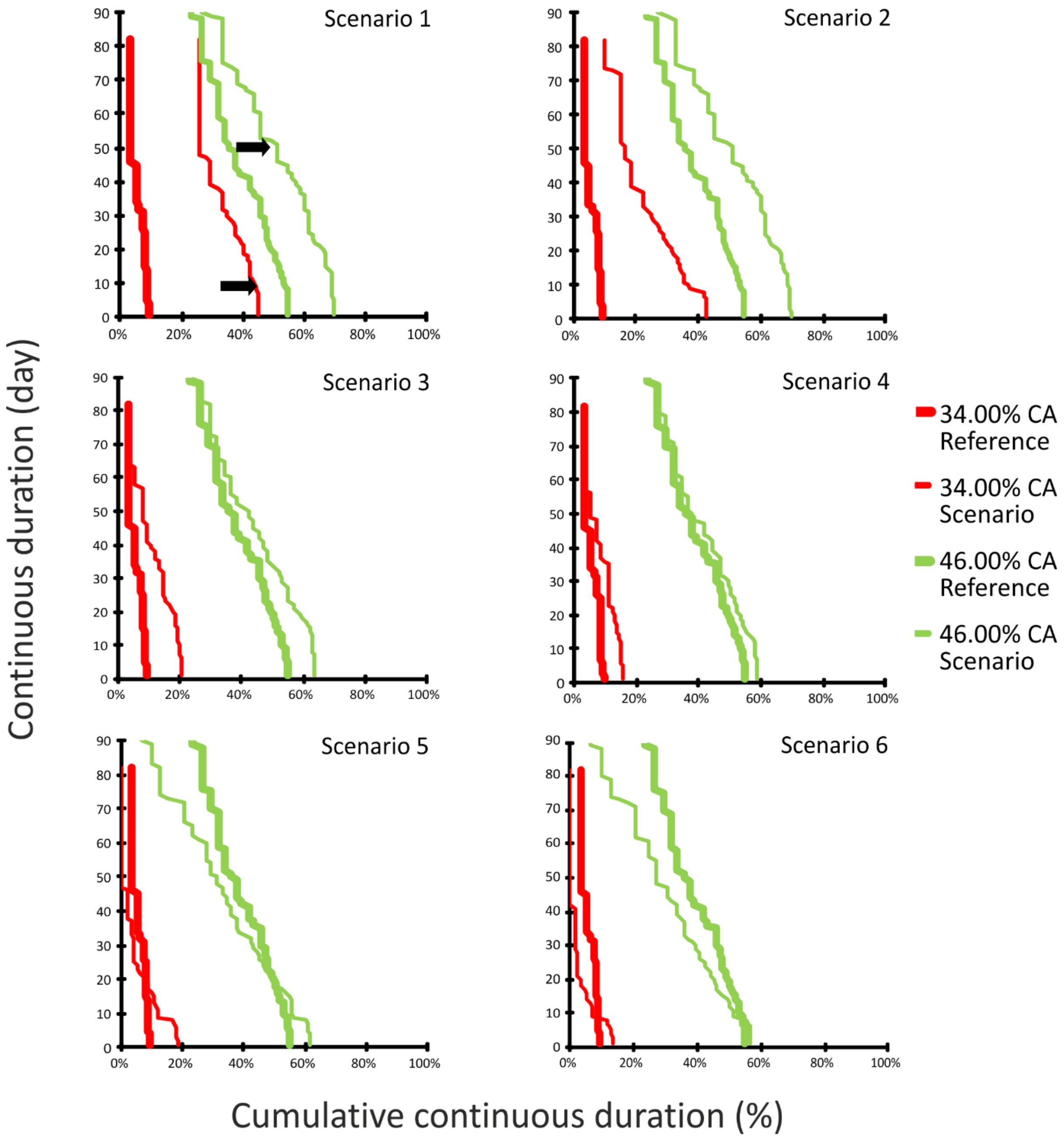


Figure 2.3.47. UCUT curves for rare and common habitat thresholds at 6 scenarios as compared with reference conditions.

Climate change scenarios

After applying the Near Future flow time series to all scenarios following results have been obtained (**Figure 2.3.48**). UCUT curves for scenario 1 indicate rare persistent habitat stress days occurring 398% of the reference, what is about 100% less than historically. However, for catastrophic duration there is no increase in number of stress days. For common threshold there is small increase in frequency of persistent HSD, but catastrophic durations decline. Very similar pattern is observed for scenario 2. In scenario 3 and 4, there is only a small difference in UCUTS for catastrophic durations at common threshold. Adding flow augmentation actually reduces frequency of stress days beyond the reference conditions.

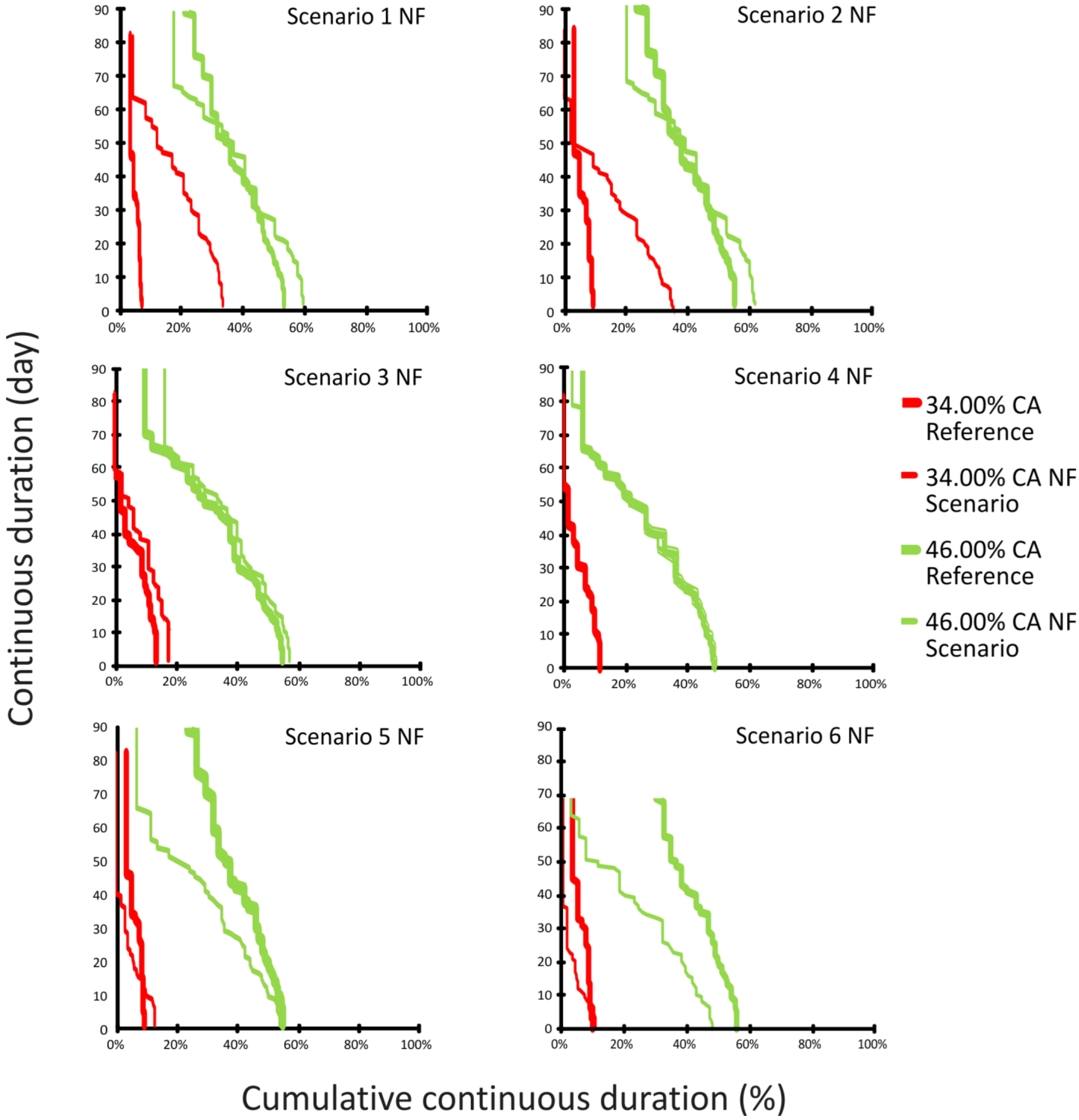


Figure 2.3.48. UCUT curves for rare and common habitat thresholds at 6 scenarios as compared with reference condition.

River Restoration Analysis Diagram

Figure 2.3.49 demonstrates the scenario analysis in Euclidian Space. According to this diagram lowering of the dam would provide the greatest benefit to fish habitat. Flow augmentation makes the most of the difference for current habitat conditions and becomes less effective when dam is being lowered. Still the best improvements in terms of habitat are accomplished with scenario 6. Here however is important to consider that with lower impoundment, less water will be available for flow augmentation, what could limit the feasibility of this solution. Hence, it looks like the best choices are scenario 4 and 5, and choice would depend on technical boundary conditions and flow availability.

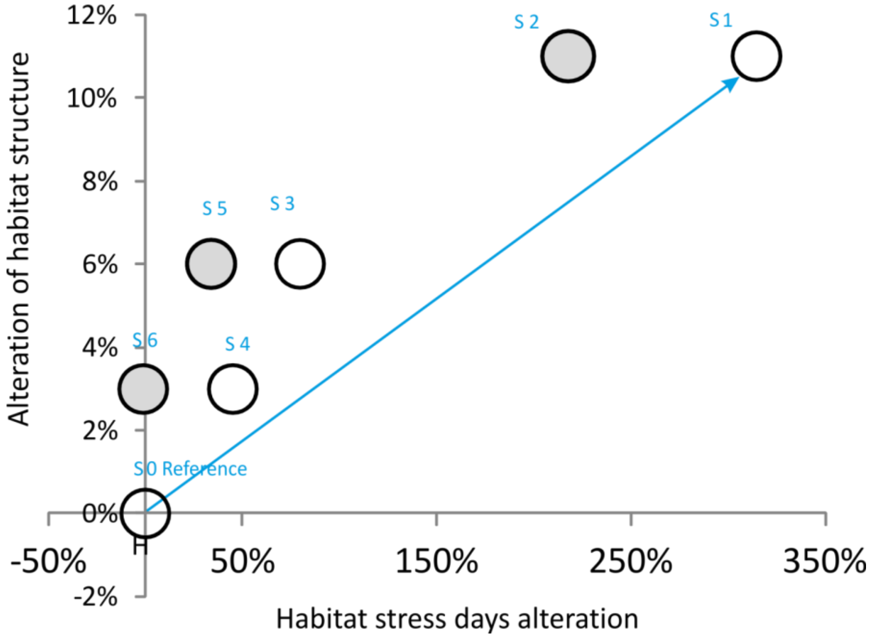


Figure 2.3.49. Restoration Alternatives Analysis for simulated scenarios (S1-6) of Vistula River case study under historical flow conditions.

Figure 2.3.50 presents the RAA analysis for predicted Near Future flow patterns, which obviously alleviate need for flow augmentation. In this situation the most desired from fish habitat perspective scenario is scenario 4.

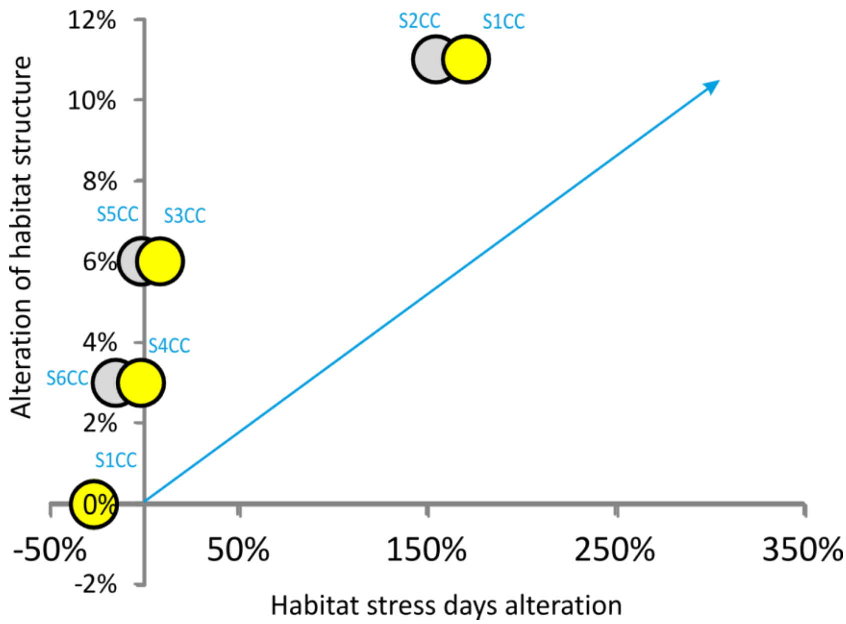


Figure 2.3.50. Restoration Alternatives Analysis for simulated scenarios (S1CC-6CC) of Vistula River case study under near future climate change flow conditions.

A.2.3.8 Discussion

The application of habitat modelling tool MesoHABSIM on the River Vistula demonstrated its utility for determination of impact and capability for finding effective management solutions. In contrast to commonly applied methods it provided a clear picture of current and future situation in quantitative terms. It offers an excellent planning tool for finding the adaptive management actions, reducing effort invested in "try-and-error" adaptive management.

First it is clear that the large impoundment beyond Włocławek dam has significant impact on up- and downstream habitats. The major mechanism is modification of habitat structure, which leads to alteration of fish communities from riverine to pond preferring species. This is observed up and downstream of the dam. Our fish observations confirm this conclusion as the fish community structure strongly resembles the habitat structure of the impounded area (AI=79%, **Figure 2.3.51**). However, it needs to be remembered that the electrofishing sample was not supported by net gear samples and therefore the deep and fast flowing areas are underrepresented in the data. Still, the resemblance is too high for this shortcoming to completely undermine the conclusion.

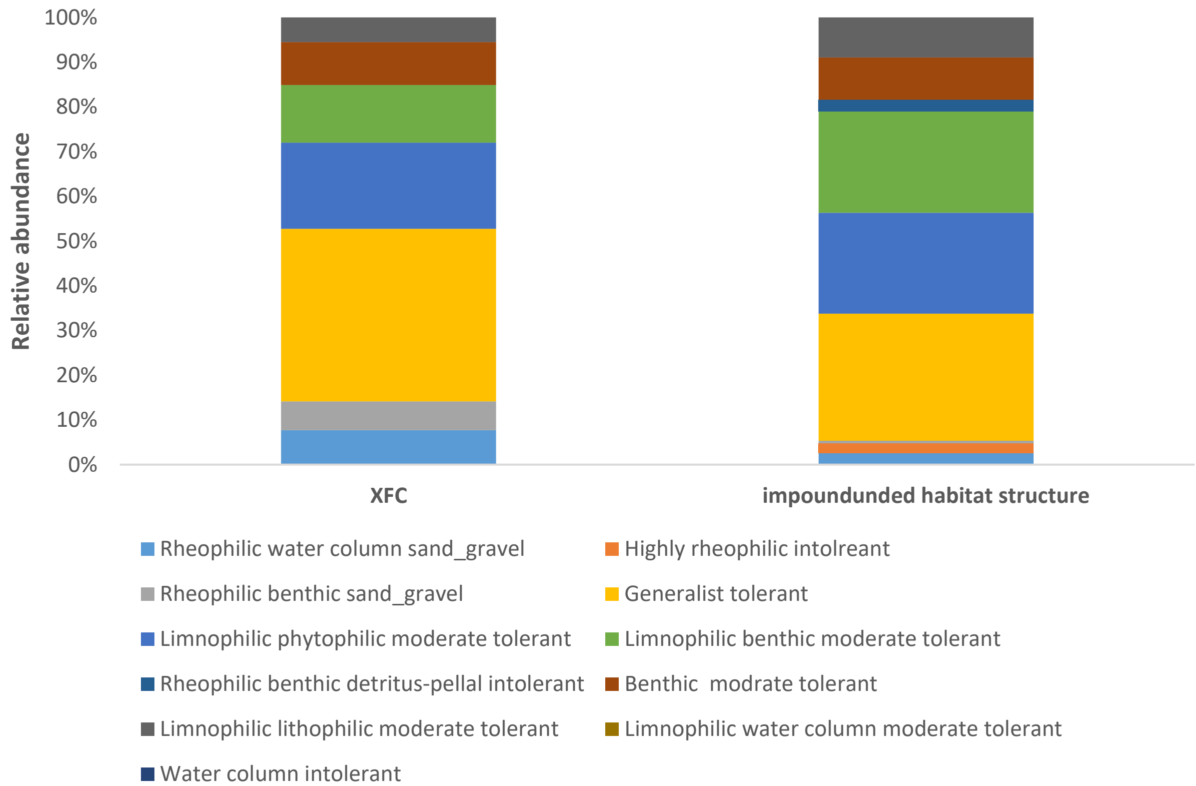


Figure 2.3.51. Comparing observed fish community structure downstream of the dam and habitat structure in the impoundment.

Downstream channel alteration, which reduces the braiding channel form of the Vistula further contributes to this change. Although less commonly that in the past, the impact of alteration of geomorphology is further exacerbated by erratic flow fluctuations and effects on water quality. Such events were observed during the study with one example of temporary raising flows for transportation purposes and second turning off the river flow for several days of maintenance of auxiliary dam below the barrier.

The habitat time series and RAA results offered a new insight into available solutions. The option of lowering the dam has not occurred intensively in any public or scientific discussions. As Włocławek Hydropower has been formerly operating in hydro-peaking mode it required large storage capacity. Since it is no longer allowed, lowering of the impoundments appears to be a logical option. Obviously, it needs to be reflected upon potential reduction of water retention capacity and the consequences for drought mitigation with possible investigation of alternative solutions.

From alternatives presented above it is clear that there are few adaptive managements steps that can be implemented:

1) Introducing flow augmentation for the time of drought appears to be the simplest option for immediate action. The scheme tested in scenario 2 is a simple one and its sophistication could be increased by taking into account seasonal flow and habitat variability. Our study focused on summer conditions as these offer the greatest flow limitations. The tendency for extensive droughts observed in Poland recently, justifies this step and may call for more immediate augmentation action.

2) The econd step would be the development of river restoration measures that will create more sidearm and braided channel forms such as those found in the sections upstream of the impoundment.

3) Next implementable option is preparation for lowering of the dam to create impoundment no longer than 20km. At this point reduction of the augmentation scheme can be considered. By that time, it may become clear if the predictions of the climate change models of future flow increases in the watershed materialized and if augmentation should be adjusted or abandoned.

Alternatives for improving fish passage
Downstream of the dam, the River Vistula is a wide river where fish migrations are concentrated in the main current at the left bank. The existing fishpass is placed in the dam pillar on the right side of the power plant. It allows sea trout and vimba to migrate but does not fully solve the problem of migration for all other fish. The auxiliary dam creates a substantial obstacle for many less intensively migrating species. Furthermore, the existing fishpass dimensions are not adapted for the migration of the Baltic sturgeon, which was a keystone species of the River Vistula and is currently in process of reintroduction. Therefore, it’s necessary to consider additional migration devices, allowing all fish species to easily and quickly find migration routes the dam in Włocławek. Here are ongoing consideration regarding adaptive management alternatives to improve fish passage.

Universal fishpass on the left side of the power plant
One of the proposals is to build another technical fishpass adapted to the passage of various species of fish and aquatic organisms, including small sturgeon individuals on the opposite side of the power plant. One of the turbines of the power plant can be used to obtain an attraction current. An important consideration removal or reconstruction of the auxiliary barrier to support the dam stability, which currently limits the access to the fish ways at the low flows.

The use of the navigation lock as a fish pass
Another option is to adapt the navigation lock to the needs of fish migration. It could be important for large species as a sturgeon, or massively migrating species like vimba. Other species of fish of the the

River Vistula will also use this route. The basic condition for the effective work of the navigation lock as a fishpass, is appropriate attraction flow. This solution will offer an additional fish migration route in downstream direction. This can be a problem during normal use of the shipping lock, so this solution needs some reconstruction of the device.

Installation of a lift for fish
An alternative variant for transferring fish upstream may be establishing a lift for fish on the left side of hydroelectric power plant. At the upper water, the fish raised by the elevator will have to be taken out to the reservoir through a channel of a fishpass. However, that solution is technically difficult to implement, and its efficiency is relatively low, therefore the installation of a fish lift should be considered only when other solutions cannot be used.

The Zuzanka Channel as a bypass of the Włocławek dam
Final alternative is the construction of a bypass channel using the existing canal on the left shore. The Zuzanka canal offers an attractive option for bypass creation with the entrance at the left shore, below the stabilizing stone ramp (in a part of the river channel where main flow through power plant turbines is located) and exit to the reservoir about 3km above the dam (**Figure 2.3.52**). There are also plans to build a canoe track adjacent to the lower section of the fishpass that will supply additional water for attraction flow.

The nature-like bypass channel should be shaped as a small, natural river, with sequences of pools and riffles, diversified riverbed morphology, gravel bottom. The channel slope should also be diversified: lower gradient in the upper part and higher in the lower part, close to the entrance (to assure sufficient attractive current). Such construction of the channel will assure not only migration route, but also habitat and spawning grounds for lithophilic fish species, as barbel (*Barbus barus* L.), asp (*Aspius aspius* L.), dace (*Leucicus leuciscus* L.), chub (*Leucisus cephalus* L.), stone loach (*Barbatula barbatula* L.) and river lamprey (*Lampetra fluviatilis* L.). The prefaced location of this bypass channel is at the left shore of the the River Vistula, along existing higly modified Zuzanka stream.

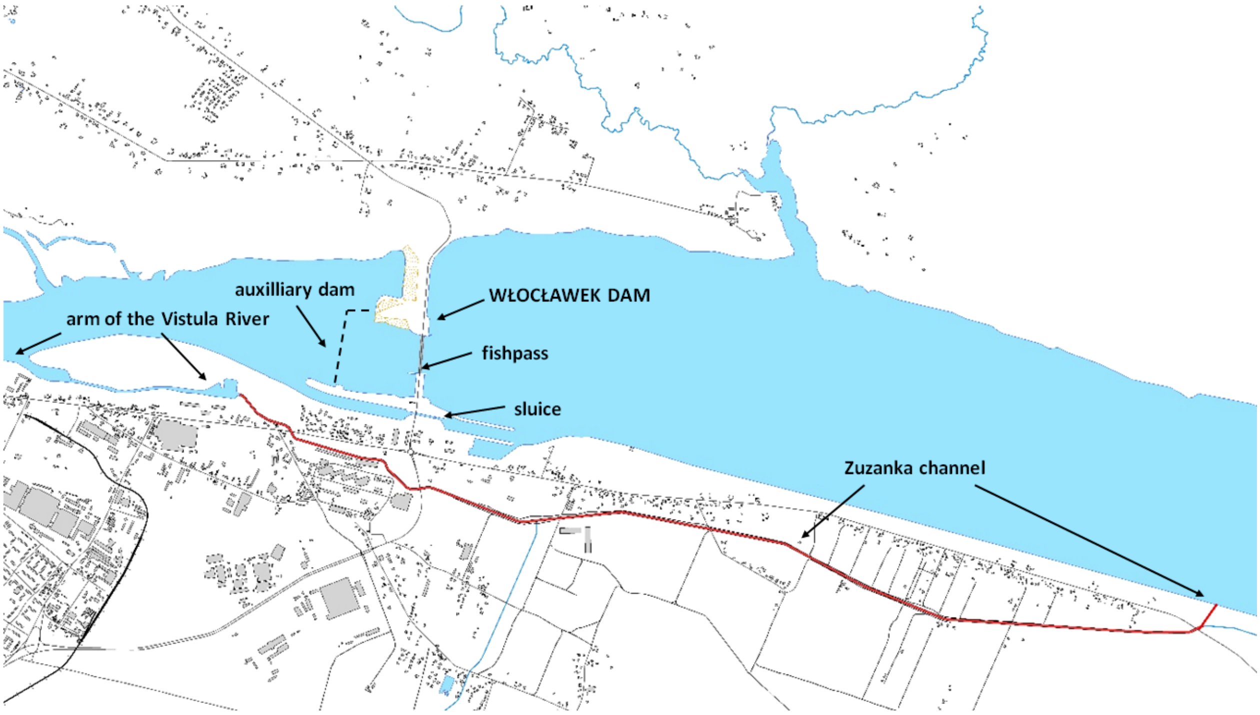


Figure 2.3.52. Map of planned seminatural bypass channel (marked with the red line, Zuzanka Channel) at Włocławek Dam on the River Vistula (Wiśniewolski 2020).

A3 BARRIER REMOVAL

A3.1 CASE STUDY 6: Clondulane and Fermoy Weirs, Munster Blackwater

A3.1.1 Background and current status of Clondulane- and Fermoy Weir

The Munster Blackwater is one of Ireland's largest rivers and famous for wild Atlantic salmon fishing. It is listed as a Special Area of Conservation (SAC) under the EU Habitats Directive for a range of habitats and species, including the diadromous species Atlantic salmon (*Salmo salar* L.), river lamprey (*Lampetra fluviatilis* L.), sea lamprey (*Petromyzon marinus* L.) and Twaite shad (*Alosa falllax* Lacepéde)). The main river has two weirs, large by Irish standards at approx. 2.5m head height, in the first 30 km of channel upstream of the tidal limit. The first weir (Clondulane) is approx. 25km upstream of the upper tidal limit and the second weir (In the town of Fermoy) is approximately 5km upstream of Clondulane. The first weir impounds water almost all the way up to the second weir. Both weirs were built to power mill wheels for agricultural actions – milling etc. over 150 – 200 years ago. Both are now derelict from that point of view. Both had fish pass structures in them – essentially for upstream-migrating salmon only.

IFI undertook fish passage surveys on structures (SNIFFER survey) in 2014, examining approx. 4 transversals or possible fish passage routes over each structure. Both weirs were either *Impassable* or *high risk* to salmon and lamprey at the time of survey. As with the fish pass structures on many large

Irish weirs, the structures installed in the Clondulane and Fermoy weirs were recorded as problematic to fish passage in the survey conditions (Barry et al. 2018).

In terms of 'recent' history, the Irish Minister of government declared the first weir, Clondulane, to be derelict, under national fisheries legislation, and ordered that it be removed in 2006. This decision was upheld in the Irish High Court. The Fermoy weir is locally important as a rowing club, of long standing, uses the flat impounded water upstream of the weir. The town of Fermoy had a flood relief scheme designed and built within the last ten years. At the time of design, the Fermoy weir was considered to be in a poor state of repair and a major mitigation proposal involved the installation of a rock ramp and the rendering safe of the weir. This would allow for fish passage. There was a level of objection locally to any lowering of the water surface level upstream of the weir, a general consequence of rock ramp design, and the rock ramp plan was abandoned. Some local interests now want money spent to fix the weir – one argument is that removing the weir would have a damaging effect on the upstream migrating salmon. This argument is difficult to understand. An alternative plan was that a fish-friendly by-pass channel would be constructed instead of a rock ramp. This is a positive idea but, in fact, the length of ground available for the proposed by-pass is such that any final by-pass channel would not look very unlike an elongated rock-ramp. In addition, the feed of water to any by-pass channel would also lead to a lowering of the head level retained by the current weir. As per previous objections, this would lead to a slight lowering of the water levels for upriver rowing activities. It has been contended at all times by those advocating mitigation measures for the Fermoy weir that the lowering of head level to facilitate any rock ramp would not in any way prejudice the recreational and competition usage of the impounded water upstream of the existing weir.

Proposals in regard to the two barriers of interest on the Munster Blackwater are currently being processed through national planning legislation, separately from the AMBER programme. It was originally envisaged that timelines would facilitate pre-and post-impact studies on the relevant fish communities and the physical habitat as part of the AMBER project.
It was envisaged that the AMBER socio-economic survey would be canvassed among stakeholders in the catchment area. However, this was not proceeded with due to on-going legal engagement in regard to the proposed removal and mitigation actions for the two weirs in this study. Much of the social attitude to these structures can be gauged through examination of internet coverage of these items.

It is unlikely at this stage that removal or mitigation will be undertaken in the case of either weir in this case study during the lifetime of AMBER, despite the extended time interval since removal was pronounced on by the Irish High Court. There is a clear impression among some stakeholders that the weirs are of importance for the ecology of Atlantic salmon in this catchment. Thus, it is problematic to convey the benefits for species dispersal provided by removal of obstacles to upstream passage. The Fermoy weir is one where adaptive management issues are particularly pertinent, given that a valuable local recreational amenity, a long-established rowing club, avails of the access to a flat surface of impounded water for training and regattas. However, the installation of a rock ramp, which would be designed to permit passage of migratory fish species, has also been argued against locally. The concern lies in the perception that a lowering of water surface level upstream, necessary for year-round flow through the rock ramp structure, would adversely impact on the surface levels of water available for recreational rowing.

Flood events in the winter-spring period of 2018-19 have caused damage to the Fermoy weir, leading to a breach at the downstream right bank and a consequent lowering of head level of water flowing over the weir. The entire medium – low flow volume discharge is now passing through one section of the overall structure and mimics, in essence, the appearance of a rock ramp but at a considerably lower stage level or Ordnance Datum level than any rock ramp that might be installed. The focussing of flow has exposed much of the current weir infrastructure and shows the extent of structural work that would be required to maintain the integrity of the structure. A re-survey of the structure for fish passability, using the SNIFFER protocol, may be appropriate during low flow if velocities and bed conditions permit accessing into the flowing water in conditions suitable on Health and Safety grounds. Prior to recent breaching, the Fermoy weir created an impounded section of river extending upstream for approximately 4km. A degree of this impounding impact has now been removed and this has led to exposure of natural gravel beds and re-emergence of natural riffle – glide – pool sequences in the channel close to Castlehyde.

In summary, the lower weir, at Clondulane, is currently the subject of Planning Permission with the local authority. The order of the Irish High Court remains in place. The current situation with the Fermoy weir is such that some measures are required to maintain the integrity of the overall structure. The weir structure extends through and under the existing main road crossing into the town, formerly the main National Primary route linking the cities of Dublin and Cork. Ongoing 'unravelling' of the weir structure may lead to hydraulic pressures on the bridge structure. Any works programme that is decided on must take account of the requirements of the SAC designation of the River Blackwater for Atlantic salmon, sea- and river lamprey and Twaite shad.

A3.1.2 Background on migratory fish species in the Munster Blackwater

The Munster Blackwater is one of Ireland's largest catchments with a surface area of 3,300km^2 and a main stem length of 168km. The catchment flows in an essentially west-east direction and follows the geology pattern of the Old Red Sandstone underlying the catchment. At its tidal extremity the channel turns sharply south and discharges to the sea at Youghal Bay. The principal population centres are in Fermoy (6500 as of census 2016) and Mallow (12,500 as of census 2016). The catchment is largely agricultural with associated major agri-food industries established. The Munster Blackwater is a major Irish salmon commercial and rod angling fishery. The commercial draft net and snap net fisheries on the Munster Blackwater recorded a catch of 1,539 salmon in 2017 (>20% of the overall commercial salmon landings for Ireland). The Munster Blackwater has yearly rod catches exceeding 5,000 fish with a large number of private or club waters located on the lower sections of the river attracting large numbers of tourist anglers to the area each year. Eel populations have been monitored and recorded in good numbers both in the estuary and into the freshwater. Sea lamprey enter the Munster Blackwater annually and have been found, in a recent eDNA study (Bracken *et al.* 2019), to penetrate to considerable distances. Float-over redd count surveys have shown a limited level of penetration upstream of the two major weirs – Clondulane and Fermoy (King and Linnane 2004). Twaite and Allis shad have been taken as bycatch in the estuary of the Munster Blackwater (King and Roche 2008) and, in recent years, by angling in the upper tidal waters of the Blackwater with juvenile fish captured in surveys of the estuary. Sampling by AMBER staff in 2017 found Twaite shad in large numbers at Lismore Castle, immediately downstream of a large, derelict weir that had a central breach. Individual reports of Allis shad have also been recorded in the Munster Blackwater, the two recorded samples both being taken on rod-and-line in the angling fishery downstream of Clondulane weir.

A3.1.3 Investigations within AMBER

Fish community investigations in deep-water impounded riverine segments

Pre-modification data on fish density was collected in 2017 using boom boat electro fishing in the deep, impounded channel segments and conventional boat- based or wading- electric fishing in natural sections, depending on water depths. Replicate sites were sampled in each water body type in both of the impounded sectors and in the natural river regime upstream of both impounded areas. In all cases, site information was compiled on water depth, bed material, riparian habitat and on emergent and instream vegetation. Fish community composition was examined with all species recorded and measured for length. This data was also used for the MesoHABSIM study (A3.1.8).

Channel width and depth, along with uniformity of habitat created by the impounding effect, prevented a whole-channel sampling in the impounded areas. For each impounded site, fishing consisted of a series of linear transects, parallel to the riverbank, each transect being of circa 200m length. Within each transect, the electric fishing gear was activated for a minimum of 10 seconds at set intervals of 2-3 boat lengths. Catch tends to be instantaneous and maximum gear activation time is dependent on the number of fish encountered. The protocol assumes that the multiple activations within each transect captures the range of species and life stages using the habitat at that transect. All fish were collected, processed and returned within the site at end of each transect. All fish were processed on board, length (cm) and weight (g) and scales samples taken before being quickly released. The team then moved on a suitable distance to the next linear transect to ensure no adverse impact of one sampling event on the next one. The length of impounded channel available upstream of each weir permitted a series of replicate linear transects to be taken.

Generator-powered twin anode electro fishing was performed in the Ballyhooly natural deep sections. Catch Per Unit Effort was calculated as the number of activations / number of fish type captured over the length of the transect. Due to gear differences between boom boat electro fishing and twin anode e-fishing, CPUE's could not be statistically compared. Length distribution of captured species was used to investigate differences in fish composition between impounded and natural sites.

Shallow riffle sections upstream of impounded sections and downstream of impounded sections were electro fished (via backpack). 3 x 10-minute e-fishing sessions were undertaken at each site.
The initial boom boat study highlighted the extent of eel populations and this has led to a detailed survey of this species in the impounded channel segments (Section 3.1.4). The fish community surveys resulted in the capture of 1050 fish from the selected sites, comprising ten species (**Figure 3.1.1**). Findings suggest differences in size structure of some target fish species, with larger resident trout being observed in impounded sections of river in comparison to unimpounded natural sections (**Figure 3.1.2**). According to their relative densities the fish fauna, when combined across habitat types, was dominated by dace (*Leuciscus leucisus* L.), Atlantic salmon (*Salmo salar* L.) and brown trout (*Salmo trutta* L.). Habitat features were broadly similar between the impounded sites with characteristically slow flow in both sections. The mean depths in the areas surveyed in the impounded sections of water at Fermoy= 1.7m and Clondulane= 2.2m with predominantly gravel cobble substrate. The natural deep zones fished downstream of Ballyhooly had slow flows with a mean depth of 1.2m with predominantly cobble gravel substrate. Species richness (Shannon index) for each site was used to investigate the influence of abiotic factors on the fish diversity index. Statistical analysis of fish assemblage data did not find any influence of abiotic factors on fish assemblage throughout the zones surveyed via boom boat electro fishing on the river. No significant difference in Catch Per Unit Effort (CPUE) of dace ($p>0.05$) salmon ($p >0.05$) and trout ($p >0.05$) was observed in the Clondulane and Fermoy impounded zones. Mean length of dace was significantly affected by the habitat variables investigated. There was a significant relationship between dace length and water velocity, with significantly larger dace being observed in the slower moving water ($p<0.05$). Dace abundance and size was significantly affected by habitat features, juvenile dace were found in shallow stretches with frequent instream vegetation

whereas larger dace were observed in deeper stretches with occasional instream vegetation (impounded areas) ($p<0.05$) (**Figure 3.1.3**).

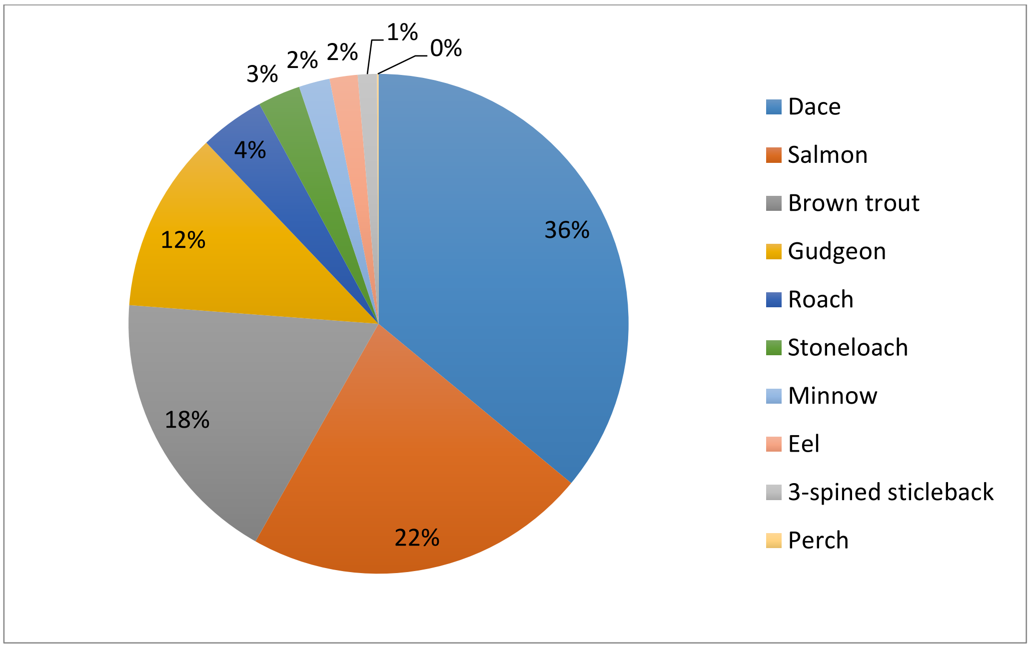


Figure 3.1.1: Fish community composition in Munster Blackwater AMBER sites, 2016

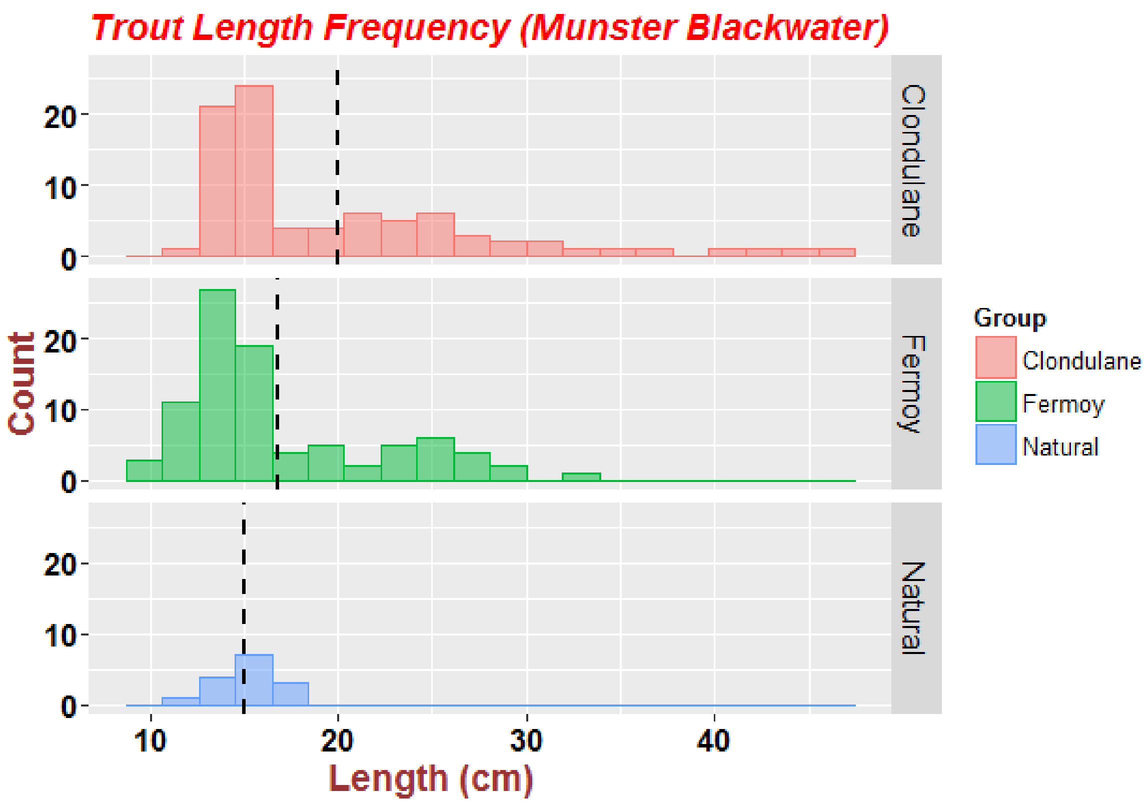


Figure 3.1.2: Length frequency distribuution of brown trout caught in Impounded and natural zones fished. Dashed line indicated mean size.

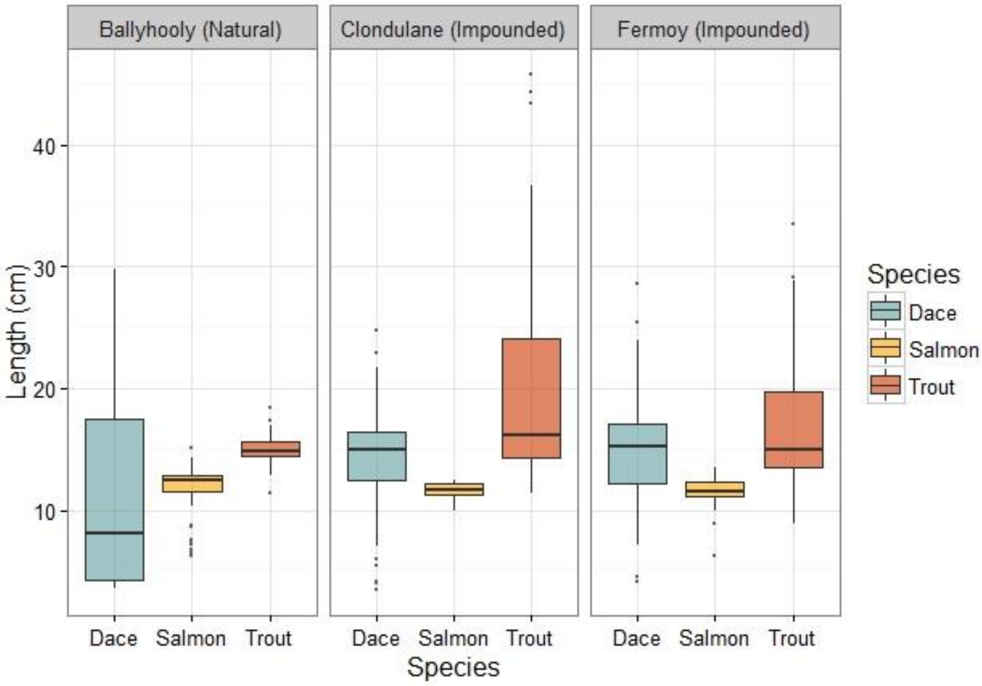


Figure 3.1.3: Mean length box plot distribution of the three most abundant species encountered in the boat fished (twin anode and boom boat) deep water sections along the Munster Blackwater.

A3.1.4 European Eel studies in deep-water impounded riverine segments

The initial fish community study of 2017 identified the appropriateness of a more detailed study on residency of European eel in the impounded channel sections. The Munster Blackwater is a national Index river for European eel. Intensive fyke netting in summer 2017 compiled measurements of length and weight of 717 eel. 583 eel were PIT tagged and the re-survey in 2018 provided data on residency and growth rate for eel in impounded riverine habitat. This eel study was continued in 2019 with further recaptures of eel originally PIT tagged in 2017. It is anticipated that this eel data set will generate a relevant peer-review publication. Collaboration between IFI's AMBER team and its National Eel Monitoring team facilitated a project to conduct a mark recapture study to estimate the eel population in the impounded section of river above Clondulane (4km impounded section above weir split into 3 zones).

- Surveyed for 6 nights in 2017 (Time 1;13th-16th June, Time 2; 20 -23 June)
- Surveyed for 2 nights in 2018 (9 -11 July)
- Surveyed for 2 nights in 2019 (29 - 31 July)

Each zone was fished every night with a single chain of 3 fyke nets (CPUE ranged from 3.8 to 12.33 eels per net per night). A total of 951 eels were captured between 2017 – 2019 (**Table 3.1.1).** A total of 583 eels were tagged with PIT tags (2017 & 2018, eels <30cm were not tagged). The average growth of recaptured eels in 2018 from 2017 tagging (n=19) was 2.8cm with a weight gain 0.310g.

Table 3.1.1. Catch distribution in fished zones and CPUE ranges for European eel fyke netting in impounded section of habitat directly upstream of Clodulane weir.

Year	No of Nights Fished	Total Catch	Zone 1	Zone 2	Zone 3	CPUE Range	No. of Recaptures
2017	6	698	138 (19.7)	168 (24.1)	392 (56.2)	5.80 - 12.33	9
2018	2	139	63 (45.3)	26 (18.7)	50 (36.0)	3.80 – 5.47	19[1]
2019	2	114	28 (24.6)	29 (25.4)	57 (50.0)	3.33 - 11.66	10[2]

A3.1.5 Spatial ecology of dace and brown trout in a shared impounded river reach –telemetry investigation

It was intended to undertake telemetry studies on sea lamprey migration into the Munster Blackwater and to track their responses at the two weirs. The very low run of sea lamprey (n=2 sea lamprey acoustically tagged) in 2017 prompted a re-organising of logistics and the tags and associated listening stations were re-deployed to monitor adult brown trout and dace within the main impounded section upstream of the lower weir at Clondulane. The impact of variations in volume discharge on the range of the two species was also examined. Outcomes from this are pertinent to the MESOHABSIM study also undertaken at this demonstration site.

A fixed receiver array was used to examine the movement patterns and spatial use of habitat by brown trout (native salmonid) and dace (invasive cyprinid) in an impounded section of river over a four month period between August and December 2017 These results provide valuable insights into the spatial and temporal distribution of the two species in an artificially impounded section of river, demonstrating that individuals remain relatively local to their release point and do not exhibit wide ranging movements from late summer into winter. Commonalities in the observed movement patterns were observed among the species despite their contrasting life histories, but there were also important differences observed both in home range and in activity patterns over the duration of the study. In general dace were much more active than brown trout. Both species exhibited a clear crepuscular diel pattern with higher average displacement rates being observed during dawn and dusk periods which remained consistent over the study period (**Figure 3.1.4** – Example from October). Both species exhibited a very high residency within the array (**Figure 3.1.5**), which may be a direct result of the artificial barrier present, promoting residency. Brown trout showed a significant increase in displacement rates and a drop in residency in November which may represent putative spawning behaviour. In general home range sizes remained stable for both species. The results exhibited a biological effect on home range size for dace with larger individuals being more localised then smaller individuals. We propose that the diel patterns observed are primarily driven by foraging activity and opportunity, which changes with seasonal influences, and by onset of potential spawning period and/or overwintering behaviour. This study demonstrates how data derived from acoustic telemetry studies can be used to highlight movement behaviours of fish species associated with fulfilling ecological needs (feeding, shelter etc.) which are regulated by predictable variation in the environment. Understanding the interplay between the environment and an animal's behaviour is important from a conservation management perspective with increasing environmental pressures and predicted regime changes. The findings of this study have been accepted for journal publication (Barry et al In Press).

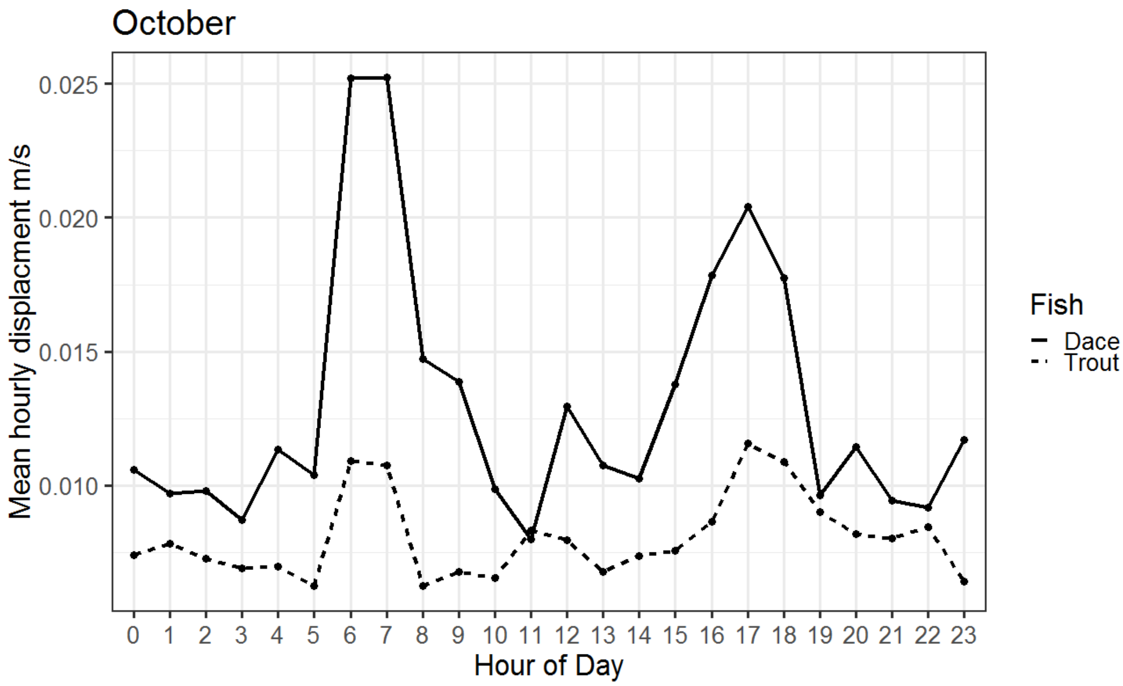


Figure 3.1.4: The displacement rate per hour (facet by month) for Trout (dashed line) and Dace (black line).

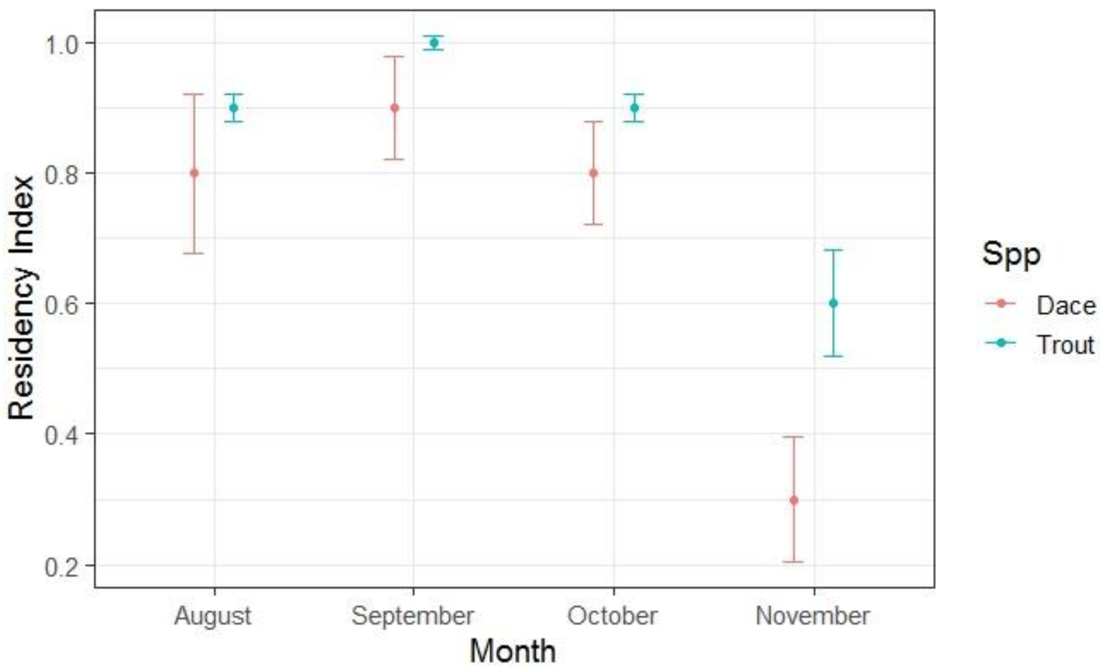


Figure 3.1.5: Residency Index (+/- SE) for Dace (red) and Trout (Blue) over the duration of the study.

A3.1.6 Barrier surveys of the Munster Blackwater and Conservation Objectives for the Munster Blackwater Special Area of Conservation

The two barriers were assessed for fish passage using the coarse-grained SNIFFER protocol. This data formed part of a larger national dataset of in excess of 60 structures used by IFI to compare the UK-led SNIFFER protocol with the French-led ICE protocol for fish passage. The outcomes were presented at the Fish Passage 2017 conference in Corvallis, Oregon, USA and a peer-review paper published, working with AMBER partners from University of Southampton (SOTON) (Barry *et al.* 2018).

The SNIFFER procedure was subsequently used to survey all of the barriers identified in the Munster Blackwater main stem during 2018-19 to provide an overall profile of levels of habitat fragmentation and of impedance to fish migration in regard to sea lamprey and Atlantic salmon (**Figure 3.1.6).** This procedure was also followed in the four other large Irish rivers in the southeast of the country designated as Special Areas of Conservation (SACs) for salmon, sea- and river lamprey and for Twaite shad (**Table 3.1.2**). The combined data will be examined in the context of the Conservation Objectives for these channels – unimpeded passage of upstream migratory species for 75% of the main stem channel length – and an initial examination of issues associated with each structure surveyed. The aim is to generate a review, using an Adaptive Management approach, in regard to the options and issues for each structure in regard to nature conservation, social, cultural/heritage and industrial uses and perspectives on the structures.

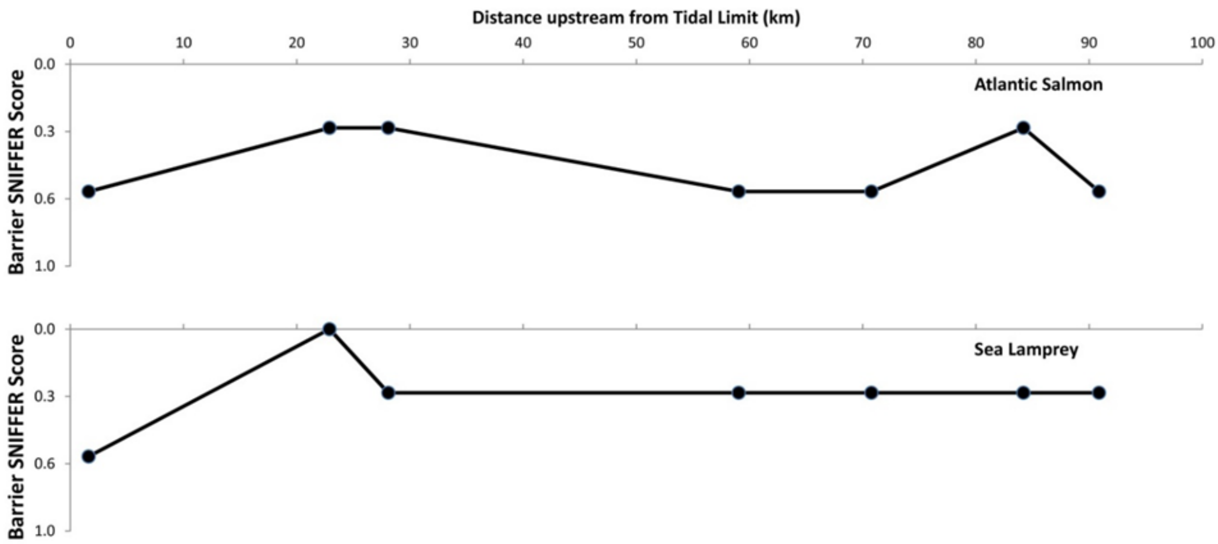


Figure 3.1.6: Atlantic salmon and sea lamprey SNIFFER scores (1.0 = No Barrier, 0.0 = Complete Barrier) for passability at barrier structures surveyed on the main stem Munster Blackwater.

The seven structures shown in **Figure 3.1.6** represent all the barriers (four weirs and 3 bridges) to upstream migratory species for 75% of the main stem channel length of the Munster Blackwater. The four weirs were all constructed in the middle of the 19th century for milling purposes. This activity is no longer taking place and the mill races are defunct. While fish passes are present in each structure all were constructed to facilitate Atlantic salmon passage and all are now in a state of disrepair. These weirs have a total hydraulic head ranging from 0.44m to 2.53m and represent the most impactful structures to upstream fish migration.

Table 3.1.2. Barrier density of the Munster Blackwater and three other SAC channels over 75% of total main stem channel length.

River	75% Main Stem Length (km)	Barrier Number	Barriers per km
Munster Blackwater	124.8	7	0.06
Nore	100.8	10	0.1
Slaney	87.8	13	0.15
Suir	127.5	9	0.07

Barrier density (barrier/km) on the Munster Blackwater, Nore, Slaney and Suir rivers (**Table 3.1.2**) is low by European and British standards. In comparison, an AMBER-based study by Jones *et al*., (2019) estimated barrier density for the UK ranging from 0.48 barriers/km in Scotland to 0.63 barriers/km in Wales, and 0.75 barriers/km in England. The low barrier density in the Munster Blackwater reflects its low-gradient, meandering nature and to a certain extent its importance as a salmon fishing river, where it was possibly more economical to use gradient breaks in the river channel for angling purposes than for generating water power.

A3.1.7 IFI investigations on thermal impact of linear impoundments – AMBER sites and IFI national studies

The issue of thermal impacts arising from impoundment of water upstream of weirs was initially examined by IFI in 2018. A series of temperature loggers were installed in discrete locations both upstream and downstream of the Clondulane weir (**Figure 3.1.7**). This AMBER work complemented a larger thermal study being undertaken by IFI as part of its National Barriers Programme, funded by the state Department of Housing, with installation of a series of loggers in association with three weirs, in channels of different Stream Order, within the catchment of the River Boyne (2650 km^2) on the Irish east coast. Initial examination of data from the Boyne study pointed to a temperature increase in water between 'entry' into the impoundment and 'exit' from it, due to impounding/residency and a reduction of this elevated effect at a discrete distance downstream of the impoundments.

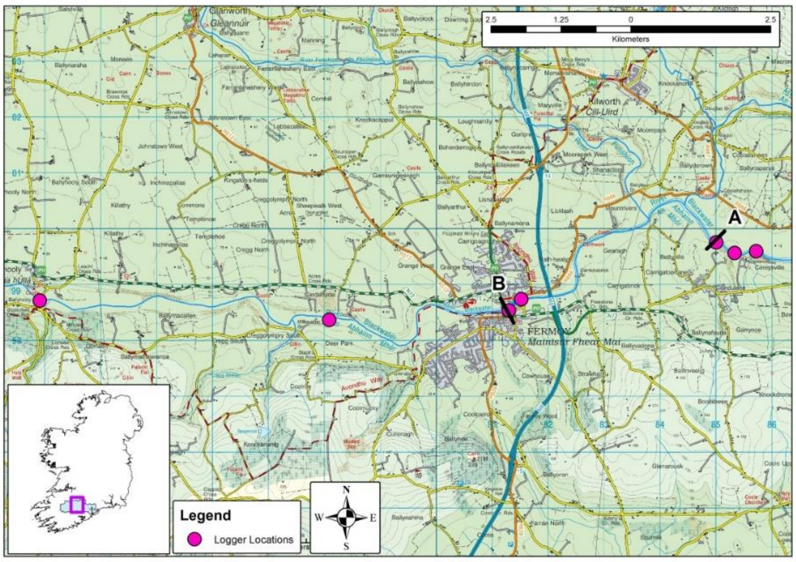


Figure 3.1.7: Location of revised logger locations (2019) in the Munster Blackwater, A = Clondulane weir, B = Fermoy Weir.

This was not apparent in the results for the Munster Blackwater and the experimental set-up was reviewed and altered for 2019 (**Figure 3.1.8**). It was concluded that the 'input' water being recorded entering the impounded Clondulane reach must be influenced by the 'output' water from the immediately upstream Fermoy weir impoundment. In re-designing for 2019, additional temperature probes were installed upstream of the Fermoy impoundment to complement the set of probes monitoring the waters flowing through the Clondulane impoundment

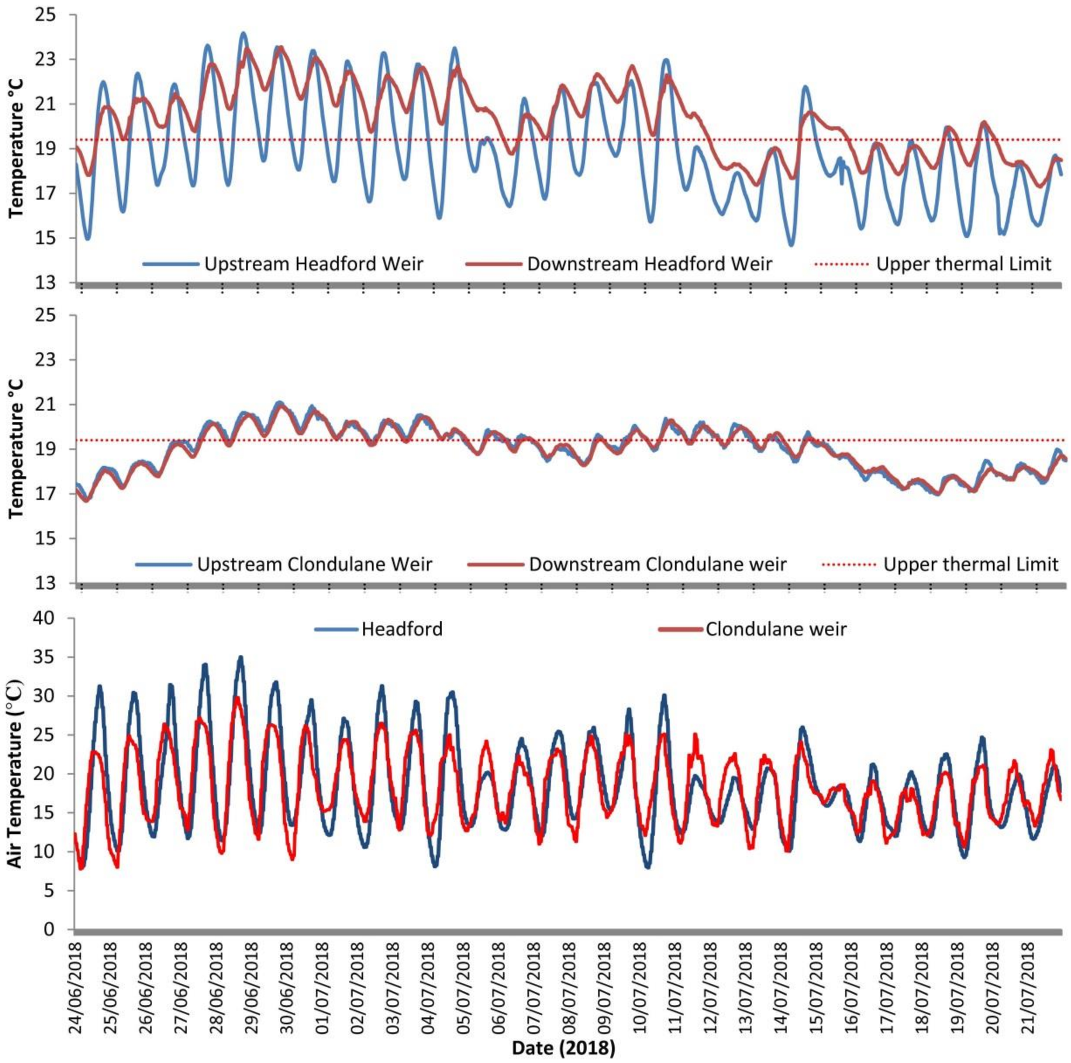


Figure 3.1.8. Fluctuations in water temperature recorded upstream (non-impounded) and immediately downstream of weirs at Headford (Kells Blackwater) and Clondulane (Munster Blackwater) from the 24 June to the 21 July 2018. Daily variations in air Temperature (°C) is also shown. The upper thermal limit for trout 19.4°C represents a threshold which when crossed may affect the long-term well-being of the population.

The thermal studies will provide baseline on the potential impact of temperature increase in impounded river segments. This is relevant in the context of overall climate change and the potential for barrier removal to mitigate for adverse impacts by restoring the natural hydromorphology of the river up- and downstream of the barrier. Elevated flow conditions throughout the winter-spring 2019-2020 period, followed by travel restrictions associated with the Covid-19 virus pandemic have meant that the relevant temperature probes remain *in situ* and information will not be downloaded and analysis undertaken until after the completion of the AMBER programme.

A3.1.8 MesoHABSIM study on the Munster Blackwater

The Polish Inland Fisheries Institute (SSIFI), one of the AMBER partners, is trialling the MesoHABSIM protocol in case study sites within the AMBER project. During the AMBER AGM of 2018, Dr. Piotr Parasewicz proposed to carry out MesoHABSIM surveying on the Munster Blackwater during 2019 (**Figure 3.1.9**). The partial breaching of the Fermoy weir in winter floods during 2018-19 provided a real impetus to the shared work as upstream water level fell sufficiently to expose gravel shoals previously 'drowned' by the weir impoundment.

The initial survey was completed in low water conditions in June 2019 with data collection for a range of elements of the model. These included an allocation of delineated habitat zones within three areas of the Munster Blackwater channel with particular focus on the Fermoy weir breach. The IFI team used drone technology to create shapefile images of the three areas of study and then worked with Dr. Parasewicz to agree on the habitat units. Within each area, replicate fish community composition was undertaken at a number of sites and data on depth-velocity was generated.

Figure 3.1.9: MesoHABSIM work on the Munster Blackwater (Ciara Fleming, IFI National Barriers Programme), James Barry (IFI AMBER), Colm Casserly (UCD Reconnect project), Piotr Parasewicz (Polish Fisheries Institute) and Brian Coghlan (IFI National Barriers Programme).

Fermoy weir breach – background to MesoHABSIM study: The weir location in overall context (**Figure 3.1.10, 3.1.11**) and the river hydrograph provide a context of location and hydrology, with high flood risks and rapid attenuation (**Figure 3.1.12**) for the weir prior to breaching impounded water for a distance of 5km upstream. In 2018, the Fermoy weir fully breached at one side following winter flood events (**Figure 3.1.13**). This rendered the existing fish pass derelict, with all water now discharging through the breach. The breach exposed underlying bed rock and sloped rapids are now the dominant feature through the weir where fish can now safely pass through in all flow conditions. The breach of the weir has altered habitat upstream, lowering water levels considerably and shortening the length of impounded water upstream of the structure. Local stakeholders have identified the need for remedial structural work due to flood relief concerns and the loss of local amenities.

As a result of the sudden change in situation at the AMBER case study site, an opportunity arose to investigate the weir breach in more detail. IFI took the opportunity to better understand the ecological effects of the Fermoy weir breach on fish habitat and modelled different scenarios using Mesohabsim software.

Specifically this study's aims were:

1) To quantify fish habitat availability below and upstream of Fermoy weir using measurements of physical conditions, including aerial mapping of habitats (using drones and satellite imagery). These results are used for modelling of environment changes and habitat loss/gain/change.
2) Within the AMBER framework, model the ecological effects of different management scenarios including; a) leaving river in current condition b) re-building Fermoy weir c) 'river restoration' to facilitate different requirements (Adaptive Management approach)
3) Using tools developed by AMBER (aerial imaging, habitat maps, habitat suitability models) as a decision support for management of the lower Munster Blackwater for migratory fish restoration in the whole catchment.

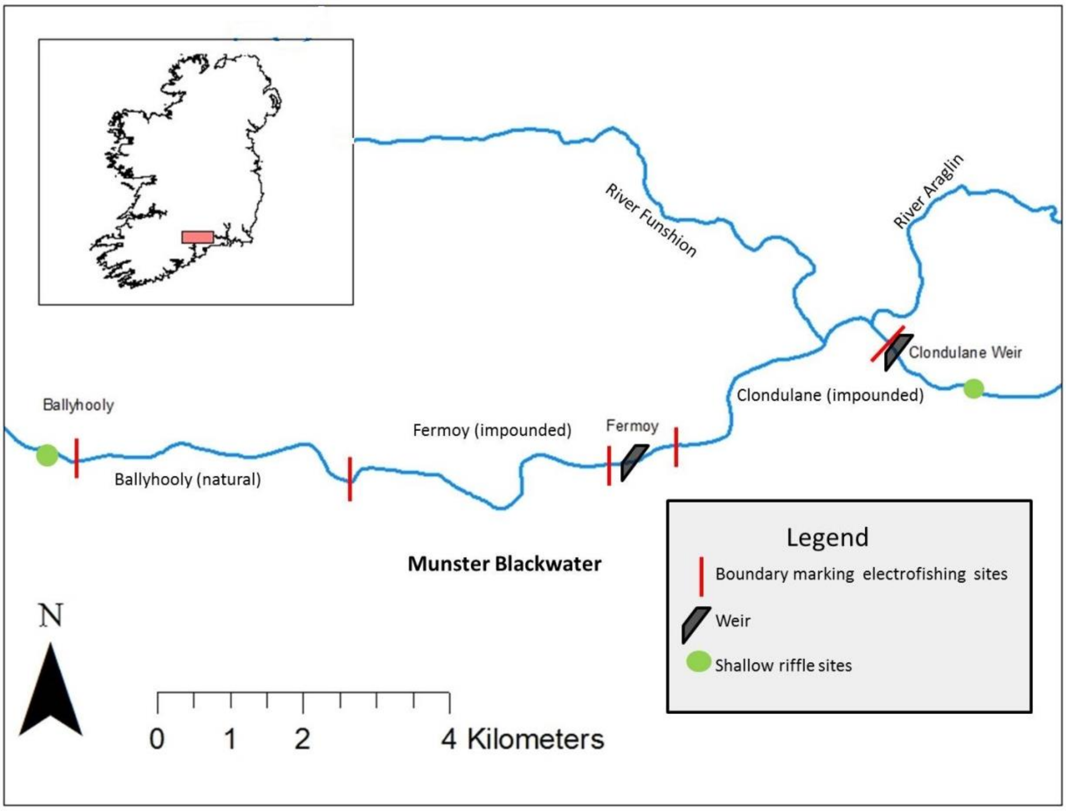


Figure 3.1.10 Map of Munster Blackwater River and location of Fermoy weir and Clondulane weir.

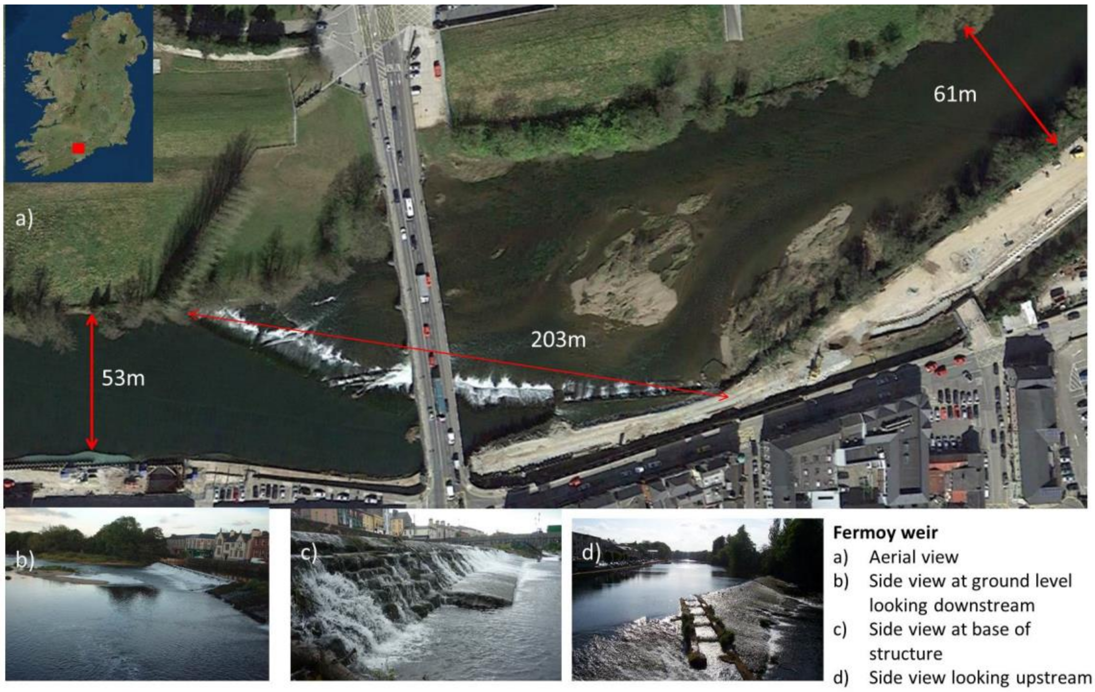


Figure 3.1.11 Fermoy weir measurements (pre breach).

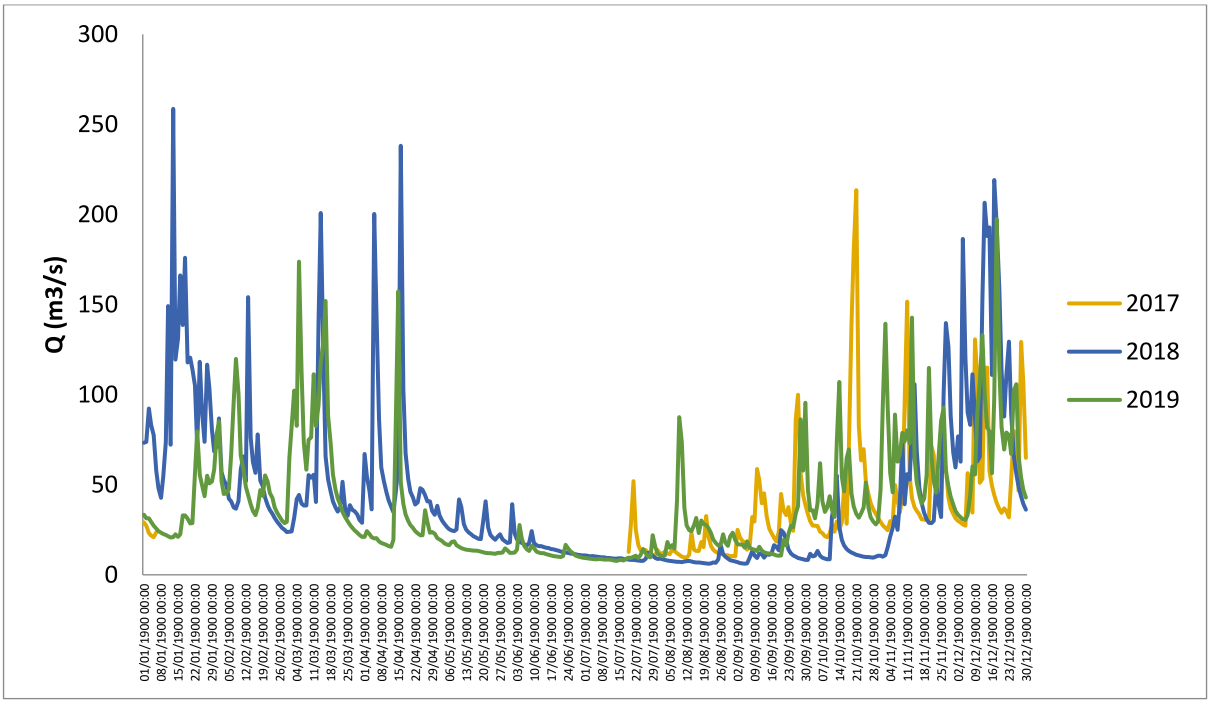


Figure 3.1.12 Hydrological conditions of the Munster Blackwater in years 2017-2019 (Jan – Dec LHS to RHS).

a)

b)

c)

Figure 3.1.13 Fermoy weir a) 2016 (fully intact weir); b) 2018 (initial breaches on RHS) and; c) 2019 (full weir breach on RHS with mimicing of 'rock ramp' facilitating migratory fish passage).

Munster Blackwater Habitat Study Sites: For the purpose of the study of the weir breach impact on fish habitat, the study area of the Muster Blackwater was divided in 3 sections:

- Site 1: Riffle – glide – pool habitat upstream of Fermoy weir (~6km) re-exposed following the breach
- Site 2: Impoundment area with newly formed habitat post-weir breach upstream of Fermoy weir (~2.5km) witihin predominantly impounded zone
- Site 3: Downstream Site: Morphologically altered habitat directly downstream of Fermoy weir

Figure 3.1.14. 3 sites on the Munster Blackwater. The Weir is located on the boundary between site 2 & 3.

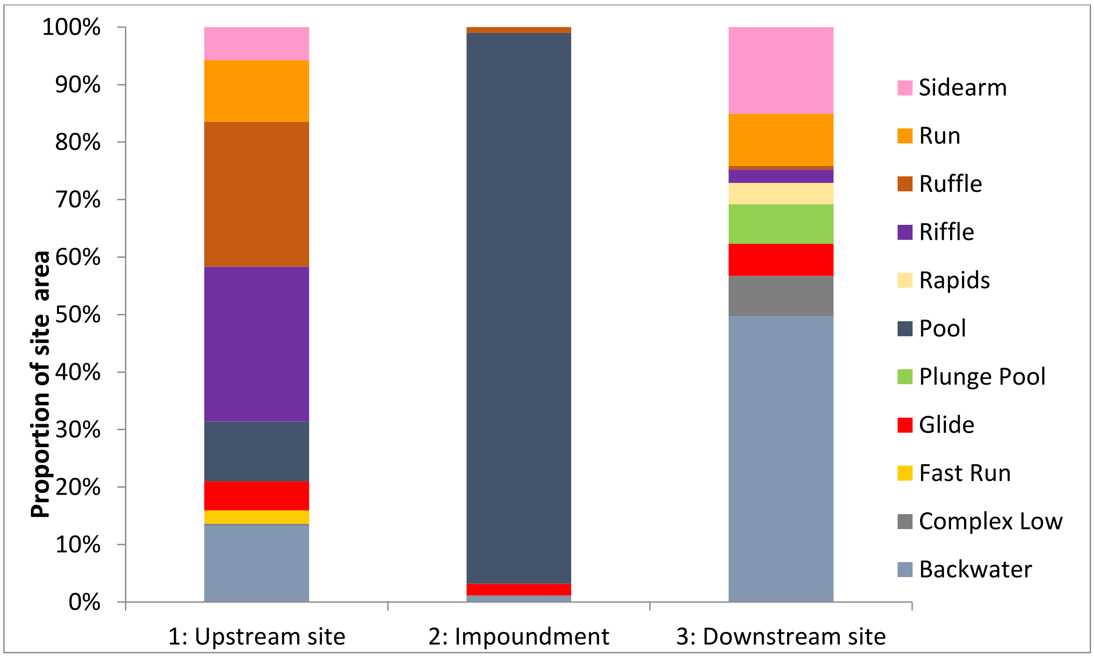


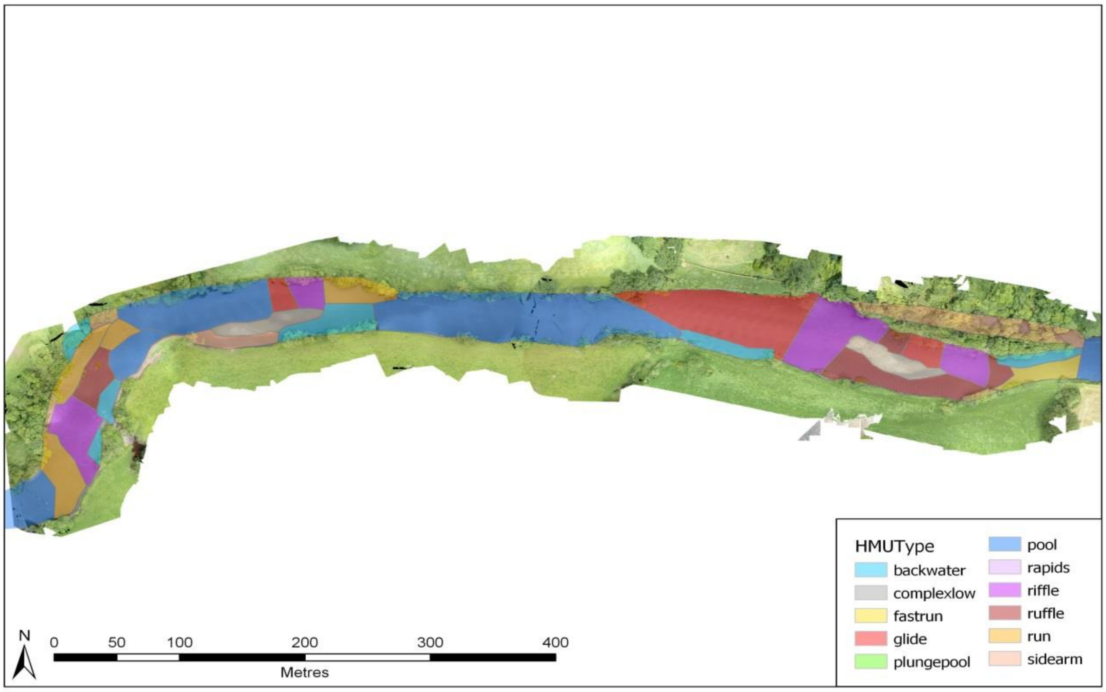
Figure 3.1.15 Distribution of hydromrphologic units (HMU) in study sites.

Implementing MesoHABSIM - Field data collection:

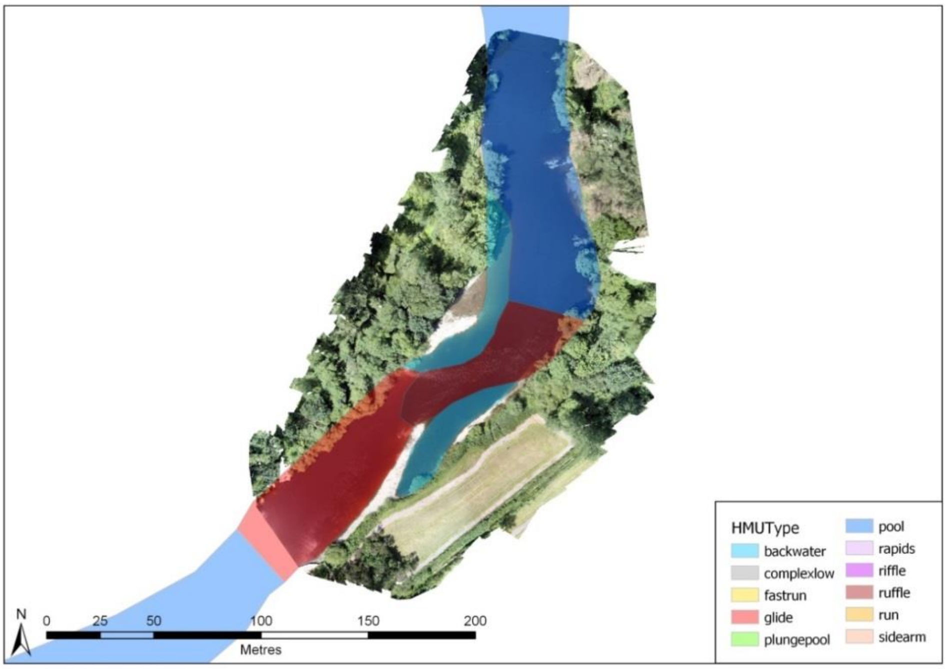
Hydromorphological Unit (HMU) mapping: Habitat data was collected at three sites in the river (**Figure 3.1.14**). Spatial distribution of fish habitat was mapped during 2 low flow conditions equivalent to specific flows of 5.52 and 6.11 l/s/km^2 (lskm2). Lightweight unmanned aerial vehicles (Phantom 4 Professional) were used for habitat data collection (Woodget et al. 2017). Aerial pictures allowed for identification of hydromorphologic units, bottom substrate in shallow areas, submerged vegetation, branches, debris and other cover source for fish. The aerial imagery was associated with hydraulic data (depth and flow velocity). ESRI Survey 123/ Collector software was used for image annotation in the field.

The habitat mapping was conducted in post-processing on GIS platform. The MesoHABSIM method (Parasiewicz 2008ab, Parasiewicz and Adamczyk 2014) was applied to identify hydromorphological units (**Figure 3.1.15 & 3.1.16**). The distribution of bottom substrate was mapped according to the Austrian Standard ÖNORM 6232 (see breakdown in **Table 3.1.1**).

Site 1



Site 2



Site 3

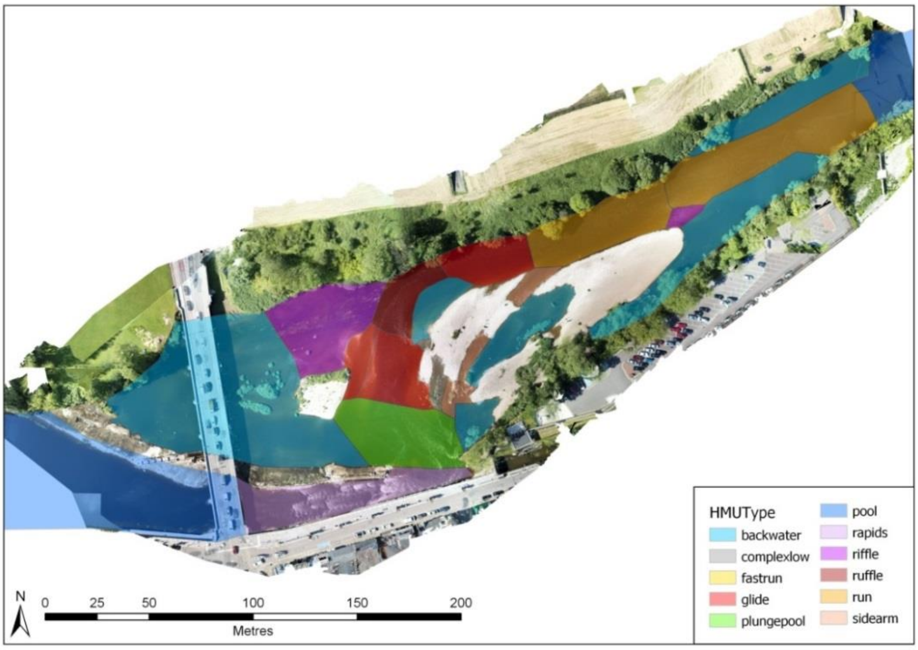


Figure 3.1.16 Hydromorphological units on the Munster Blackwater at lowest water flow conditions: at Sites 1 & 2 upstream of Fermoy weir and Site 3 directly downstream of Fermoy weir.

Fish sampling: Standard electrofishing techniques have been applied to sample habitats for fish in all sites. Due to the size of the river and gear selectivity, the deep fast flowing areas were sampled around the shore areas and, where appropriate, data from boom boat electrofishing surveys undertaken by IFI in 2016 were used, which provided species composition in deep pools and impounded habitat in the Munster Blackwater (Section 3.1.1). Fish samples were processed at the location, measuring length and weight of each individual.

Substrate types were collected following the MesoHABSIM protocol (**Table 3.1.3**).

Table 3.1.3 Substrate types were collected following the MesoHABSIM protocol.

Substrate type	Description
Akal	Medium to fine gravel (0.2 – 2 cm)
Gigalithal	Bedrock substrate
Macrolithal	Coarse blocks: mix of cobbles gravel and sand (20-40cm)
Megalithal	Large cobbles (>40cm)
Mesolithal	Fist to hand sized cobble (6-20cm)
Microlithal	Coarse gravel with mix of fine gravel (2-6 cm)
Peial	Silt, clay and suldge
Psammal	Sand (0.06 – 2mm)
Sapropel	Organic sludge

Expected fish community habitat distribution for the Munster Blackwater in the study area was estimated from Fish Community Macrohabitat Types (FCMacHT) map created in the AMBER project (Parasiewicz et al., in prep). The Munster Blackwater corresponded with the FCMacHT Highland Medium sediment rivers, which provided target proportions of habitat for Habitat Use Guilds in expected natural fish community (**Figure 3.1.17**). To verify model predictions and potentially adjust the model, additional fish data collection has been conducted in the reference section of the study area. Based on the observations of fish presence and on expert assessment of the ranking of the Habitat Use Guilds in the community, expected habitat proportions were adjusted by applying the Target Fish Community model to recalculate expected habitat proportions (Bain and Meixler 2008).

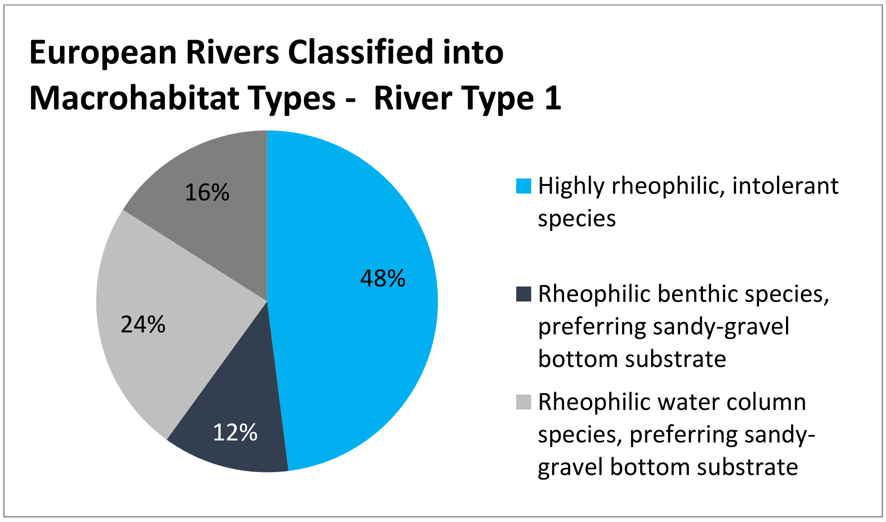


Figure 3.1.17 Expected proportions of macrohabitats in the FCMacHT of Central European Lowland, Medium Sediment Rivers.

For determination of habitat suitability for fish communities, suitability criteria were established from literature information. Using the Conditional Suitability Criteria Approach of MesoHABSIM the preferable ranges of substrate, depth, velocity, cover and hydromorphologic units (HMU) are specified.

HMU and Fish data*:* A total of 27 hydromorphologic units and 8 different HMU types were sampled. To take into account the unit sampling bias, the proportion of captured guilds are weighted with the proportion of the area of each unit type represented in the study sites. For determination of the proportion of the guilds in existing fish communities (XFC), the guilds were ranked according to their abundance. Then the proportions of the reciprocal rank values were used to calculate existing fish community structure. Such processed data could be compared with the structure of the expected fish community.

The data was also used for model validation purposes and each sample compared with predicted habitat suitability. The sampled habitat units were classified into unsuitable, suitable and optimal habitats and these classes compared with the abundance of fish in a sample. If less than a 25-quantile of individuals observed in all samples for one guild was captured at one location, the fish was considered to be present only. Otherwise it was either absent or abundant. The proportions of unsuitable, suitable and optimal habitat were plotted for each of the abundance classes for all fish guilds together, expecting a higher share of suitable habitat in areas where fish were captured.

Sim Stream
The Sim-Stream Software of the Rushing Rivers Institute was applied to organize collected habitat data and to calculate the amounts of suitable habitat area for each guild presented on habitat suitability maps. Every mapped unit was colour coded as unsuitable, suitable and optimal habitats.

Management scenarios for the Blackwater
To evaluate the consequences for fish habitat of different management options for Fermoy weir 3 scenarios were developed:

Scenario 1 – current conditions (weir breach)
Scenario 2 – re-building the weir to former state
Scenario 3 – current hydromorphology but introduction of dynamic habitat restoration at key sites

MesoHABSIM outcomes - Fish Data
The breakdown of fish species into the various fish guilds (**Table 3.1.4**) refers to the total of 1,179 individual fish captured in 8 types of hydromorphologic units (backwater, complexhigh, fastrun, glide, pool, run, ruffle and sidearm) during the overall study. Relative abundance of captured guilds observed in each HMU type were weighted by proportions of HMU type areas occurring during the sampling time. These values were ranked to calculate the existing fish community model (XFC).

Table 3.1.4 Breakdown of species guilds.

Species	Common Name	Guild
Salmo salar	Atlantic Salmon	Highly rheophilic, intolerant species
Salmo trutta trutta	Brown Trout	
Salmo trutta fario	Sea Trout	
Lampetra fluviatilis	Brook Lamprey	
Gobio gobio	Gudgeon	Rheophilic benthic species, preferring sandy-gravel bottom substrate
Barbatula barbatula	Stone Loach	
Phoxinus phoxinus	Minnow	Rheophilic water column species, preferring sandy-gravel bottom substrate
Leuciscus leuciscus	Dace	
Anguilla anguilla	European Eel	Generalists - tolerant species
Gasterosteus aculeatus	Three-spined stickleback	

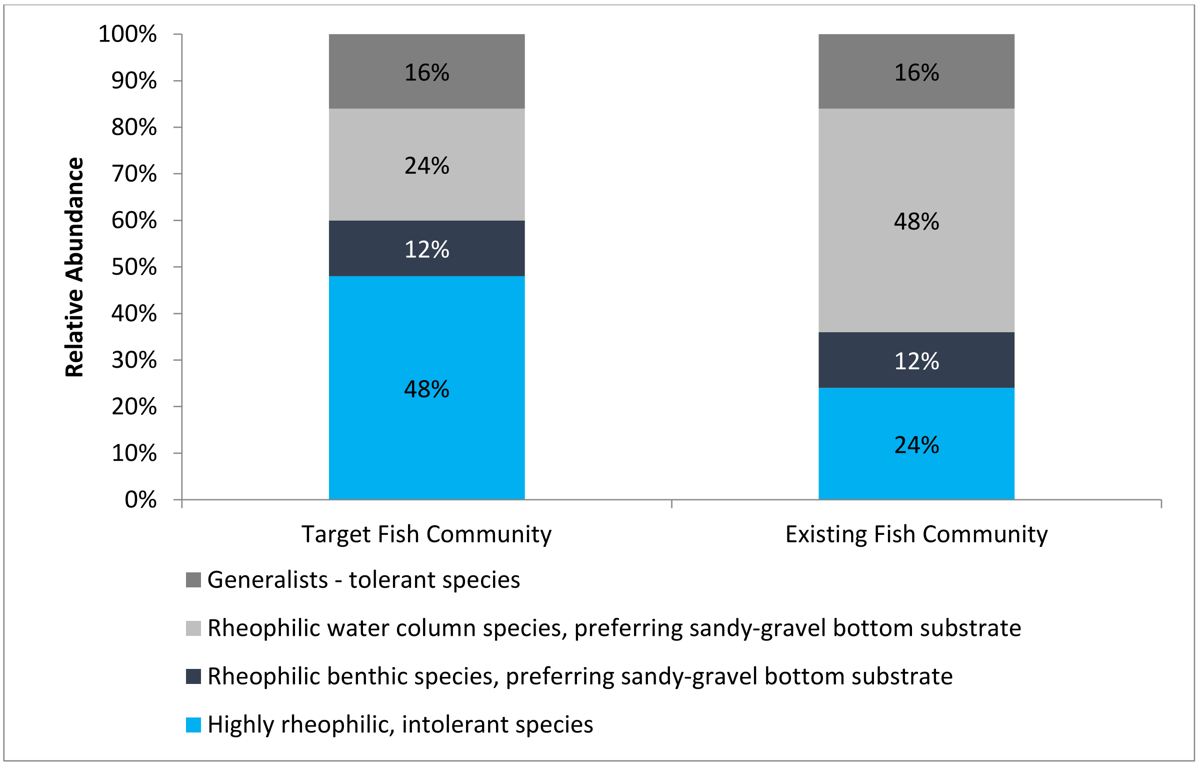


Figure 3.1.18 Comparison of Target Fish Community and Existing Fish Community Structure.

The existing fish community (XFC) match to the fish community expected according to FCMacHT (Target Fish Community – TFC) (**Figure 3.1.18)** indicaties a strong overabundance of rheophilic water column species, 24% higher than expected for this river type based on the HMU units surveyed.

Habitat Use Criteria

Table 3.1.5 Conditional Habitat Use Criteria for the guilds occurring in the Munster Blackwater. The attributes in bold are critical for guild presence and those in red are reducing the area suitability.

No	Fish Guilds	Depth [m]	Velocity [m s^{-1}]	Choriotope	HMU Type	Covers
1	**Highly rheophilic, intolerant species**	0.50-1.5	0,3-1,2 (max. 2,0)	gigalithal megalithal >40 cm, makrolithal 20-40 cm, mesolithal6-20 cm, microlithal 2-6 cm, psammal, akal	riffle, ruffle, cascade, rapid, fast run, plunge-pool, pool, glide, sidearm	boulders, woody debris
2	**Rheophilic benthic species**, preferring sandy-gravel bottom substrate	0,3-2,0	0,3-0,1.5	megalithal >40 cm, makrolithal 20-40 cm, mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, xylal, pelal, sapropel	riffle, ruffle, cascade, rapid, fast run, run, glide, plunge-pool, pool,	boulders, undercut banks woody
3	**Rheophilic water column species**, preferring sandy-gravel bottom substrate	0,5-4,0	0,15-0,7	mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, xylal	run, fast run, pool, plunge-pool	undercut banks woody
4	**Generalists** - tolerant species	0,25-4,0	0,0-0,45	mesolithal 6-20 cm, microlithal 2-6 cm psammal, akal, debris, pelal, sapropel, xylal	run, pool, glide, sidearm, backwater	woody debries, undercut

Model Verification
In total 27 hydromorphologic units were sampled for fish in the Munster Blackwater sites. The proportions of not suitable, suitable and optimal habitats occurring in the areas where fish were not captured, present or abundant (**Figure 3.1.19**) indicated increased fish numbers with an increase in the quantity of suitable habitat. 25% of the samples were missing at least one guild and 41% of those within suitable and optimal habitats were missing a guild. No HUM had no fish present, the lowest number of fish captured in an HMU was two, the average was 44 (S.E. 3.9). Highly rheophilic, intolerant species were only absent from two HMU's with optimal habitat and from six HMU's with suitable habitat. From 54% of high abundance samples, 52% is in optimal habitat and only 10.7% in not suitable habitats. This documents a good level of model performance (**Figure 3.1.19)**.

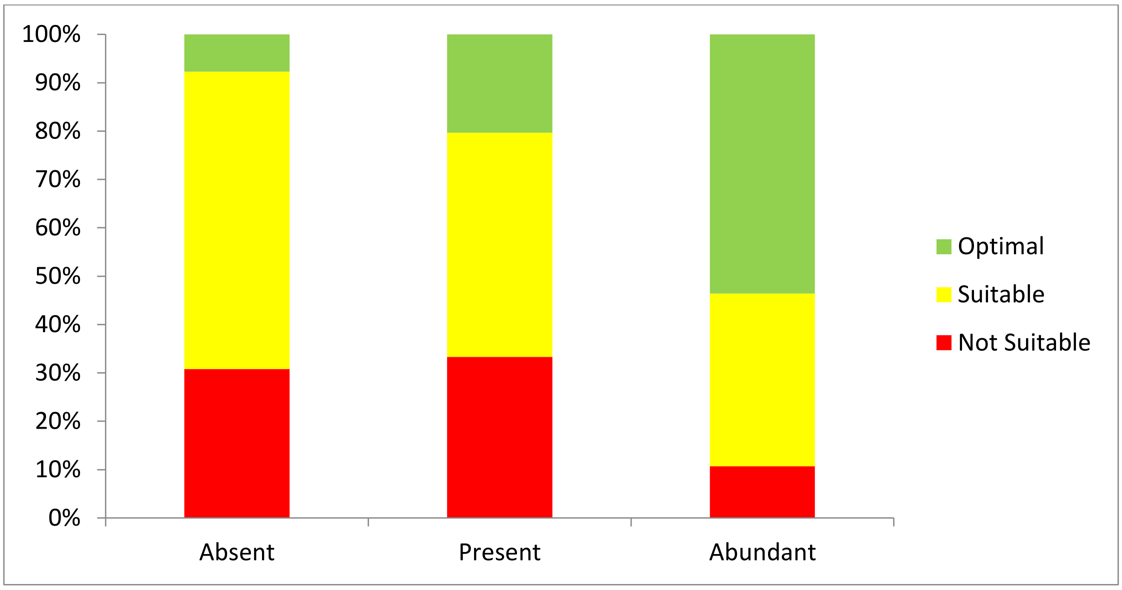


Figure 3.1.19. Verification of habitat model predictions by comparing abundance of captured guilds with habitat suitability classes.

Habitat Maps (highly rheophilic)
Hydromorphological units as mapped in sections upstream and downstream of Fermoy weir: dam and reservoir are shown in **Figures 3.1.20; 3.1.21 & 3.1.22.**

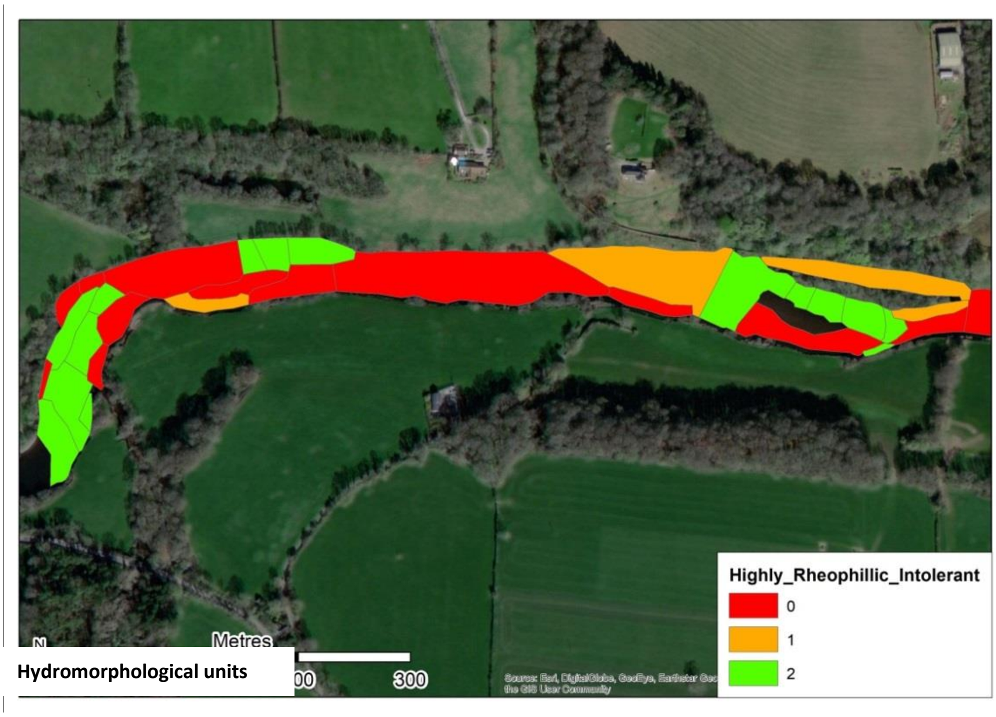


Figure 3.1.20 Hydromorphological units in Site 1 (1,6 l/sec/m^2), (0=not suitable, 1=suitable, 2=optimal).

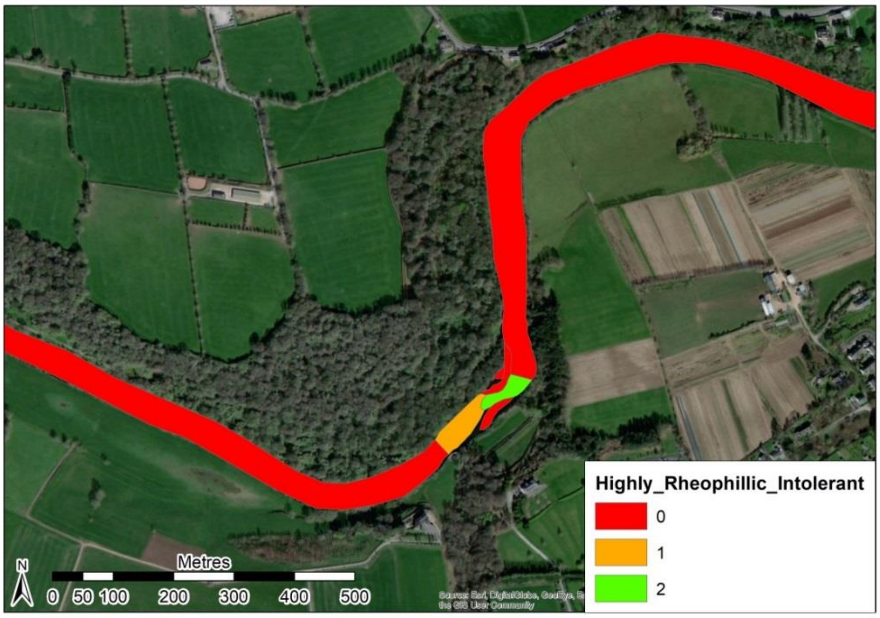


Figure 3.1.21. Hydromorphological units Site 2 (2,3 l/sec/m^2), (0=not suitable, 1=suitable, 2=optimal).

Figure 3.1.22. Hydromorphological units Site 3 (1,6 l/sec/m^2), (0=not suitable, 1=suitable, 2=optimal).

Highly rheophilic intolerant species in the Munster Blackwater at: Q=5.52 l/s·km^2 in Site 1 have 31% of the optimal, 48% of the unsuitable and only 21% of the suitable area; at Q=6.11 l/s·km^2 have 19% of optimal and 52% of unsuitable area and 28% of the suitable area. This guild in Site 2: at Q=5.52 l/s·km^2 (d) has 1% of optimal and 97% of unsuitable area; at Q=6.11 l/s·km^2 has 0% of optimal and 98% of unsuitable area. This guild in Site 3: at Q=5.52 l/s·km^2 has 46% of optimal and 5% of unsuitable area; at Q=6.11 l/s·km^2 has 30% of optimal and 68% of unsuitable area.

Optimal habitats are mainly in the main riverbed especially at low water flow. Highly rheophilic intolerant species in the Munster Blackwater at site 2 above Fermoy Weir have 97-98% of unsuitable habitat and only 0-1% of optimal habitat area, the latter occurring in the section created by the breach in the weir.

Rheohilic water column species in the Munster Blackwater at: Q=5.52 l/s·km^2 in Site 1 have 20% of the optimal, 14% of the unsuitable and 66% of the suitable habitat area; at Q=6.11 l/s·km^2 have 23% of optimal, 18% of unsuitable area and 59% of the suitable area. This guild in Site 2: at Q=5.52 l/s·km^2 has 0% of optimal and 98% of suitable area; at Q=6.11 l/s·km^2 has 0% of optimal and 99% of the suitable area. This guild in Site 3: at Q=5.52 l/s·km^2 has 32% of optimal and 47% of the suitable area; at Q=6.11 l/s·km^2 has 19% of optimal and 44% of the suitable area.

On average, 69% of the available river habitat area is suitable for rheohilic water column species, compared to just 10% for the highly rheophilic intolerant species. For the highly rheophilic intolerant species under the 2 flow regimes examined here on average 69% of the river area is not suitable with 21% being optimal habitat.

Modelling different scenarios

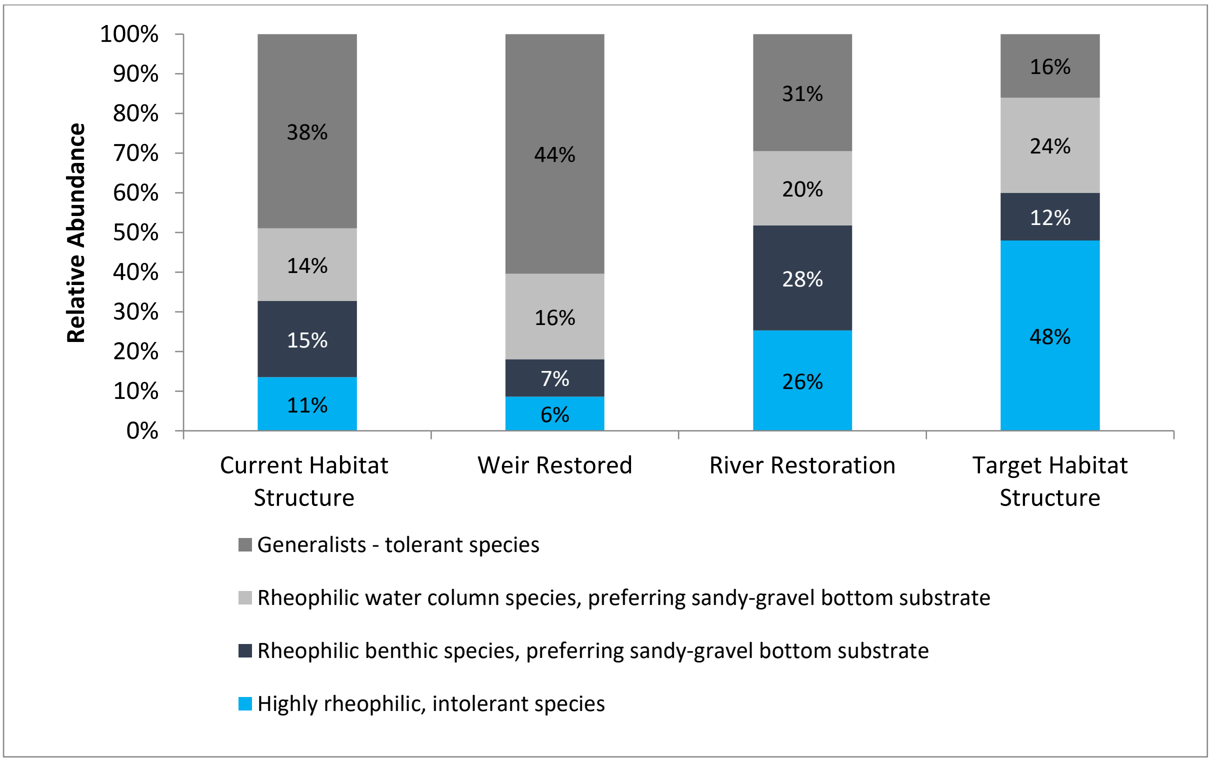


Figure 3.1.23. Habitat structure observed at Munster Blackwater site compared to FCMacHT target.

In the Fermoy weir sites, the affinity between the FCMacHT habitat were as follows; 58% under weir restored conditions; 63.75% under current weir breach conditions and 73.3% following hypothetical restoration methods.

Figure 3.1.23 demonstrates community abundance for all three sites for each scenario. As previously mentioned, it is calculated by weighting the habitat area for each guild with its expected proportion in FCMacH. Re-building the weir will result in an increase in poor habitat structure (impounded habitat) and modelled fish abundance based on habitat characteristics will decrease from 11% to 6% for highly rheophilic intolerant species. Although new habitat has formed as a result of the weir breach, there is still a deficit of 37% for highly rheophilic, intolerant species from the target fish community abundance. However, this deficit can be lowered to 22% when hypothetical restoration methods are modelled.

Habitat availability (new habitat post breach)
The Fermoy weir breach has had significant effects on the habitat type and suitability for species guilds present in the Munster Blackwater. With the breach, water levels above the weir dropped by ~1m in low flow summer conditions, leading to the exposure of impounded habitat both at site 1 and site 2. Between sites 1 and 2, a total habitat area of 68,257m^2 (**Table 3.1.4**) was exposed with the breaching of Fermoy weir. MesoHabisim modeling indicates that 28,032m^2 of this new habitat is optimal for highly rheophilic intolerant species such as salmon and trout.

At site 2, a newly formed ruffle/run sequences has appeared upstream of the weir breach. Within months of this new habitat formation, sea lamprey were observed to be utilizing this habitat for spawning (**Figure 3.1.24**). This outcome is highly relevant given the EU Habitats Directive designation of SAC status to the Munster Blackwater for salmon, lamprey species and shad. The altered hydromorphology is consistent with the EU Water Framework Directive requirement in regard to hydromrohology and river connectivity – the breach contributing to a re-instatement of a degree of natural

Table 3.1.6 Hydromorphological units type areas and three habitat suitability classes for Highly rheophilic intolerant species created with the breaching of Fermoy Weir.

Habitat Type/ Suitability	Fast Run	Glide	Plunge Pool	Rapids	Riffle	Ruffle	Sidearm	Total Area (m^2)
0 - not suitable	2,508					6,136		8,644
1 - suitable		24,107					7,475	31,582
2 - optimal		1,886	4,193	4,242	10,691	7,020		28,032
Total Area (m^2)	2,508	25,993	4,193	4,242	10,691	13,156	7,475	68,257

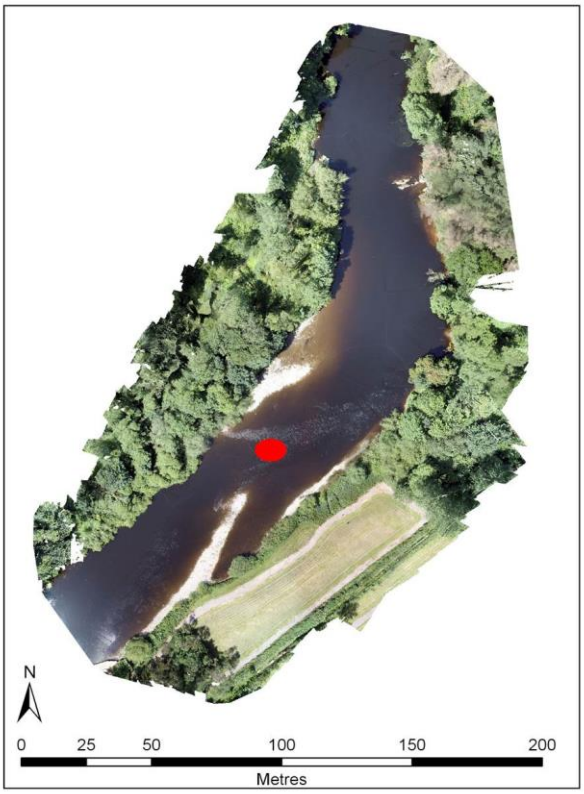


Figure 3.1.24. Newly formed habitat upstream of Fermoy weir (Run/Ruffle). Red circle marks the location where 2 sea lamprey spawning redds were recorded in Summer 2019.

A3.1.9 Adaptive Management: issues

To provide for optimal compliance with hydromorphology aspirations of the Water Framework Directive, barrier removal should be the target. This may not be feasible in every case, for a variety of reasons, and there is a requirement to look at the full range of issues, options and consequences in any actions proposed in regard to mitigating adverse impacts of barriers. Inland Fisheries Ireland has identified barrier removal as the preferred option as this removes any negative impacts in regard to movement of diadromous and potadromous fish, permits for normal sediment transport scenarios (including downstream movement of gravels suitable for spawning use by salmonid and lamprey species) and eliminates the impounded and generally over-deep and unproductive waters upstream of the impounding structure. There are a range of valid concerns that will surface in the context of any proposals to impact on a barrier:

- Change in the status quo – communities are accustomed to the things they are used to and are commonly reticent in regard to changes
- The structure may have cultural significance
- It may have architectural or antique significance and may be listed on a state register as a National Monument
- The impacts on upstream and downstream habitats and on river flows are a source of concern
- People have a fear of increased flood risk in downstream areas
- Angling groups may have concerns about change in the habitat types following mitigation, with consequent knock-on impact on angling style and niches for holding angling-sized prey

- There may be issues in regard to the channel starting to erode and incise into the riverbed to develop an equilibrium between the downstream bed levels and the upstream levels, with concerns for bank erosion and impact on bank stability and on dwellings etc. adjacent to the channel
- There may be *bona fide* and long-established users of the impounded waters upstream, such as leisure boating groups, or kayak groups who use the head differential at the barriers for their sport
- There may be abstractions, for potable water supply or for commercial or industrial users availing of the impoundment for drawing off water for large-scale domestic or industrial use

In any of the above scenarios it is imperative that all concerns are considered and addressed insofar as possible. As a minimum, all concerns and reservations should be recorded in some formal manner.

In the context of the Irish demonstration site, comments below address issues relating to both the Clondulane and the Fermoy weirs.

A3.1.9.1 Clondulane

The Clondulane structure was identified as a derelict structure, in the meaning of the Irish fisheries legislation, and, under this legislation, an order for its removal was issued. The fundamental rationale for the weir no longer exists. A secondary outcome of the weir was that it may have impacted on upstream migration of adult Atlantic salmon to spawning grounds. The impact was not necessarily one of complete and irreversible blockage but rather one of creating delay, as the salmon may have had to await optimal flow, velocity and stage level conditions to ascend the weir with reduced difficulty. The delaying impact may have facilitated the success of a private angling fishery of considerable quality. This fishery will not be impacted, in the context of number of salmon passing through it, but may be impacted insofar as salmon may not be delayed at the fishery in their upstream migration. The nature of unimpounded river sections on the Munster Blackwater, due to the overall river gradient in this area, is such that the river contains long extended deep-water pool or glide areas and relatively short shallow riffles. Thus, the river naturally contains the type of holding waters that adult salmon may choose to use in the course of their upstream migrations. Any such areas within the current angling fishery downstream of the Clondulane weir will remain intact in the case of any removal or breaching of the weir.

At present, the impounded nature of the waters upstream of the Clondulane weir is such that the angling fishery operating in this water actually uses boats for fishing. This is highly unusual in an Irish setting. The lowering of the water levels upstream of the weir, a consequence of weir removal, will permit a re-emergence of the natural pool – riffle sequence characteristic of the river here. This sequence is currently drowned by the impounding effect of the weir. The re-emergence of the natural riverbed form may permit a similar quality of angling experience for salmon anglers as is currently enjoyed downstream of the impoundment.

One Adaptive Management option at Clondulane would be to construct a fish passage solution that permitted up- and downstream movement of all life stages of fish species occurring in the river. Such a goal could maybe be obtained by running all the water through a rock-ramp type of fish passage. However, this would have no positive contribution to the WFD aspirations in regard to river continuity and the IUCN – UK report (Addy *et al.* 2016) calling for measures to restore natural river processes.

The Clondulane case is currently undergoing investigation by the competent local authority In respect of the national planning legislation. As such, all aspects of this case are being examined and reports in regard to cultural, architectural etc. issues have been required and furnished.

A3.1.9.2 Fermoy

No Ministerial order has been made in respect of the Fermoy structure. There is a requirement to manage the situation at this weir, given its current partial breach and the vulnerable status of the weir infrastructure. Any repairs to the weir would, realistically, require installation of a fish passage solution that would be consistent with the Water Framework, Habitats Directive and the Floods Directive.

The town of Fermoy had a flood relief scheme designed and constructed in the last 5 years or so with walls and embankments along the immediate river frontage as part of the overall scheme design. These have worked efficiently in recent high flow events. The strengthened bank and riparian scenario may, in turn, place additional pressures on the current weir in flood flow conditions. A proposal to install a rock ramp fish pass into the existing weir was made as a part of the flood scheme design but this was not proceeded with.

Currently, the Fermoy weir has a partial breach at one side, accommodating all of the low-medium flow discharge. This renders the existing fish pass derelict in these flow conditions. The concentration of flow exposes much the remaining weir infrastructure and identifies the need for remedial structural work.

The Adaptive Management scenario at Fermoy weir, in the view of the IFI AMBER team consists of the requirements to:

- Accommodate the upstream and downstream passage of diadromous fish species, in line with the SAC status of the river and Conservation Objectives for the designated diadromous fish – Atlantic salmon, sea- and river lamprey, Twaite shad - and for migratory European eel
- Ensure integrity of infrastructure – the existing road bridge, until recent motorway completion, was the national primary route linking the two main cities in the Republic – Dublin and Cork. The existing weir in Fermoy is constructed in a manner that takes it through the road bridge – the left-hand side of the weir is upstream of the bridge and the right-hand side is downstream
- There is a long-established rowing club on the river, and it avails of the flat, impounded waters upstream of the weir for competitions and for training. This is a valued local amenity and its continued functioning requires a level of 'flat' water upstream of the weir

A rock ramp structure linked to part of the existing weir would facilitate migratory fish passage. The surface level of the ramp would require to be set at a level lower than the current weir crest in order to ensure that sufficient water passed over the rock ramp at all flow conditions. The adjusted surface level of the rock ramp wold require to be set in a manner that permitted continued future usage of the upstream impounded area for leisure and competition rowing.

The partial breaching of the Fermoy weir and focussing of flow, as observed during June 2019 at time of the MesoHABSIM survey, led to exposure of gravel shoals in the channel *circa* 4 km upstream. Observations in Fermoy at this time showed that rowing training was ongoing, with several single sculls boats in action on the river I the impounded reach.

A3.2 CASE STUDY 7: Small Barriers, Denmark and United Kingdom

A3.2.1 Introduction

Small barriers, such as weirs and water gauging stations, are highly abundant worldwide, though perhaps especially in Europe (Garcia de Leaniz et al. 2018; Jones et al. 2019). Smaller barriers are often deemed to have fewer impacts on fish populations though their abundance and cumulative impact makes for widespread effects (Lucas and Baras 2001; Cooke et al. 2005; Birnie-Gauvin et al. 2017). Too often, these barriers are left unnoticed and simply grow old, unsafe and obsolete whilst still limiting fish movements. We would argue that their removal provides a cost-effective way of reinstating connectivity and promoting sustainability of freshwater ecosystems. Small barriers are, by their nature, most common on smaller, low stream order watercourses (Jones et al. 2019). The extent of their effects on biota depends primarily on their effects on habitat and connectivity. The ponding effect upstream of small barriers may be very localised if the stream gradient is steep, but much larger if stream gradient is low. The effect on connectivity depends particularly upon the location (Kemp and O'Hanley, 2010); a small barrier immediately upstream of a confluence may restrict access by migrating species, while the connectivity impacts of multiple adjacent barriers is cumulative. The primary aim of this case study, duplicated in Denmark and northern England was to determine the changes in mesohabitats and to record the short-term (mostly 1-2 years) changes in fish community and abundance after removal of small barriers in stream systems climatically suited for salmonids.

A3.2.2 Denmark: lowland rivers and other Danish peculiarities

In Denmark, many small barriers are erected in association with fish farms. Weirs are put in place to divert water into the fish farming facilities. A grid is, by law, required at the water intake with a minimum spacing of 8mm. Many young fish nonetheless manage to get through this grid and find their way into the fish farm, where no exit is possible. As a result, young-of-the-year fish are highly threatened, even by small barriers.

Denmark is particular for two reasons: 1) all rivers are "lowland" rivers and have very little gradient, and 2) rivers are relatively species-poor, with brown trout (*Salmo trutta*) as the dominating species in east-running rivers, and Atlantic salmon (*Salmo salar*) in most west-running rivers. Some rivers will also be home to European eels (*Anguilla anguilla*) and brook lamprey (*Lampetra planeri*). Because species like brown trout and Atlantic salmon are rheophilic species, they rely on fast-moving and highly-oxygenated water to thrive, especially during spawning and early development. These areas are particularly rare in Denmark given the rivers' low gradient, and are therefore exceptionally valuable. Unfortunately, these areas are also those favoured for barriers, and their installation obliterates the vital habitat that salmonids depend on (Birnie-Gauvin et al. 2017a).

In Denmark, rivers are mainly managed by local municipalities (98 in total). Each municipality is therefore responsible for restoring rivers. In addition to this, rivers (or parts of rivers) can be privately owned if a river runs through one's property. This also means that removing privately-owned barriers can be rather expensive as removals also include a payout to the barrier owner in addition to the cost of removal itself. Thus, the main cost of barrier removal in Denmark has been compensation paid to fish farm owners.

In the section below, we report on the effects of 12 barrier removals in lowland Danish rivers.

A3.2.3. Twelve weir removals in Denmark

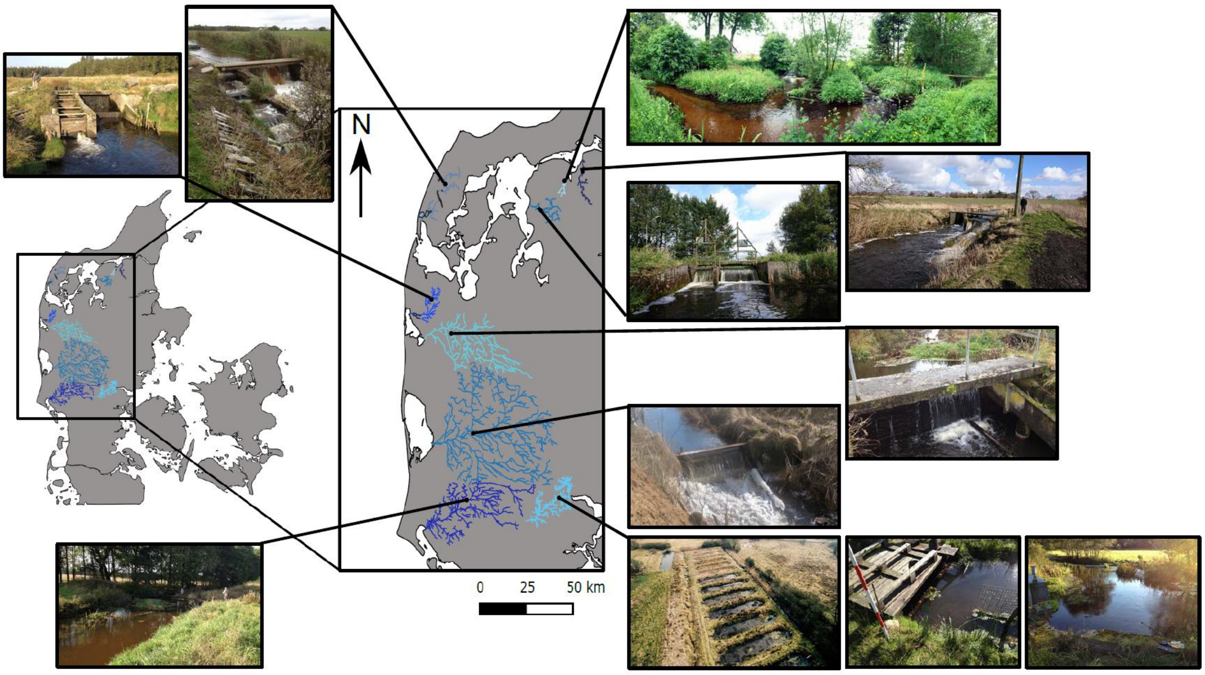


Figure 3.2.1. Site locations in Denmark.

A total of 12 weirs were removed across the Jutland peninsula of Denmark during the lifetime of AMBER. Changes in habitat (including depth, substrate and flow) and fish density were monitored in the 50m directly upstream of the barriers.

Table 3.2.1. Summary data for Danish sites.

Site name	Distance to outlet (km)	Height of weir (m)	Length of ponded zone (m)	Cost of removal (€)*	Gain in river (km)
Trend Dambrug	10.945	1.4	1230	80 349	58.733
Idom Dambrug	18.252	1.1	1000	281 200	15.198
Risbøl Dambrug	52.250	0.91	300	283 488	4.400
Gelstrup Dambrug	7.101	1.33	1000	468 668	2.800
Refsgårdslund Dambrug	22.639	0.3	300	241 216	49.033
Slotsbjerg Fiskeri	24.904	1.1	215	66 953	1.959
Gl. Potkær Fiskeri	24.640	1.8	280	66 953	3.223
Ny Potkær Fiskeri	24.230	2.6	250	66 953	3.563
Nørhå Fiskeri	10.368	1.4	2500	261 337	32.550
Øster Ørts Dambrug	22.893	1.5	600	200 858	27.486
Vidkær Dambrug	1.170	2.9	1500	200 873	21.241
Clasonsborg§	49.023	2.0	2000	562 010	90.918
Total				**2 783 858**	**311.104**

*Note that the cost of removal also includes a 'payout' to the fish farm owners for closing or repurposing their facility into a recirculating system. The costs were converted from Danish kroners to Euros on 4 June 2019.
§ Weir not associated with a fish farm.

A total of 311km of river were reconnected as a result of the 12 barrier removals presented here. While most barriers were small in comparison to most of the other WP4 case studies, their effects are *not* negligible despite common thinking. Below are images of a few of the sites, both before and after removals were done. Remote sensing was used in a few of the case studies, but the drone was mostly used for the purpose of imaging rather than evaluating habitat and geomorphology. This is because most of the rivers presented here were densely covered with trees on the banks, making it difficult to bring the drone close enough to evaluate flow and substrate, and the water was unclear thus preventing visibility.

Figure 3.2.2. Trend Dambrug before (left) and after (right) removal.

Figure 3.2.3. Idom Dambrug before (left) and after (right) removal.

Figure 3.2.4. Gelstrup Dambrug before (left) and after (right) removal.

Figure 3.2.5. Refsgårdslund Dambrug before (left) and after (right) removal.

A3.2.4 Geomorphological and hydrological changes

Habitat measurements were performed as per the Environmental Agency of the United Kingdom. All sites were evaluated once prior to removal, and twice after removal except for Clasonsborg which was added to the study later one, and thus only has one set of post-removal measurements.

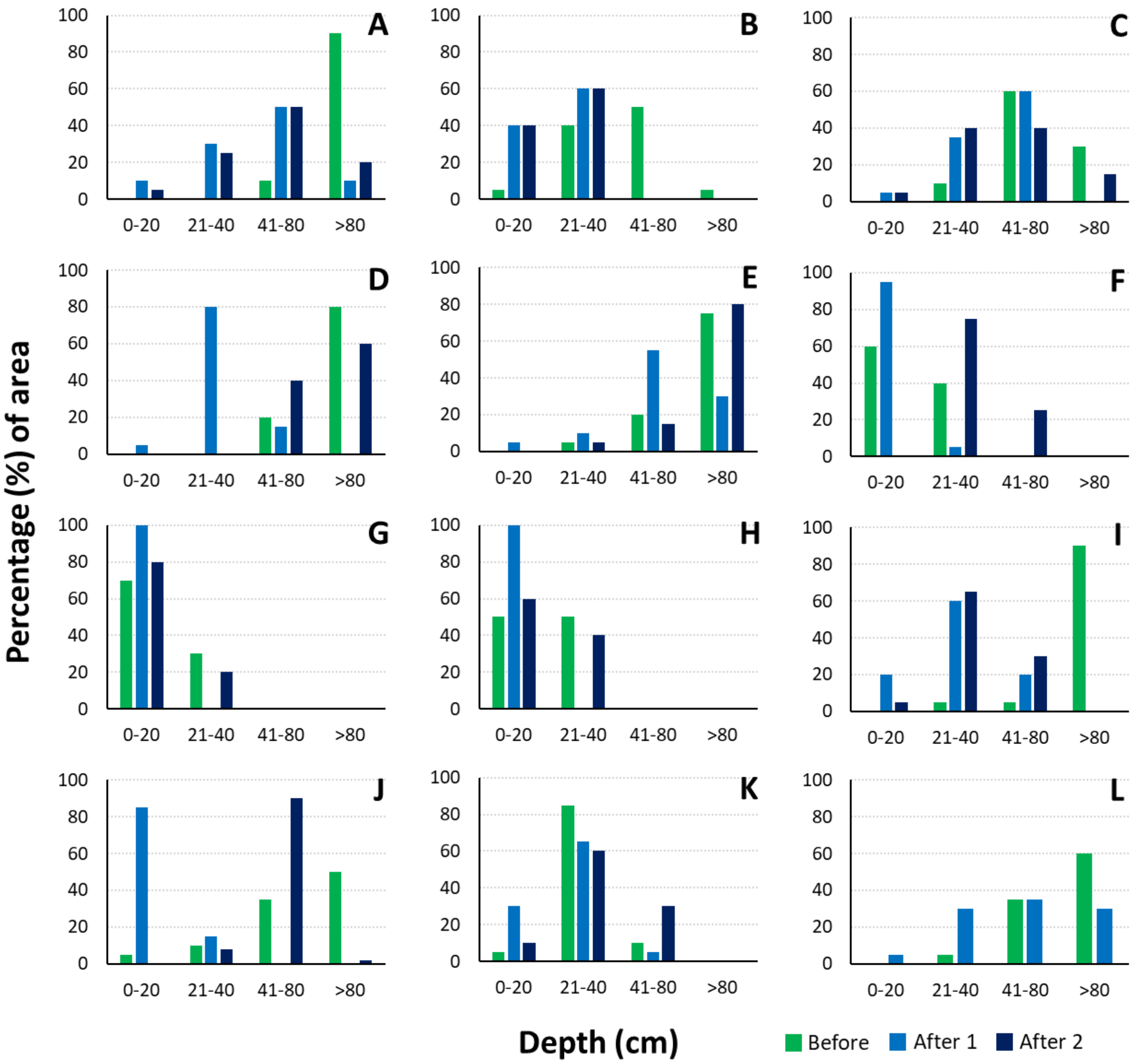


Figure 3.2.6. Changes in depth at the ponded zones. A) Trend Dambrug, B) Idom Dambrug, C) Risbøl Dambrug, D) Gelstrup Dambrug, E) Refsgårdslund Dambrug, F) Slotsbjerg Dambrug, G) Gl. Potkær Dambrug, H) Ny Potkær Dambrug, I) Nørhå Dambrug, J) Øster Ørts Dambrug, K) Vidkær Dambrug, L) Clasonsborg.

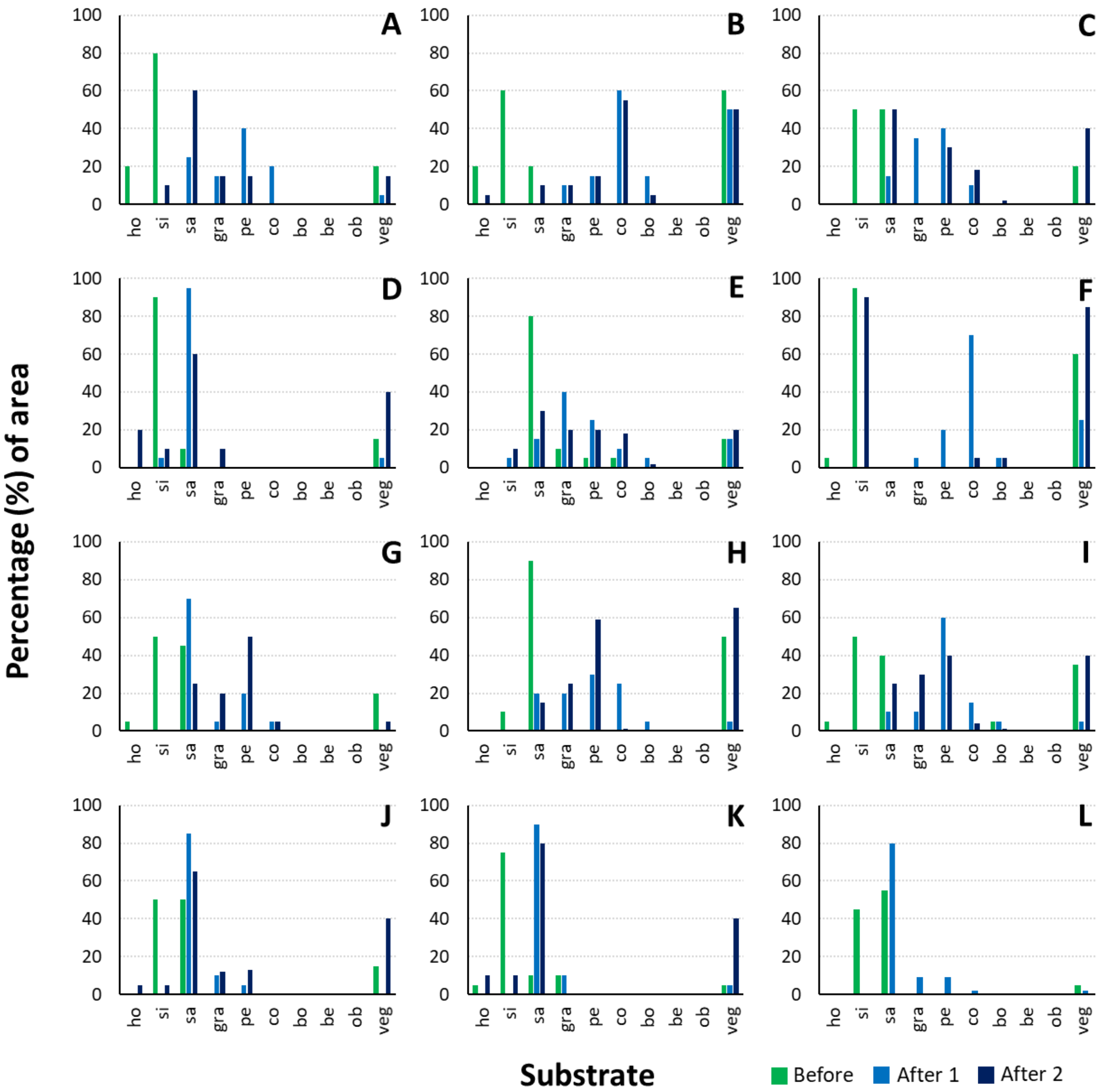


Figure 3.2.7. Changes in substrate type at the ponded zones. A) Trend Dambrug, B) Idom Dambrug, C) Risbøl Dambrug, D) Gelstrup Dambrug, E) Refsgårdslund Dambrug, F) Slotsbjerg Dambrug, G) Gl. Potkær Dambrug, H) Ny Potkær Dambrug, I) Nørhå Dambrug, J) Øster Ørts Dambrug, K) Vidkær Dambrug, L) Clasonsborg. Abbreviations ho: high organic, si: silt, sa: sand, gr: gravel, pe: pebble, co: cobble, bo: boulder, be: bedrock, ob: obscured, veg: vegetation.

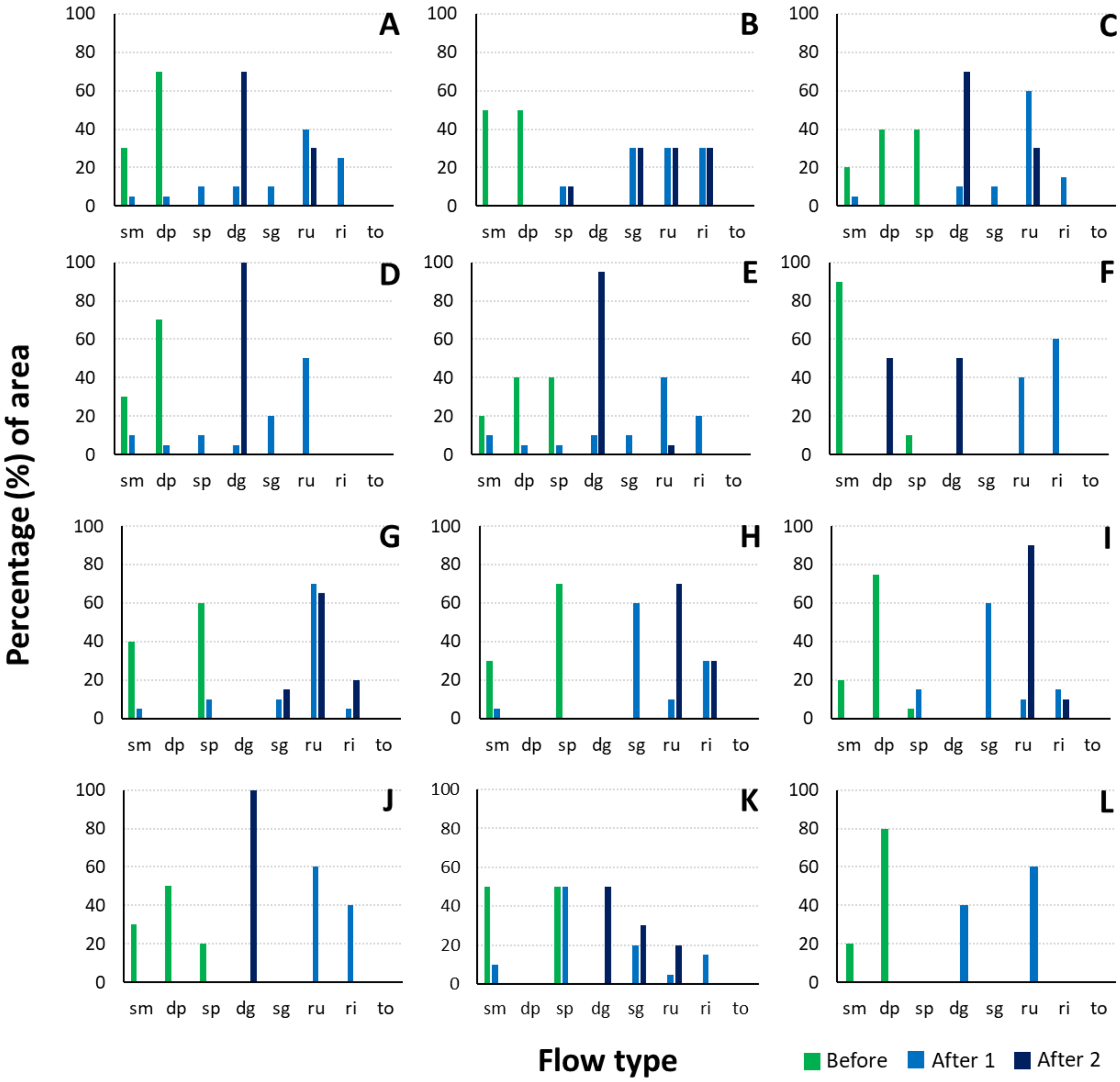


Figure 3.2.8. Changes in flow at the ponded zones. A) Trend Dambrug, B) Idom Dambrug, C) Risbøl Dambrug, D) Gelstrup Dambrug, E) Refsgårdslund Dambrug, F) Slotsbjerg Dambrug, G) Gl. Potkær Dambrug, H) Ny Potkær Dambrug, I) Nørhå Dambrug, J) Øster Ørts Dambrug, K) Vidkær Dambrug, L) Clasonsborg. Abbreviations sm: still marginal, dp: deep pool, sp: shallow pool, dg: deep glide, sg: shallow glide, ru: run, ri: riffle, to: torrent.

Prior to removal, the sites were characterized by deeper water, silty and sandy substrate with very little gravel-like substrate (with some vegetation) as well as still waters with both deep and shallow pools. Following the removals, the sites can be characterized by lower water depth, a great increase in gravel, pebbles and cobble (with some vegetation) and a significant increase in glides, runs and riffles. These habitat changes reflect the restoration of the natural rheophilic habitat previously present, ie. a return to a more original habitat type.

A3.2.5. Fish density and diversity changes

Fish density was evaluated via the commonly used two-pass electrofishing surveys developed by Lockwood and Schneider 2000.

$$p = \frac{C_1 - C_2}{C_1},$$

$$N = \frac{{C_1}^2}{(C_1 - C_2)},$$

$$Variance\ of\ N = \frac{{C_1}^2 \cdot {C_2}^2 (C_1 + C_2)}{(C_1 - C_2)^4},$$

$$Standard\ error\ of\ N = \sqrt{Variance\ of\ N}$$

All sites were evaluated once prior to removal, and twice after removal except for Clasonsborg which was added to the study later one, and thus only has one set of post-removal measurements.

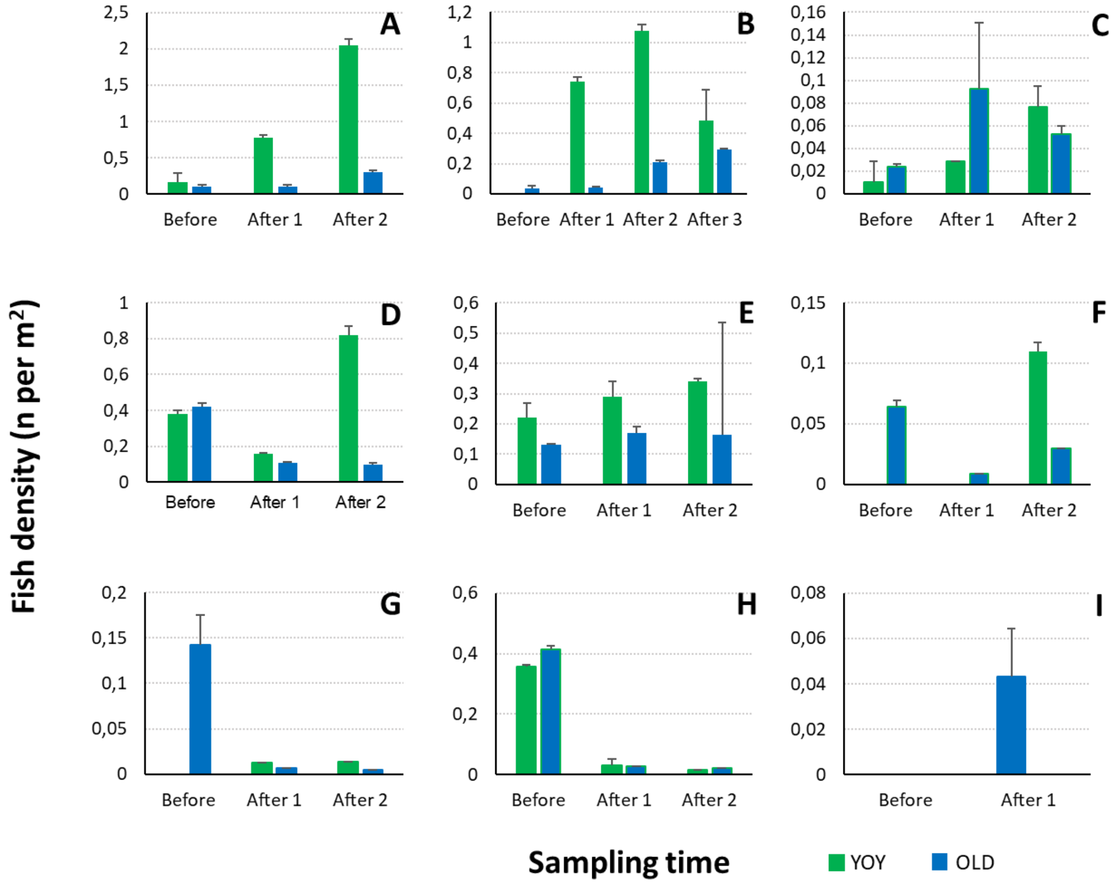


Figure 3.2.9. Changes fish density (n per m^2) of dominant species in the river. A) Trend Dambrug (*Salmo trutta*), B) Idom Dambrug (*Salmo salar*), C) Risbøl Dambrug (*Salmo trutta*), D) Gelstrup Dambrug (*Salmo trutta*), E) Refsgårdslund Dambrug (*Salmo trutta*), F) Nørhå Dambrug (*Salmo trutta*), G) Øster Ørts (*Salmo trutta*), H) Vidkær Dambrug (*Salmo trutta*), and I) Clasonsborg (*Salmo salar*). YOY: young-of-the-year, OLD: older year classes.

The density of the respective dominant species at the case study locations increased significantly after the removals, especially for young-of-the-year, with a few exceptions. At two sites, Øster Ørts and Vidkær (**G** and **H** on **Figure 3.2.9**), the stream was completely dug out and re-meandered following removal, while all other sites were left as is following removal. This form of restoration appears to have done more harm than good in the short term, with a decrease in fish density, resulting from the loss of suitable vegetation and cover. It is likely that over time, nature will recover and so will the fish, but we were unable to detect this benefit in the course of 2 years (within the lifetime of AMBER). At sites where this form of restoration did not occur however, the increase in density was very significant, suggesting that:

- Connectivity was re-established and thus;
- More adults (both sea trout and resident individuals) successfully reached spawning grounds;
- These spawning grounds were now suitable for successful spawning (egg survival);
- Once emerged, young fish likely had an increased survival due to restored habitat and thus;
- We observed an increased density of young-of-the-year during our surveys.

These results are in line with several studies at similar locations which found that barriel removal led to several benefits for salmonid species and resulted in significant increases (Birnie-Gauvin et al. 2017b, 2018).

We note that at 3 sites – Slotsbjerg, Gl. Potkær and Ny Potkær (all sites being within 500m of each other) – fish were absent prior to removal and still absent following removal despite the habitat having been restored and deemed highly suitable for brown trout (the dominant species). This could be due to factors unrelated to the removed barrier, such as pollution from surrounding farms, another impassable barrier below the 3 barriers, or a collapse in the local trout population. Unfortunately, we were unable to identify the cause for these results and thus we can only speculate.

A3.2.6 United Kingdom

Rivers and streams across the UK contain numerous old weirs, culverts and barriers which were built for historic reasons such as powering mills, raising riverbed levels or redirecting water courses. Recent estimates suggest that in England there are 0.75 barriers river-km^{-1} (Jones et al. 2019) and across Great Britain only 1% of rivers are free of artificial barriers. During the lifetime of AMBER there has been increased attention and efforts focussed on the removal of low head barriers often initiated and coordinated by local rivers trusts.

In this section we report on the effects of barrier removal at 10 sites across northern England. Sites were chosen on streams that, climatically, are suitable for salmonids and that historically have contained brown trout *Salmo trutta*, together with a variety of other species determined by the local conditions.

A3.2.7 Barrier removals in northern England

A total of 10 low-head barriers distributed across northern England (**Figure 3.2.10**) which were removed between 2014 and 2018 were studied. The barriers ranged from a stepped weir (1.6m head) to a multi pipe culvert (0.12m head; **Figure 3.2.11**). Site choice was limited by accessible sites where barriers were being removed and, as a result, river gradients, widths and length of ponded zones vary considerably between sites (**Table 3.2.2**). River widths at the sites were between 2.9m (site TR10) and

23.3m (site TR7); the upper values were at the limit of feasibility for the quantitative electrofishing survey methods employed (see below). Barriers at sites TR3 (North Burn, Tees catchment) and TR7 (Caldew Mouth, Eden Catchment) were at or close to the tidal limit; the remainder were exclusively in fresh, non-tidal water. The barriers had been installed for a variety of reasons many decades ago, but in all cases no longer served a valid purpose (TR1-7), or could be removed and replaced by a full channel-width bridge (TR8-10). The impetus and coordination of the removal of the barriers was primarily coordinated by local rivers trusts (TR1 - Tyne Rivers Trust, TR2, TR5 & TR7 - Eden Rivers Trust, TR3 – Tees Rivers Trust, TR4 - Wild Trout Trust, TR6 – Ribble Rivers Trust, TR8, TR9, TR10 – Wear Rivers Trust) in association with the Environment Agency, England. At all sites only the barrier was removed; reprofiling and/or remeandering of the river was not carried out following barrier removal. The funding for the barrier removals came from a variety of sources, but primarily government grants, the aim of which was to assist meeting the objectives of the Water Framework Directive to reduce hydromorphological modification and obstacles to fish migration. Changes in stream habitat and fish community were assessed at the ten sites. At all sites surveys were carried out prior to the barrier removal. A second survey was carried out in the same year after the barrier had been removed (except for sites TR2 and TR7). A third survey was conducted in the year following the barrier removal at all sites. Habitat and fish surveying was normally carried out in summer or early autumn at base flows.

Stream habitat was measured by standardised survey methods. During each survey, fish density and composition was assessed using 3-pass electrofishing upstream and downstream of the barrier. Between 37 m and 80 m was surveyed upstream and downstream of barriers at each site. Downstream of the barrier was surveyed to act as a paired control site against which to compare changes occurring upstream of the removed barrier. Fish densities were calculated by the Carle & Strub (1978) removal method. Three of the barrier removal sites (TR8, TR9 and TR10) at which barriers were removed in 2014 were monitored yearly throughout the duration of AMBER to provide information over a longer duration.

In addition to fish density, a fish community diversity index score was calculated for each site surveyed. Since ponded reaches above weirs generate more homogenous deeper, slower-flowing habitats, this would be expected to result in fewer mesohabitat niches for fishes and a dominance of species preferring slower, deeper water with finer substrate. For this reason, the Shannon-Wiener Index (which incorporates number of taxa, as well as their relative abundance) was used. In this index, a higher score represents a site with higher diversity.

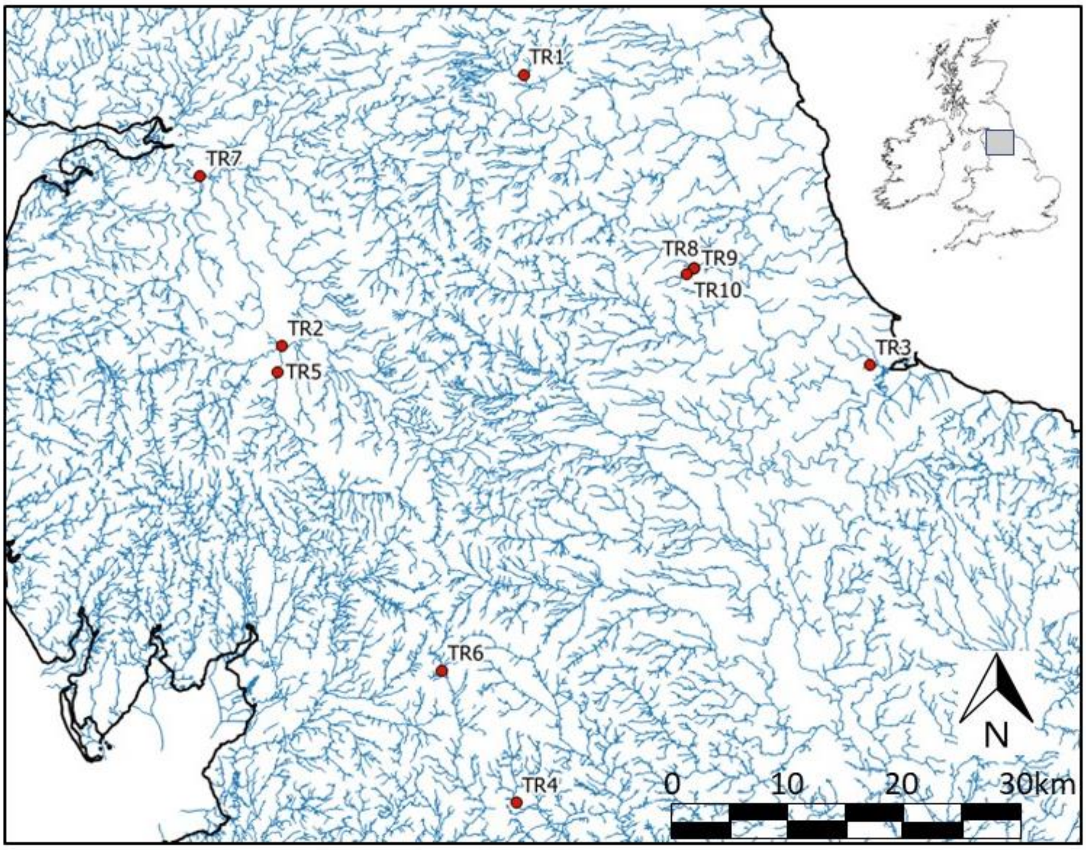


Figure 3.2.10. Site locations for barrier removals across northern England.

Table 3.2.2. Summary data for United Kingdom (northern England) sites.

Site	Coordinates (lat.; long.)	River	Distance to outlet (km)	Obstruction (head at Q_{95} water level)	Restoration action done	Timing of removal / mitigation	Cost of removal (€)	Length of ponded zone (m)	Gain in unobstructed river (km)
TR1	55.054648;-2.1265957	Swin Burn (R. Tyne trib.)	68.4	Vertical weir (0.5 m head)	Removal	14 August 2018	1 244	7	4.46
TR2	54.655525;-2.733025	R. Eamont	77.2	Sloped boulder weir remant (0.5 m head)	Removal	15 September 2016	33 629	70	0.76
TR3	54.627439;-1.2538384	North Burn, (R. Tees trib.)	10.9	Stepped (4) weir, 20% slope, (1.6 m head)	Removal	30 April 2018	67 871	118	1.84
TR4	53.989631;-2.1408107	R. Aire	131.4	Vertical weir x2 (0.3 m head)	Breached	18 June 2018	10 181	47	3.12
TR5	54.618172;-2.742908	R. Lowther	82.6	Vertical weir (0.4 m head)	Removal	14 August 2017	149 285	55	1.28
TR6	54.182486;-2.3265897	R. Ribble	119.4	Vertical weir (0.7 m head)	Removal	12 June 2017	4 072	46	3.31
TR7	54.902403;-2.944192	R. Caldew	36.3	Vertical sheet-piling weir (0.5 m head)	Removal	30 June 2016	33 091	67	0.39
TR8	54.770754;-1.6944252	R. Deerness	64.9	Multi-pipe-culvert crossing (0.12 m head)	Removal	01 April 2014	90 494	12	5.52*
TR9	54.770376;-1.6960801	R. Deerness	65.1	Multi-pipe-culvert crossing (0.15 m head)	Removal	01 April 2014	90 494	17	5.37*
TR10	54.761972;-1.7138799	R. Deerness	67.2	Multi-pipe-culvert crossing (0.14 m head)	Removal	01 August 2014	56 559	27	3.46*

*Gain in unobstructed river length for TR8, TR9 and TR10 are calculated after all three barriers had been removed.

Figure 3.2.11. Photos of barriers prior to removal. Images of TR9 and TR10 prior to removal are not presented but both were multi-culvert structures similar to TR8.

A3.2.8 Geomorphological and hydrological changes

Most sites were characterized by a mix of pool, glide, run and riffle habitats upstream and downstream of the barrier (**Figure 3.2.12**). Changes in depth, substrate and flow were relatively minor overall (**Figures 3.2.12, 3.2.13** and **3.2.14**). This is likely to be linked with the relatively small ponded areas (**Table 3.2.2**) at most sites compared to the length of river surveyed. Those sites which had a larger ponded zone and were of lower gradient (TR2, TR3) showed more of a tendency for the upstream site to become faster flowing (increase in percentage glide, run and riffle) and substrate size to increase following barrier removal.

A3.2.9 Fish density and diversity changes

A total of 12 fish species were recorded across all surveys (**Figure 3.2.15**). Bullhead (*Cottus gobio*), brown trout (*Salmo trutta*) and stone loach (*Barbatula barbatula*) were recorded at all sites, minnow (*Phoxinus phoxinus*) at 9 sites, eel (*Anguilla anguilla*) at 6 sites, Three-spine stickleback (*Gasterosteus aculaeatus*), brook lamprey (*Lampetra plenari*) and grayling (*Thymallus thymallus*) at 3 sites, flounder (*Platichthys flesus*) at 2 sites, salmon (*Salmo salar*), common goby (*Pomatoschistus microps*) and roach (*Rutilus rutilus*) at 1 site. The short-term response of the fish community following barrier removal was variable between sites with no uniform pattern across all sites (Figure 3.2.15). Upstream of the barrier the Shannon Weiner Diversity Index before and after barrier removal was not significantly different. Similarly, there was no significant diffence in fish density upstream of the barriers comparing before and after barrier removal.

Site TR3 did appear to show an impact of barrier removal with diversity and density higher upstream following barrier removal. This was the lowest gradient site of the ten studied in northern England, with the largest barrier (1.6m head) and the largest ponded zone. It is also a site where the habitat showed a substantial change. In contrast, most of the other sites did not change before and after barrier removal. It is important to note that prior to barrier removal there was no consistent difference in the numbers of species and density when comparing upstream and downstream of the barrier suggesting that the barriers studied may not have been having a substantial impact when only the fish assembledge is considered. In this study only the fish assembledge has been considered at these ten sites and this does not provide information on population connectivity or dispersal, both factors which have been shown to be strongly impacted by removal of low-head barriers (Tummers et al. 2016).

The three sites (all on the River Deerness) which were monitored for 5 years after barrier removal appeared to show a delayed response to barrier removal with an increase in density occurring 3-5 years after barrier removal (**Figure 3.2.16**). It may be that the relatively short duration of monitoring carried out at the majority of sites was not sufficient to record longer term changes which barrier removal may have on fish populations and the fish assemblege. That is not surprising as, for most fish species in temperate streams, changes are initially only a result of local redistribution and demographic changes take years.

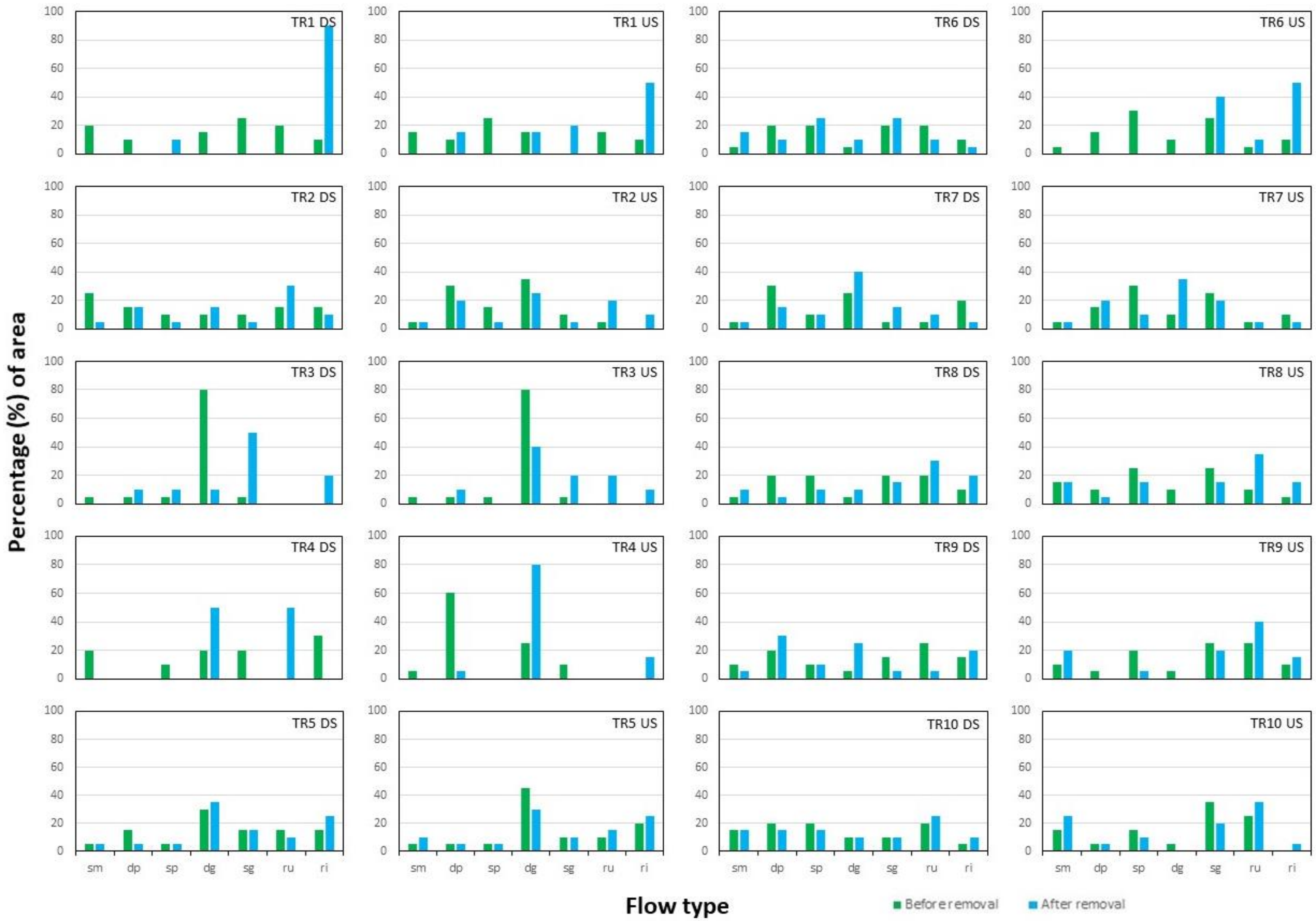


Figure 3.2.12. Changes in flow type in study stretch upstream and downstream of the barriers before (green) and after (blue) removal. Abbreviations sm: still marginal, dp: deep pool, sp: shallow pool, dg: deep glide, sg: shallow glide, ru: run, ri: riffle.

Figure 3.2.13. Changes in substrate in study stretch upstream and downstream of the barriers before (green) and after (blue) removal. Abbreviations ho: high organic, si: silt, sa: sand, gr: gravel, pe: pebble, co: cobble, bo: boulder, be: bedrock.

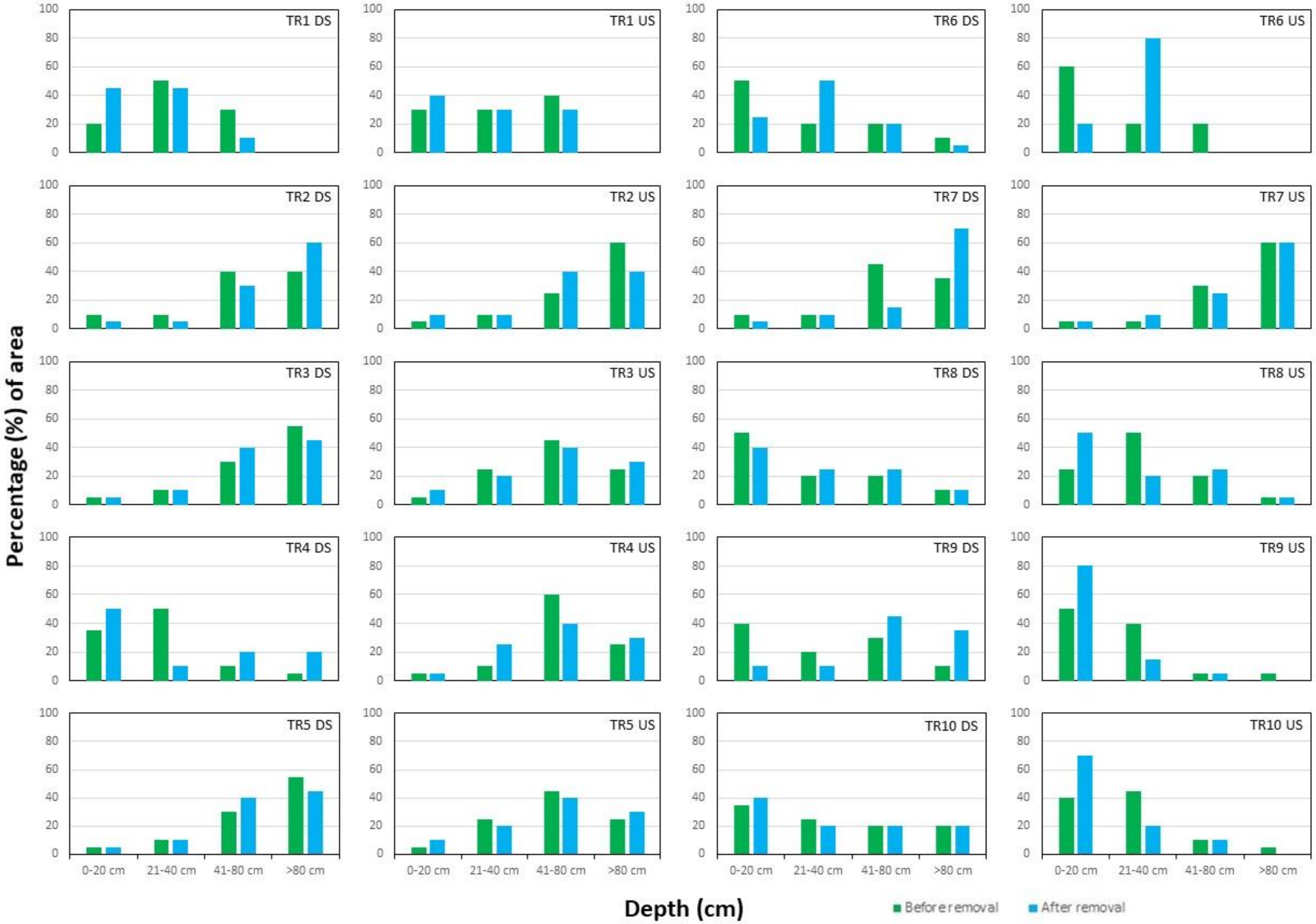


Figure 3.2.14. Changes in depth in study stretch upstream and downstream of the barriers before (green) and after (blue) removal.

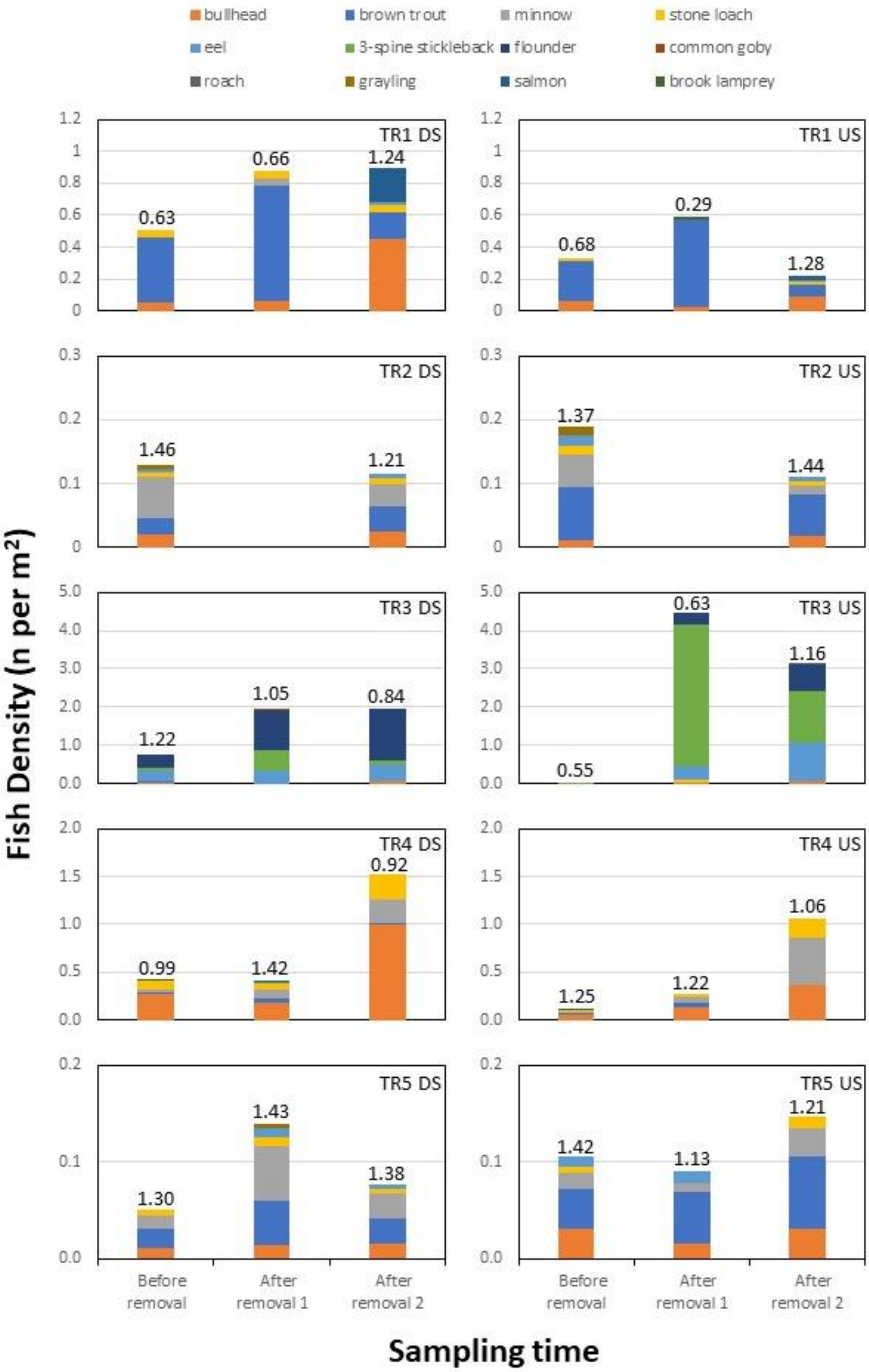


Figure 3.2.15a. Density and diversity of fish pre- and post-removal of barriers in study stretch upstream (US) and downstream (DS). After removal 1 refers to fish survey in same calender year as barrier removal whilst After removal 2 refers to fish survey in calender year after barrier removal. Figures above bars give Shannon Wiener diversity index.

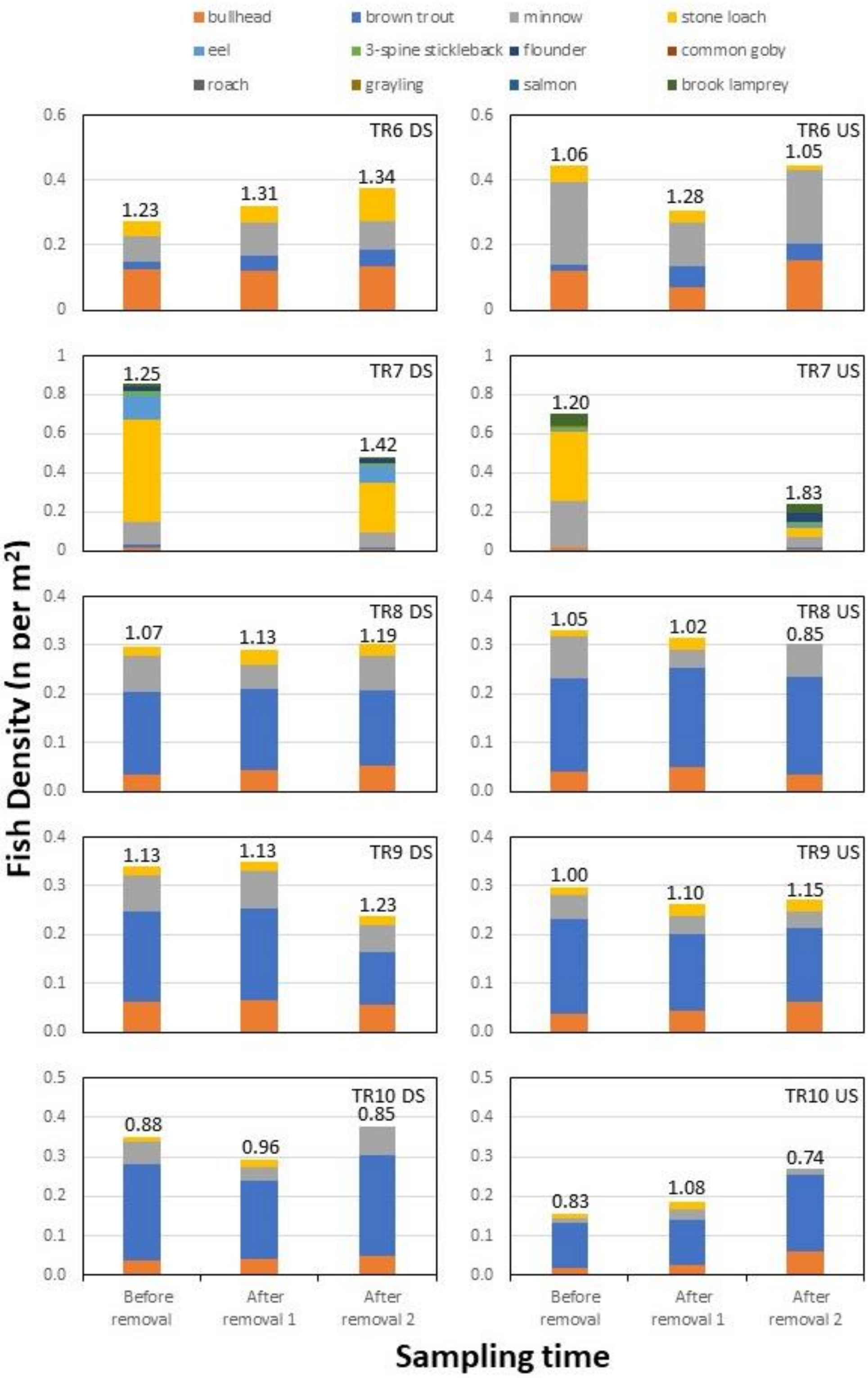


Figure 3.2.15b. Density and diversity of fish pre- and post-removal of barriers in study stretch upstream (US) and downstream (DS). After removal 1 refers to fish survey in same calender year as barrier removal whilst After removal 2 refers to fish survey in calender year after barrier removal. Figures above bars give Shannon Wiener diversity index.

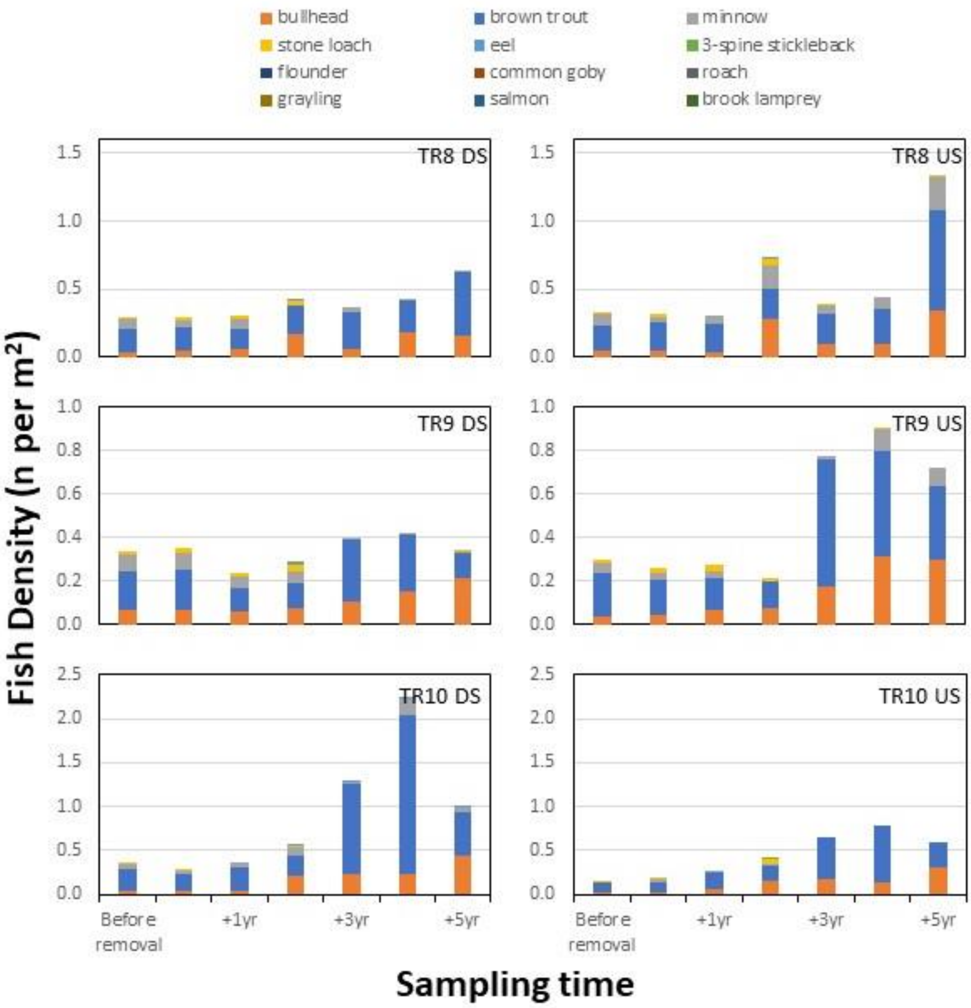


Figure 3.2.16. Medium-term sampling of fish assemblages of sites TR8-10, River Deerness, before and after-removal of stream barriers. Density of fish pre- and post-removal of barriers in study stretch upstream (US) and downstream (DS). First fish sample after barrier removal is in same calendar year as barrier removal, and thereafter at yearly intervals.

A3.2.10 Adaptive management of small barriers

The short-term impacts of barrier removal on the fish community at the Danish and northern English sites studied were quite different. Whilst a rapid response of the fish community to barrier removal was observed at the Danish sites, the impact of barrier removal at sites in northern England was variable with no uniform pattern across all sites. There were several differences in the sites studied in Denmark and England which appear to have contributed to the observed differences in reponse. The barriers removed in Denmark were larger (mean height of weir 1.53m) compared to the English sites (mean 0.49m) with a longer ponded length (Mean length of ponded zone: Denmark 931m; Northern England 47m) and lower gradient. At the one site studied in northern England that did have a barrier >1m and a large ponded zone a clear response of the fish community was recorded following barrier removal.

The differences suggest that the greatest improvements derived from barrier removal are likely to be achieved when relatively large barriers (1-2m head) are removed at sites that have low gradient but which are not impacted by other factors such a poor water quality and have good potential for habitat restoration. Single obstacles that are near key sites such as confluences and which open long stretches of habitat are likely to have strong positive restoration effects. In contrast, where there are many small barriers (<0.5m) in a stream with moderate gradients (as was the case for most of the barrier removed in northern England), removal of individual barriers may not have an immediate effect and changes to more natural conditions may only be seen after the removal of multiple obstacles and take longer to see effects. When migratory fish species reappear and start using once-lost habitat it must be expected to see changes after some years. In England, our selection of barriers for removal (and as a consequence, those studied here) are not necessarily the ones that would be prioritised based on restoration reasons. Only a small proportion (<10%) of small barrier sites in Britain that would benefit from removal are approved because of flood protection, infrastructure, heritage, cost and other factors, restricting which ones are selected to be removed. The main driver for the significant change in Danish streams is that the barrier removals enabled sea-trout to access areas where they were not before or where there was no spawning habitat before. Thus, in comparable streams without a good sea-trout population downstream a barrier, the response will be less significant and less immediate.

We also recorded the recolonization of some rarer species at some of the Danish sites. European eels (*Anguilla Anguilla*), gudgeon (*Gobio gobio*), brook lamprey (*Lampetra plenari*) and grayling (*Thymallus thymallus*) were detected at 7 of the 12 sites, and were previously completely absent, suggesting some form of benefit for those species as well. Gudgeon tend to prefer sandy bottoms, and may have recolonized the area due to sediment release. As such, we may expect them to become absent in the future once all the trapped sediment has flowed away. However, eel, grayling and brook lamprey are all species that require rather pristine conditions, and are thus a positive indicator of the benefits of barrier removal.

Although little change in fish abundance or community was seen in England, barrier removal provides connectivity for migration, dispersal and recolonization that is not reflected in the abundance/assemblage measures recorded in this study. The lack of a short-term improvement in fish community at the English sites should not be misinterpreted as showing that barrier removal has not been beneficial.

Figure 3.2.17. Species detected during electrofishing surveys following the removal of the barriers. From top to bottom: brown trout (*Salmo trutta*), brook lamprey (*Lampetra plenari*), grayling (*Thymallus thymallus*), gudgeon (*Gobio gobio*) and European eel (*Anguilla anguilla*). Images by Kim Birnie-Gauvin © (reproduction without permission is prohibited).

6 REFERENCES

Aadland, L. R. 1993. Stream habitat types: Their fish assemblages and relationship to flow. North *American Journal of Fisheries Management* 13: 790-806.

Abbaspour, K.C., 2011. SWAT-CUP4: SWAT calibration and uncertainty programs–a user manual. Swiss Federal Institute of Aquatic Science and Technology, Eawag.

Addy, S., Cooksley, S., Dodd, N., Waylen, K., Stockan, J., Byg, A. & Holstead, K. 2016. *River Restoration and Biodiversity*. IUCN, New York.

Alba-Tercedor, J. & Sanchez-Ortega, A. 1988. Un método rápido y simple para evaluar la calidad biológica de las aguas corrientes basado en el de Hellawell (1978). *Limnetica* 4: 51-56.

Atkinson, S., Carlsson, J.E.L., Ball, B., Egan, D., Kelly-Quinn, M., Whelan, K., Carlsson, J. 2018. A quantitative PCR-based environmental DNA assay for detecting Atlantic salmon (Salmo salar L.). *Aquatic Conserv: Mar Freshw Ecosyst* 28: 1238–1243. https://doi.org/10.1002/aqc.2931

Atlas y Libro Rojo de los Peces Continentales de España. Madrid: Dirección General de Conservación de la Naturaleza, Museo Nacional de Ciencias Naturales.

Bach, J. M., I. Caut, M. Lelièvre & J. Viallard. 2004. Suivi de la dévalaison 2004 des saumoneaux au droit du barrage de Poutès. LOGRAMI, Saint Pourçain sur Sioule.

Backiel, T. 1985. Fall of migratory fish populations and changes in commercial fisheries in impounded rivers in Poland - *Habitat Modification and Freshwater Fisheries*: 28-41.

Bain, M.B. & Meixler, M.M. (2008). A Target Fish Community to Guide River Restoration. *River Research and Applications* 24(4): 453 – 458. doi: 10.1002/rra.1065.

Baisez, A., J.-M. Bach, C. Leon, T. Parouty, R. Terrade, M. Hoffmann & P. Laffaille. 2011. Migration delays and mortality of adult Atlantic salmon Salmo salar en route to spawning grounds on the River Allier, France. Endangered species research 15:265-270.

Barea-Azcon, J.M., Ballesteros-Duperón, E. & Moreno, D. (coords.) 2008. Libro Rojo de los Invertebrados de Andalucía. Sevilla: Junta de Andalucía, Consejería de Medio Ambiente.

Barry, J., Coghlan, B., Cullagh, A., Kerr, J. R. & King, J. J. 2018. Comparison of coarse-resolution rapid methods for assessing fish passage at riverine barriers: ICE and SNIFFER protocols. *River Research and Applications*, *34*(9), 1168-1178.

Barry, J., Mc Loone, P., Fitzgerald, C., King, J.J. (In Press) The Spatial ecology of Brown Trout (Salmo trutta) and Dace (Leuciscus leuciscus) in an artificially impounded riverine habitat: results from an acoustic telemetry study. *Aquatic Sciences*.

Bartel, R. 1993. Present situation of the Vistula sea trout. *Arch.Ryb.Pol*. 1: 101-203.

Bartel, R. 2002. Diadromous fish, their commercial importance, and restoration programs for these species. *Supplement of Acta Hydrobiologica* 3: 37-55 (in Polish).

Bartel, R., Wiśniewolski, W. & Prus, P. 2007. Impact of the Wloclawek dam on migratory fish in the Vistula River. *Archives of Polish Fisheries* 15: 141-156.

Baselga, A. & Orme, C.D.L., 2012. betapart: an R package for the study of beta diversity. *Methods in Ecology and Evolution* 3: 808–812. https://doi.org/10.1111/j.2041-210X.2012.00224.x

Baselga, A. 2012. The relationship between species replacement, dissimilarity derived from nestedness, and nestedness. *Global Ecology and Biogeography* 21: 1223–1232. https://doi.org/10.1111/j.1466-8238.2011.00756.x

Baumgartner, L., Bettanin, M., McPherson, J., Jones, M., Zampatti, B. & Beyer K. 2012. Influence of turbidity and passage rate on the efficiency of an infrared counter to enumerate and measure riverine fish. *Journal of Applied Ichthyology* 28: 531-536.

Baumgartner, L., Bettanin, M., McPherson, J., Jones, M., Zampatti, B. & Beyer, K. 2010. Assessment of an infrared fish counter (Vaki Riverwatcher) to quantify fish migrations in the Murray-Darling Basin, Industry & Investment NSW. *Fisheries Final Report Series* 116: 1-47. ISSN 1837-2112.

Benejam, Ll. 2008. Fish as ecological indicators in Mediterranean freshwater ecosystems Ph.D. Thesis.

Benson, D., Fritsch, O., Cook, H. & Schmid, M. 2014. Evaluating participation in WFD river basin management in England and Wales: Processes, communities, outputs and outcomes. *Land Use Policy* 38: 213–222. https://doi.org/10.1016/J.LANDUSEPOL.2013.11.004

Biegała, L. 1972. Fishway at the barrage in Włocławek - *Gospodarka Wodna* 5: 192-194 (in Polish).

Birnie-Gauvin, K., Aarestrup, K., Riis, T. M., Jepsen, N. & Koed, A. 2017. Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers, and its implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27: 1345-1349.

Birnie-Gauvin, K., Candee, M. M., Baktoft, H., Larsen, M. H., Koed, A. & Aarestrup, K. 2018. River connectivity reestablished: effects and implications of six weir removals on brown trout smolt migration. *River Research and Applications*, 34, 548-554. doi: 10.1002/rra.3271.

Birnie-Gauvin, K., Franklin, P., Wilkes, M. & Aarestrup, K. 2019. Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29, 1095-1105. doi: 10.1002/aqc.2946.

Birnie-Gauvin, K., Larsen, M. H., Nielsen, J. & Aarestrup, K. 2017b. 30 years of data reveal a dramatic increase in abundance of brown trout following the removal of a small hydrodam. *Journal of Environmental Management*, 204, 467-471. doi: 10.1016/j.jenvman.2017.09.022.

Birnie-Gauvin, K., Tummers, J.S., Lucas, M.C. & Aarestrup, K. 2017. Adaptive management in the context of barriers in European freshwater ecosystems. *Journal of Environmental* Management 204: 436-441.

Blackstock, K.L., Waylen, K.A., Dunglinson, J. & Marshall, K.M., 2012. Linking process to outcomes — Internal and external criteria for a stakeholder involvement in River Basin Management Planning. *Ecological Economics* 77: 113–122. https://doi.org/10.1016/J.ECOLECON.2012.02.015

Blanco, V., Brown, C., Holzhauer, S., Vulturius, G. & Rounsevell, M.D.A., 2017. The importance of socio-ecological system dynamics in understanding adaptation to global change in the forestry sector. *Journal of Environmental Management* 196. https://doi.org/10.1016/j.jenvman.2017.02.066

Bontemps, S. 1977. Fish migration through the fishway at the damn on the Vistula River. *Gospodarka Rybacka* 29: 18-19 (in Polish).

Bosc, S., Nars, A. & Menchi, O. 2017. Contrôle de la migration des smolts de saumon atlantique en dévalaison. Stations de Camon et Pointis sur la Garonne. Année 2017. Rapport MIGADO:51.

Bracken, F. S., Rooney, S. M., Kelly-Quinn, M., King, J. J. & Carlsson, J. 2019. Identifying spawning sites and other critical habitat in lotic systems using eDNA "snapshots": A case study using the sea lamprey Petromyzon marinus L. *Ecology and evolution*, *9*(1), 553-567.

Burnett, J. 2001. The highlands and Islands of Scotland as a 'cultural museum', 1900–2000: A century of migration. *Immigrants & Minorities* 20: 35–70. https://doi.org/10.1080/02619288.2001.9975008

Byrne, C. J., Poole, R.G. Rogan, Dillane, M. & Whelan, K. F. 2003. Temporal and environmental influences on the variation in Atlantic salmon smolt migration in the Burrishoole system 1970–2000. *Journal of fish biology* 63:1552-1564.

Calenge, C. 2011. Home range estimation in R: the adehabitatHR package. Office national de la classe et de la faune sauvage: Saint Benoist, Auffargis, France.

Callahan, B.J., McMurdie, P.J., Rosen, M.J., Han, A.W., Johnson, A.J.A. & Holmes, S.P. 2016. DADA2: High-resolution sample inference from Illumina amplicon data. *Nat Methods* 13: 581–583. https://doi.org/10.1038/nmeth.3869

Calles, O., Karlsson, S., Vezza, P., Comoglio, C. & Tielman, J. 2013. Success of a low-sloping rack for improving downstream passage of silver eels at a hydroelectric plant. *Freshwater Biology* 58:2168-2179.

Capra, H, Breil, P. & Souchon Y. 1995. A new tool to interpret magnitude and duration of fish habitat variations. *Regulated Rivers: Research & Management* 10(2-4): 281-289. https://doi.org/10.1002/rrr.3450100221.

Carle, F.L. & Strub, M.R. 1978. A new method for estimating population size from removal data. *Biometrics* 34: 621-630.

Castro-Santos, T., Haro, A. & Walk, S. 1996. A passive integrated transponder (PIT) tag system for monitoring fishways. *Fisheries Research* 28: 253-262.

Chisholm, C, 1876. Transactions, Transactions of the Gaelic Society of Inverness. Stirling, Scot.

Cimarelli, L., Singh, K. S., Mai, N. T., Dhar, B. C., Brandi, A., Brandi, L., & Spurio, R. 2015. Molecular tools for the selective detection of nine diatom species biomarkers of various water quality levels. *International Journal of Environmental Research and Public Health, 12(5)*, 5485–5504.

CNSS. 2013. Suivi de la dévalaison dans la zone refuge à l'aide de tambours rotatifs à Alleyras et Chanteuges Année 2013. Conservatoire National du Saumon Sauvage, Chanteuges.

CNSS. 2014. Suivi de la dévalaison dans la zone refuge à l'aide de tambours rotatifs à Alleyras et Chanteuges. Année 2014. Conservatoire National du Saumon Sauvage, Chanteuges.
Cooke, S. J., Bunt, C. M., Hamilton, S. J., Jennings, C. A., Pearson, M. P., Cooperman, M. S., & Markle, D. F. 2005. Threats, conservation strategies, and prognosis for suckers (Catostomidae) in North America: insights from regional case studies of a diverse family of non-game fishes. *Biological Conservation*, 121: 317-331.

Cortes, R., Peredo, A., Terêncio, D., Sanches Fernandes, L., Moura, J., Jesus, J., Magalhães, M., Ferreira, P. & Pacheco, F., 2019. Undamming the Douro River Catchment: A Stepwise Approach for Prioritizing Dam Removal. *Water* 11: 693. https://doi.org/10.3390/w11040693

Courret, D., & Larinier, M. 2008. Guide pour la conception de prises d'eau Ichtyocompatibles pour les petites centrales hydroélectriques. GHAAPPE.

Coutant, C. C. & Whitney, R. R. 2000. Fish Behavior in Relation to Passage through Hydropower Turbines: A Review. *Transactions of the American Fisheries Society* 129:351-380.

Crozier, L. G. & Hutchings, J. A. 2014. Plastic and evolutionary responses to climate change in fish. *Evolutionary Applications* 7:68-87.

Cuinat, R. 1988. Atlantic Salmon in Extensive French River System: The Loire-Allier. In: Mills D., Piggins D. (eds) *Atlantic Salmon*. Springer, Dordrecht.

Dębowski, P. 2018c. The largest Baltic population of sea trout (*Salmo trutta* L.): its decline, restoration attempts, and current status. *Fisheries & Aquatic Life* 26: 81-100.

Dębowski, P. 2016. Fish passage through the Włocławek dam fishway in 2015. *Komunikaty Rybackie* 153: 1-7 (in Polish).

Dębowski, P. 2017. Fish passage through the Włocławek dam fishway in 2016. *Komunikaty Rybackie* 157: 1-6 (in Polish).

Dębowski, P. 2018a. Passage of vimba, Vimba vimba (L.), through the fish pass on the Włocławek dam, Vistula. *Roczniki Naukowe* PZW 31: 57-71(in Polish).

Dębowski, P. 2018b. Fish passage through the Włocławek dam fishway in 2017 and preliminary analysis of fish runs in 2015-17. *Komunikaty Rybackie* 163: 7-12 (in Polish).

Doadrio, S. Perea, Garzon-Heydt, P. & Gonzales, J. L. 2011. Ictiofauna continental española. Bases para su seguimiento. Madrid: Ministerio de Medio Ambiente y Medio Rural y Marino, D. G. Medio Natural y Política Forestal.

Dobson, D. 1994. Scottish emigration to Colonial America, 1607-1785. University of Georgia Press, Athens.

Drouineau, H., Carter, C., Rambonilaza, M., Beaufaron, G., Bouleau, G., Gassiat, A., Lambert, P., Le Floch, S., Tétard, S. & De Oliveira, E. 2018. River continuity restoration and diadromous fishes: Much more than an ecological issue. *Environmental Management* 61:671-686.

DWI, 2010. What are the drinking water standards? London.

Fee, E., Gerber, K., Rust, J., Haggenmueller, K., Korn, H. & Ibisch, P., 2009. Stuck in the clouds :Bringing the CBD's Ecosystem Approach for conservation management down to Earth in Canada and Germany. *Journal for Nature Conservation* 17: 212–227.

Fernández, S., Rodríguez, S., Martínez, J. L., Borrell, Y. J., Ardura, A. & García-Vázquez, E. 2018b. Evaluating freshwater macroinvertebrates from eDNA metabarcoding: A river Nalón case study. *PLoS ONE, 13*(8), e0201741.

Fernández, S., Sandin, M. M., Beaulieu, P. G., Clusa, L., Martinez, J. L., Ardura, A. & Garcia-Vazquez, E. 2018a. Environmental DNA for freshwater fish monitoring: insights for conservation within a protected area. *PeerJ, 6*, e4486.

Folke, C., Hahn, T., Olsson, P. & Norberg, J. 2005. Adaptive governance of socio-ecological systems. *Annual Review of Environmental Resources* 30: 441–473.

Folmar, L. C., & Dickhoff, W. W. 1980. The parr—Smolt transformation (smoltification) and seawater adaptation in salmonids: A review of selected literature. *Aquaculture* 21:1-37.

Forest Research, 2019. Phyto-threats workshop [WWW Document]. Workshop publication (November 2019). URL https://www.forestresearch.gov.uk/research/global-threats-from-phytophthora-spp/phytothreats-meetings-and-events/phyto-threats-workshop-november-2019/ (accessed 1.28.20).

Fraser-Mackintosh, C., 1897. Antiquarian notes, historical, genealogical, and social; second series: Inverness-shire, parish by parish. Inverness A & W. Mackenzie.

Friedland, K. D., MacLean, J. C., Hansen, L. P., Peyronnet, A. J., Karlsson, L., Reddin, D. G., Ó Maoiléidigh, N. & McCarthy, J. L. 2009. The recruitment of Atlantic salmon in Europe. *ICES Journal of Marine Science* 66:289-304.

Garcia de Leaniz, C., Belletti, B., Bizzi, S., Segura, G., Borger, L., Jones, J.,the AMBER consortium. 2018. The importance of having a good database for restoring river connectivity: The AMBER barrier atlas in Europe. In: Brink, K., Gough, P., Royte, J., Schollema, P.P., Wanningen, H. Eds. From Sea to Source 2.0. Protection and Restoration of Fish Migration in Rivers Worldwide. World Fish Migration Foundation, Groningen, 142–145.

Gauld, N. R., Campbell, R. N. B. & Lucas, M. C. 2013. Reduced flow impacts salmonid smolt emigration in a river with low-head weirs. *Science of the Total Environment* 458:435-443.

Gavira, O. & Garrido, S. 2019. Some notes on the river ecology of the Guadalhorce River. Symposium on connectivity in Mediterranean Rivers – AMBER project. September 2019.Gawne, B., Capon, S.J., Hale, J., Brooks, S.S., Campbell, C., Stewardson, M.J., Grace, M.R., Stoffels, R.J., Guarino, F. &

Everingham, P. 2018. Different conceptualizations of river basins to inform management of environmental flows. *Frontiers in Environmental Science*. https://doi.org/10.3389/fenvs.2018.00111

Geller, J., Meyer, C., Parker, M. & Hawk, H., 2013. Redesign of PCR primers for mitochondrial cytochrome c oxidase subunit I for marine invertebrates and application in all-taxa biotic surveys. *Mol Ecol Resour* 13: 851–861. https://doi.org/10.1111/1755-0998.12138

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. & Sitch, S. 2004. Terrestrial vegetation and water balance–Hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology* 286(1–4): 249–270.

Gilvear, D.J., Heal, K.V. & Stephen, A. 2002. Hydrology and the ecological quality of Scottish river ecosystems. *Science of The Total Environment*, 294: 131–159. https://doi.org/10.1016/S0048-9697(02)00060-8

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., et al. 2019. Mapping the world's free-flowing rivers. *Nature*, 569: 215.

Hagemann, S. & Dümenil, L. 2001. Validation of the hydrological cycle of ECMWF and NCEP reanalyses using the MPI hydrological discharge model. *Journal of Geophysical Research* 106: 1503–1510. doi:10.1029/2000JD900568.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y. & Tanaka, K. 2008. An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing. *Hydrology and Earth System Sciences* 12: 1007–1025. doi.org/10.5194/hess-12-1007-2008.

Hanasaki, N., Yoshikawa, S., Pokhrel, Y. & Kanae, S. 2018. A global hydrological simulation to specify the sources of water used by humans. *Hydrology and Earth System Sciences* 22: 789–817. doi.org/10.5194/hess-22-789-2018.

Havn, T. B., Thorstad, E. B., Teichert, M. A. K., Sæther, S. A., Heermann, L., Hedger, R. D., Tambets, M., Diserud, O. H., Borcherding, J. & Økland, F.. 2018. Hydropower-related mortality and behaviour of Atlantic salmon smolts in the River Sieg, a German tributary to the Rhine. *Hydrobiologia* 805:273-290.

Herrera Grao, T. (editor.) 2008. Evaluación de los ecosistemas, grado de estado ecológico de las aguas y valores histórico-patrimoniales de Río Grande (Málaga) y campaña educativa, de divulgación y sensibilización ciudadana de sus valores. Málaga: Informe elaborado para la Fundación Nueva Cultura del Agua.

Hüesker, F. & Moss, T. 2015. The politics of multi-scalar action in river basin management: Implementing the EU Water Framework Directive (WFD). *Land Use Policy* 42: 38–47. https://doi.org/10.1016/J.LANDUSEPOL.2014.07.003

Huson, D.H., Beier, S., Flade, I., Górska, A., El-Hadidi, M., Mitra, S., Ruscheweyh, H.-J. & Tappu, R. 2016. MEGAN Community Edition - Interactive Exploration and Analysis of Large-Scale Microbiome Sequencing Data. *PLoS Computational Biology* 12, e1004957.

Huusko, R., P. Hyvärinen, M. Jaukkuri, A. Mäki-Petäys, P. Orell & J. Erkinaro. 2017. Survival and migration speed of radio-tagged Atlantic salmon (Salmo salar) smolts in two large rivers: one without and one with dams. *Canadian journal of fisheries and aquatic sciences* 75:1177-1184.

Junta de Andalucía. 2009. Memoria: Plan Hidrológico de la Demarcación Hidrográfica de las cuencas mediterráneas andaluzas. 343 pp.

Imbert, H., Martin, P., Rancon, J., Graffin, V. & Dufour, S. 2013. Evidence of late migrant smolts of Atlantic salmon (Salmo salar) in the Loire-Allier System, France. *Cybium* 37:5-14.

Isaak, D. J., Young, M. K., Nagel, D. E., Horan, D. L. & Groce, M. C. 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. *Global Change Biology* 21:2540-2553.

Jábega Magazine No. 1 (1973) Edition Center of the Diputación de Málaga.

Jones, J., Börger,L., Tummers, J., Jones, P., Lucas, M., Kerr,J., Kemp, P. et al. 2019. A comprehensive assessment of stream fragmentation in Great Britain. *Science of the total environment* 673: 756-762.

Jonsson, B. & Jonsson, N. 2009. A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. *Journal of fish biology* 75:2381-2447.

Jonsson, N. & Jonsson, B. 2014. Time and size at seaward migration influence the sea survival of Salmo salar. *Journal of fish biology* 84:1457-1473.

Kemp, P.S. & O'Hanley, J.R. 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. *Fisheries Management and Ecology* 17: 297-322.

Kiesel, J., Gericke, A., Rathjens, H., Wetzig, A., Kakouei, K., Jähnig, S.C. & Fohrer, N. 2019. Climate change impacts on ecologically relevant hydrological indicators in three catchments in three European ecoregions. *Ecological Engineering* 127: 404–416.

King, J. J., & Linnane, S. M. 2004. *The status and distribution of lamprey and shad in the Slaney and Munster Blackwater SACs*. National Parks and Wildlife Service.

Kołder, W. 1958. Stocking of the upper Vistula River system with salmon and sea trout from 1879 to 1954. RNR 73-B-2: 215-267(in Polish).

Larinier, M. & Dartiguelongue, J. 1989. La circulation des poissons migrateurs: le transit a travers les turbines des installations hydroélectriques. *Bulletin français de la pêche et de la pisciculture* 312-313:1-94.

Larinier, M. & Travade, F. 2002. Downstream migration: problems and facilities. *Bulletin français de la pêche et de la pisciculture* 364 supplément:181-207.

Lea, K.J. 1969. Hydro-Electric Power Generation in the Highlands of Scotland. *Transactions of the Institute of British Geographers* 155. https://doi.org/10.2307/621414

Leray, M., Yang, J.Y., Meyer, C.P., Mills, S.C., Agudelo, N., Ranwez, V., Boehm, J.T. & Machida, R.J. 2013. A new versatile primer set targeting a short fragment of the mitochondrial COI region for metabarcoding metazoan diversity: application for characterizing coral reef fish gut contents. *Frontiers in Zoology* 10: 34. https://doi.org/10.1186/1742-9994-10-34

Limburg, K. E. & Waldman, J. R. 2009. Dramatic declines in North Atlantic diadromous fishes. *Bioscience* 59:955-965.

Linnik, V., Malinin, L.K., Woźniewski, M., Sych, R. & Dębowski, P. 1998. Movements of adult sea trout Salmo trutta L. in the tailrace of a low-head damat Wloclawek hydroelectric station on the Vistula River, Poland. *Hydrobiologia* 371/372: 335-337.

Lobb, M.D.& Orth, D. J. 1991. Habitat Use by an Assemblage of Fish in a Large Warmwater Stream. *Transactions of the American Fisheries Society* 120(1): 65-78. doi: 10.1577/1548-8659(1991)120<0065:HUBAAO>2.3.CO;2.

Lockwood, R. N. & Schneider, J. C. 2000. Stream fish population estimates by markand-recapture and depletion methods. Chapter 7 in Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, *Fisheries Special Report* 25, Ann Arbor.

Lucas, M. C. & Baras, E. 2001. Migration of Freshwater Fishes. Blackwell Science, Oxford, UK.

Marschall, E. A., Mather, M. E., Parrish, D. L., Allison, G. W. & McMenemy, J. R. 2011. Migration delays caused by anthropogenic barriers: modeling dams, temperature, and success of migrating salmon smolts. *Ecological Applications* 21:3014-3031.

McCormick, S. D., Hansen, L. P., Quinn, T. P. & Saunders, R. L. 1998. Movement, migration, and smolting of Atlantic salmon (Salmo salar). *Canadian journal of fisheries and aquatic sciences* 55:77-92.

McLean, M. 1991. People of Glengarry: Highlanders in Transition, 1745-1820. MQUP, Montreal, CANADA.

Migration delays and mortality of adult Atlantic salmon Salmo salar en route to spawning grounds on the River Allier, France. *Endangered species research* 15:265-270.

Minster, A. M. & Bomassi, P. 1999. Repérage et évaluation des surfaces potentielles de développement de juvéniles de saumons atlantiques. Proposition d'un modèle de gestion des stocks sur les bassins de l'Allier et de l'Arroux. LOGRAMI/CSP DR6.

Miya, M., Sato, Y., Fukunaga, T., Sado, T., Poulsen, J.Y., Sato, K., Minamoto, T., Yamamoto, S., Yamanaka, H., Araki, H., Kondoh, M. & Iwasaki, W. 2015. MiFish, a set of universal PCR primers for metabarcoding environmental DNA from fishes: detection of more than 230 subtropical marine species. *Royal Society Open Science* 2: 150088. https://doi.org/10.1098/rsos.150088

Monserrat, J. & Gavira, O. 2014. A new European species of Nevrorthus in the Iberian Peninsula (Insecta, Neuropterida). *Zootaxa*, 3796, (2): 349-360.

Morawska, B. 1968. Fish and fishery in Vistula River near Włocławek. Zesz.Nauk.SGGW, Zootechnika 7, Rybactwo 3: 23-56 (in Polish).

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3): 885-900.

Morita, K. 2018. Earlier migration timing of salmonids: an adaptation to climate change or maladaptation to the fishery? *Canadian journal of fisheries and aquatic sciences*: 1-5.

Mudie, R. (Ed.), 1842. The Caledonian Canal. surveyor, engineer and architect, 1840-1842; London 3, [97]-106.

National Records of Scotland Web, 2013. Electoral Ward Population Estimates (2011 Data Zone based) [WWW Document]. National Records of Scotland. URL /statistics-and-data/statistics/statistics-by-theme/population/population-estimates/2011-based-special-area-population-estimates/electoral-ward-population-estimates (accessed 3.8.20).

National Records of Scotland Web, 2016. Mid-2016 population estimates Scotland [WWW Document]. National Records of Scotland. URL /statistics-and-data/statistics/statistics-by-theme/population/population-estimates/mid-year-population-estimates/archive/mid-2016/list-of-tables (accessed 3.8.20).

Neto, S., Camkin, J., Fenemor, A., Tan, P.-L., Baptista, J.M., Ribeiro, M., Schulze, R., Stuart-Hill, S., Spray, C. & Elfithri, R. 2018. OECD Principles on Water Governance in practice: an assessment of existing frameworks in Europe, Asia-Pacific, Africa and South America. *Water International* 43: 60–89. https://doi.org/10.1080/02508060.2018.1402650

Niemi, G. J., Devore, P., Detenbeck, P., Taylor, N., Lima, D., Pastor, A. J., Yoint, J. D. & Naiman, R. J. 1990. Overview of case studies on recovery of aquatic systems from disturbance. *Environmental Management* 14: 571–587.

Nilsson, C., Reidy, C. A., Dynesius, M. & Revenga, C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science*, 308 : 405-408.

Novak, M. A. & Bode, R.W. 1992. Percent Model Affinity: A New Measure of Macroinvertebrate Community Composition. *Journal of the North American Benthological Society* 11(1): 80-85.

Nyqvist, D., Elghagen, J., Heiss, M. & Calles, O. 2018. An angled rack with a bypass and a nature- like fishway pass Atlantic salmon smolts downstream at a hydropower dam. *Marine and freshwater research* 69:1894-1904.

Nyqvist, D., Greenberg, L. A., Goerig, E., Calles, O., Bergman, E., Ardren, W. R. & Castro-Santos, T. 2017a. Migratory delay leads to reduced passage success of Atlantic salmon smolts at a hydroelectric dam. *Ecology of Freshwater Fish* 26:707-718.

Nyqvist, D., McCormick, S., Greenberg, L., Ardren, W., Bergman, E., Calles, O. & Castro-Santos, T. 2017b. Downstream Migration and Multiple Dam Passage by Atlantic Salmon Smolts. *North American Journal of Fisheries Management* 37:816-828.

Oleson K., Dai Y., Bonan G. B., Bosilovichm M., Dickinson R., Dirmeyer P., … Zeng, X. 2004. Technical Description of the Community Land Model (CLM) (No. NCAR/TN-461+STR). *University Corporation for Atmospheric Research*. doi:10.5065/D6N877R0.

Otero, J., L'Abée-Lund, J. H., Castro-Santos, T., Leonardsson, K., Storvik, G. O., Jonsson, B., Dempson, B., Russell, I. C., Jensen, A. J. & Baglinière, J. L. 2014. Basin-scale phenology and effects of climate variability on global timing of initial seaward migration of Atlantic salmon (Salmo salar). *Global Change Biology* 20:61-75.

Parasiewicz, P. & Adamczyk, M. 2014. Mesohabsim Simulation Model for riparian ichthyofauna habitats in consideration of stock conservation and fisheries management requirements. *Komunikaty Rybackie* 5 (142): 5-10.

Parasiewicz, P. 2007a. The MesoHABSIM model revisited. *River Research and Application* 23: 893–903.

Parasiewicz, P. 2007b. Using MesoHABSIM to develop reference habitat template and ecological management scenarios. *River Research and Application* 23: 924–932.

Parasiewicz, P. 2008a. Habitat time-series analysis to define flow-augmentation strategy for the Quinebaug River, Connecticut and Massachusetts, USA. *River Research and Application* 24: 439–452. doi: 10.1002/rra.1066.

Parasiewicz, P. 2008b. Application of MesoHABSIM and target fish community approaches for selecting restoration measures of the Quinebaug River, Connecticut and Massachusetts, USA. *River Research and Application* 24: 459–471. doi: 10.1002/rra.1064.

Parasiewicz, P., Ryan, K., Vezza, P., Comoglio, C., Ballestero, T. & Rogers, J.N. 2012. Use of quantitative habitat models for establishing performance metrics in river restoration planning. *Ecohydrology* 6(4): 668–678. doi:10.1002/eco.1350.

Parsons, K.M., Piertney, S.B., Middlemas, S.J., Hammond, P.S. & Armstrong, J.D. 2005. DNA-based identification of salmonid prey species in seal faeces. *J. Zoology* 266: 275–281.

Pires, A., Morato, J., Peixoto, H., Botero, V., Zuluaga, L. & Figueroa, A. 2017. Sustainability Assessment of indicators for integrated water resources management. *Science of the Total Environment* 578: 139–147. https://doi.org/10.1016/j.scitotenv.2016.10.217

Poff, N.L. & Ward, J. V. 1990. Physical habitat template of lotic systems: Recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management* 14(5): 629-645. doi: 10.1007/BF02394714.

Pracheil, B. M., DeRolph, C. R., Schramm, M. P. & Bevelhimer, M. S. 2016. A fish-eye view of riverine hydropower systems: the current understanding of the biological response to turbine passage. *Reviews in fish biology and fisheries* 26:153-167.

Prentice, E.F., Flagg, T.A., McCutcheon, C.A. & Brastow, D.F. 1990. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. *American Fisheries Society Symposium* 7: 323-334.

Priestley, J. 1831. Historical Account of the Navigable Rivers, Canals, and Railways of Great Britain. London.

R Development Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

R Development Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rivera, S. F., Vasselon, V., Jacquet, S., Bouchez, A., Ariztegui, D. & Rimet, F. 2018. Metabarcoding of lake benthic diatoms: from structure assemblages to ecological assessment. *Hydrobiologia, 807*(1): 37-51.

Robbins, P. & Fraser, A. 2003. A Forest of Contradictions: Producing the Landscapes of the Scottish Highlands. *Antipode* 35: 95–118. https://doi.org/10.1111/1467-8330.00304.

Roy, R., Beguin, J., Argillier, C., Tissot, L., Smith, F., Smedbol, S. & De-Oliveira, E. 2014. Testing the VEMCO Positioning System: spatial distribution of the probability of location and the positioning error in a reservoir. *Animal Biotelemetry* 2:1-7.

Sáez Gómez, P. 2010. *Análisis de la distribución histórica de la trucha común (Salmo trutta, Linnaeus, 1758) en Andalucía*. Revista Ríos con Vida nº 85. Pp 16-19. Madrid.

Santos, J.M., Pinheiro, P.J., Ferreira, M.T. & Bochechas, J. 2008. Monitoring fish passes using infrared beaming: a case study in an Iberian river. *Journal of Applied Ichthyology* 24: 26-30.

Schultz, L., Folke, C., Österblom, H. & Olsson, P. 2015. Adaptive governance, ecosystem management, and natural capital. *Proceedings of the National Academy of Sciences* 112: 7369–7374.

Scottish and Southern Energy, 2005. Power from the Glens - Neart nan Gleann.

Shardlow, T.F. & Hyatt, K.D. 2004. Assessment of the Counting Accuracy of the Vaki Infrared Counter on Chum Salmon. *North American Journal of Fisheries Management* 24: 249-252.

Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., et al. 2018. The future of fish passage science, engineering, and practice. *Fish and Fisheries*, 19: 340-362.

Silverman, B. W. 1986. Density estimation for statistics and data analysis. CRC press.

SNH, 2001. Natural heritage zones: a national assessment of Scotland’s fresh waters.

Steven, H.M., Carlisle, A. (Eds.), 1959. The native pinewoods of Scotland. Hartnolls Limited.

Stich, D. S., Bailey, M. M., Holbrook, C. M., Kinnison, M. T. & Zydlewski, J. D. 2015. Catchment- wide survival of wild-and hatchery-reared Atlantic salmon smolts in a changing system. *Canadian journal of fisheries and aquatic sciences* 72:1352-1365.

Stoof-Leichsenring, K.R., Epp, L.S., Trauth, M.H. & Tiedemann, R. 2012. Hidden diversity in diatoms of Kenyan Lake Naivasha: a genetic approach detects temporal variation. *Molecular Ecology* 21: 1918–1930. https://doi.org/10.1111/j.1365-294X.2011.05412.x

Sykes, G. E., Johnson, C. J. & Shrimpton, J. M. 2009. Temperature and flow effects on migration timing of Chinook salmon smolts. *Transactions of the American Fisheries Society* 138:1252- 1265.

Szupryczyński, J. 1986. Influence of the Włocławek reservoir on the geographical environment (summary), In: Szupryczyński J., ed., The Włocławek Reservoir – Some problems of physical geography. *Dokumentacja Geograficzna*. Instytut Geografii i Przestrzennego Zagospodarowania PAN, 7-24 (in Polish).

Teichert, N., Benitez, J. P., Dierckx, A., Tétard, S., Oliveira, E., De Trancart, T. Feunteun, E. & Ovidio, M. manuscript submitted for publication. Development of an accurate model to predict the phenology of Atlantic salmon smolt spring migration.

Tétard, S., Lemaire, M., De Oliveira, E. & Martin, P. 2016a. Use of 2D acoustic telemetry to study the behaviour of atlantic salmon smolts (Salmo salar) approaching Poutès Dam (Allier River, France). Paper 26123 in, Tétard S, Lemaire M, De Oliveira E, Martin P (eds.)in Proceedings of the 11th International Symposium on Ecohydraulics, The University of Melbourne, Australia.

Tétard, S., Lemaire, M., Martin, A. & De Oliveira, E. 2016b. Comportement des smolts de saumon atlantique (Salmo salar) au voisinage du barrage de Poutès (Allier, France). Bilan des études de télémétrie acoustique réalisées en 2014 et 2015. EDF R&D.

Tétard, S., Maire, A., Lemaire, M., De Oliveira, E., Martin, P. & Courret, D. 2019. Behaviour of Atlantic salmon smolts approaching a bypass under light and dark conditions: Importance of fish development. *Ecological Engineering* 131:39-52.

The Scottish Government, 2014. Environmental Protection - The Scotland River Basin District (Standards) Directions 2014.

Thorstad, E. B., Havn, T. B., Sæther, S. A., Heermann, L., Teichert, M. A. K., Diserud, O. H., Tambets, M., Borcherding, J. & Økland, F. 2017. Survival and behaviour of Atlantic salmon smolts passing a run-of-river hydropower facility with a movable bulb turbine. *Fisheries Management and Ecology* 24:199-207.

Thorstad, E. B., Økland, F., Aarestrup, K. & Heggberget, T. G. 2008. Factors affecting the within- river spawning migration of Atlantic salmon, with emphasis on human impacts. *Reviews in fish biology and fisheries* 18:345-371.

Thorstad, E. B., Whoriskey, F., Uglem, I., Moore, A., Rikardsen, A. H. & Finstad, B. 2012. A critical life stage of the Atlantic salmon Salmo salar: behaviour and survival during the smolt and initial post-smolt migration. *Journal of fish biology* 81:500-542.

Tomanova, S., Courret, D. & Alric, A. 2017. Protecting fish from entering turbines: the efficiency of a low-sloping rack for downstream migration of Atlantic salmon smolts. *La Houille Blanche*: 11-13.

Tomanova, S., Courret, D., Alric, A., De Oliveira, E., Lagarrigue, T. & Tétard, S. 2018. Protecting efficiently sea-migrating salmon smolts from entering hydropower plant turbines with inclined or oriented low bar spacing racks. *Ecological Engineering* 122:143-152.

Toro, M., Robles, S., Tejero, I., Cristóbal, E., Velasco, S., Sánchez, J.R. & Pujante, A. 2009. Grupo 32. Tipo Ecológico Nº 7. Ríos mineralizados mediterráneos de baja altitud. En: VV.AA., Bases ecológicas preliminares para la conservación de los tipos de hábitat de interés comunitario en España. Madrid: Ministerio de Medio Ambiente, y Medio Rural y Marino. 14 pp.
Tummers, J.S., Hudson, S. & Lucas, M.C. 2016. Evaluating the effectiveness of restoring longitudinal connectivity for stream fish communities: towards a more holistic approach. *Science of the Total Environment* 569: 850-860.

van Beek, L.P.H., Wada, Y. & Bierkens, M.F.P. 2011. Global monthly water stress: 1. Water balance and water availability. *Water Resources Research* 47: 1-25. doi.org/10.1029/2010WR009791.

van Vuuren, D.P., Edmonds, J., Kainuma, M. et al. 2011. The representative concentration pathways: an overview. *Climatic Change* 109(5). doi.org/10.1007/s10584-011-0148-z.

Vörösmarty, C., Sahagian, D. & Vörösmarty, C.J. 2000. Articles Anthropogenic Disturbance of the Terrestrial Water Cycle RECENT ANALYSIS DEMONSTRATES THAT HYDRAULIC ENGINEERING HAS PRODUCED GLOBAL-SCALE IMPACTS ON THE TERRESTRIAL WATER CYCLE, BioScience.

Vörösmarty, C.J., Federer, C.A. & Schloss, A. 1998. Potential evaporation functions compared on US watersheds: possible implications for global-scale water balance and terrestrial ecosystem modeling. *Journal of Hydrology* 207: 147–169. doi:10.1016/S0022-1694(98)00109-7.

Vörösmarty, C.J., Pahl-Wostl, C., Bunn, S.E. & Lawford, R. 2013. Global water, the anthropocene and the transformation of a science. *Current Opinion in Environmental Sustainability*. https://doi.org/10.1016/j.cosust.2013.10.005

Whalen, K. G., Parrish, D. L. & McCormick, S. D. 1999. Migration timing of Atlantic salmon smolts relative to environmental and physiological factors. *Transactions of the American Fisheries Society* 128:289-301.

Wightman, A., Higgins, P., Jarvie, G. & Nicol, R. 2002. The Cultural Politics of Hunting: Sporting Estates and Recreational Land Use in the Highlands and Islands of Scotland. Culture, Sport, *Society 5*: 53–70. https://doi.org/10.1080/713999852

Williams, J. G., Armstrong, G., Katopodis, C., Larinier, M. & Travade, F. 2012. Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. *River Research and Applications* 28:407-417.

Winter, J. 1996. Advances in underwater biotelemetry. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland: 555-590.

Wiśniewolski, W. 1987. Commercial fish catches in the Vistula, Oder, and Warta rivers from 1953 to 1978. *Roczniki Nauk Rolniczych*, Seria H 101: 71-114 (in Polish).

Wiśniewolski, W. 1985. Population of vimba in multiannual fishery statistics. *Gosp.Ryb*.: 3-6 (in Polish).

Wiśniewolski, W. 2020. Przywrócenie migracji ryb na zaporze Zbiornika Włocławskiego warunkiem powodzenia restytucji ryb wędrownych w systemie środkowej i górnej Wisły. Konferencja Wylęgarnia 2020 (referat in Polish).

Wiśniewolski, W., Augustyn, L., Bartel, R., Depowski, R., Dębowski, P., Klich, M., Kolman, R. & Witkowski, A. 2004. Polish river continuity and restoring migratory fish. WWF Polska, Warszawa, 1-42 (in Polish).

Wood, E., 2010. The hydro boys: pioneers of renewable energy.

Woodget, A. S., Austrums, R., Maddock, I. P. & Habit, E. 2017. Drones and digital photogrammetry: from classifications to continuums for monitoring river habitat and hydromorphology. *WIREs Water* 2017, 4:e1222. doi: 10.1002/wat2.1222.

Woźniewski, M., Dębowski, P. & Bartel, R. 1999. Telemetric observations of the behaviour of Vistula sea trout (Salmo trutta morpha trutta L.) below the dam of Włocławek Reservoir in an attempt to improve fish passage. *Roczniki Naukowe* PZW 12: 5-18 (in Polish).

Żarnecki, S. 1960. Recent Changes in the Spawning Habits of Sea Trout in the Upper Vistula. *ICES Journal of Marine Science* 25: 326-331.

7 SUPPLEMENTARY INFORMATION

7.1 Quoich Dam, Upper River Garry

7.1.1 Bringing the evidence of Gaelic and material culture to freshwater ecology – Professor Hugh Cheape

[Gleanna Garadh agus Gleann na Cuaich, RLI AMBER Project, Inverness College, lecture Tuesday 13 March 2018.]

'Bu tu 'm bradan anns an fhìor-uisg' …' You were the salmon in freshwater…. Bringing the evidence of Gaelic and material culture to freshwater ecology.
Hugh Cheape

Preliminaries
Our title adopts a line from a Gaelic song composed in the early 1720s. It is from a moving elegy by Sileas na Ceapaich (c. 1660-1729) for *Alasdair Dubh*, Chief of Glengarry who died in 1721, and is highly significant for us because the poet uses a system of rhetoric and the formulae of classic panegyric widely recognised at the time. She enumerates the heroic and princely qualities of her subject, in this case in expressing the heroic virtues in a variety of 'kennings' as form of circumlocution; Alasdair is the 'noble' tree: 'Death often cuts and takes from us / the choicest and the tallest oaks'. He is likened

to the trees traditionally considered as 'noble' such as ash, apple, blackthorn, fir, hazel, oak and yew, and distanced from the trees considered 'servile' such as alder, aspen, birch, elder, elm and hawthorn.

This song, *Oran do Alasdair Ghlinne Garadh* (Watson 1932, 128-130), is outstanding in the Scottish Gaelic canon for its adherence to the conventions of the code of panegyric. The code offered a conceptual framework and sets of conventional images; these reaffirmed the traditional values of the community or the tribe by, *inter alia*, enumerating friends (and enemies) and the subject's place in a network of relationships, that is, of family, of ancestors and of allies. The conventional mode of address of the chief of Glengarry - *Mac 'ic Alasdair Chnòideart* – also fixed the subject within the network. Addressing the subject thus, *Bu tu 'm bradan* ……, comparing Alasdair to the salmon in freshwater, was not exceptional but was in fact in the bardic tradition a relative commonplace.

In lifting a Gaelic voice from the district from the early-eighteenth century to open a talk about Glengarry and Glen Quoich in the early-twenty-first century, I am making an unequivocal statement about my intentions. My aims are to explore the 'human ecology' of this area from the ground up, in order to enlarge our understanding of long-term settlement patterns and processes of change and movement of population, and, by drawing on a Gaelic voice, to mount a challenge to the conventional treatment of Highland history.

This talk and the research underpinning it is a contribution to the initiative of the Rivers and Lochs Institute's research in freshwater fisheries and biodiversity. It offers some pointers from history and language for the present-day management and conservation of the freshwater environment. It is built on a conviction that exploration of the human ecology of most parts of the Highlands and Islands should not or cannot neglect the Scottish Gaelic language and what the voice of the people of the area can tell us. In investigating the biodiversity of river systems, the AMBER project seeks to ameliorate or mitigate the impact of hydro-electric dams which are particularly prominent in Glengarry and Glen Quoich. The impact of barriers on people and landscapes is now a well-understood area of study, but these Highland dams have rarely been seen as such, since politico-cultural attitudes emphasize benefits and advantages. It is curious and perhaps a paradox that, in Gaelic tradition, this process has been described as *bàthadh nan Gleann* or 'the drowning of the Glens', and this is also significant for the usage of *bàthadh* in relation to the hydro schemes' 'smothering' or 'extinguishing' of life.

The 'hero' of the creation of a national hydro-electric energy scheme was Tom Johnston (1882-1965), Labour MP for West Stirlingshire. He was appointed by Churchill as Secretary of State for Scotland in 1941 and later described as 'the greatest of secretaries of state for Scotland'. He had nursed a scheme for hydro-electricity in the Highlands and saw in it a potential role in the reconstruction of post-war Scotland. The North of Scotland Hydro-Electric Board (*Bòrd Dealain-uisge Cheann-a-Tuath na h-Alba*) was set up by Act of Parliament in 1943, the *Achd Leasachaidh Dealain-uisge (Alba)* 1943. Tom Johnston withdrew from active political life at the end of the Second World War, but continued to direct the Hydro-Electric Board as a nationalised industry built on natural resources and strongly supported by public opinion.

Historiography

The assembling and writing of Highland and Island history has been subject to sometimes dramatic changes of fashion. An alternative or insider view might insist today that it had been blighted by this, not least because it can be assumed that this history had been composed and articulated - and consumed and regurgitated - outside the region. An early commentator on this intellectual status quo was Calum Maclean whose remarkable book in a Batsford series was published in 1960. Here we find: 'A new culture had penetrated the Rough Bounds – *Na Garbh-chriochan* – of the Gael and was sweeping before it all traces, all memories of the past. Before it became too late, I had to recover something that would give our contemporaries and the generations of the future some picture of the past. My sources of information were not to be guide-books, travellers' accounts or the prejudiced writings of formal historians. They had to be living sources breathing the air and treading the soil of Lochaber. They are, of course, the people who know most about Lochaber. In the past, generation after generation of them returned slowly to the dust and left not one single record of what they ever knew or leaned about their "patria". Without doubt, the transmission of knowledge had proceeded orally for centuries. The time had come when the process had ceased or was about to cease' (Maclean 1960, 40).

Recent scholarship in this subject area has improved hugely on what prevailed, but to an extent one stereotype has come to replace another. Earlier treatment was influenced by Sir Walter Scott and Romanticism and had depended heavily on an emphatic Highland-Lowland divide separating two races. This suited the critics and detractors because it also fed off an apartheid of 'them' and 'us', 'barbaric' and 'civilised'. The romantic reading of this took as its text the seductive prose of Scott which might take us to Loch Katrine and the Trossachs where we experience Highland grandeur and in which we encounter (in our imagination?) a kilted figure such as Rob Roy. On top of this critique we have the widely recognised image of a mountain landscape sparsely populated - or not populated at all if we are to accept SNH's 'wild land' classifications – the detailed scrutiny of which employs geology, botany, zoology and perhaps a little archaeology, but tends to ignore the living voice.

Scottish Historical Studies took on a new vitality from the 1970s, embedding itself in higher educational institutions and growing its quotient of Scottish history specialists in academic departments, not just in Scotland, but elsewhere in the UK and overseas, especially in North America. By moving into social and economic history in line with contemporary developments, it also developed specialisms that took on ideas and influences beyond a conventional discipline of history. This laid the basis of multi-disciplinary and inter-disciplinary studies which are now part of the academic currency of today.

One almost universal comment (or complaint) of the historian embarking on their study of the Highlands and Islands has been the absence of documentation for a satisfactory narrative and the lack of archival sources for any systematic analysis. This too-prevalent excuse has tended to a default position of cultural and ideological stereotypes. Current stereotypes forming the premise to analysis and interpretation, especially in the anglophone world, include the Jacobite wars, relative economic decline, rise in rents and land values, social and economic collapse, the move into large-scale sheep-farming, the 'Highland Clearances' and emigration, the creation of 'deer forests' and increasing government intervention with royal commissions and legislation. These themes of course are important and should not be abandoned. Without further theorising however, they form the baseline of an economic 'determinist' model. The Clearances for sheep tend to supply the lead story for what happened, and indeed this is largely true for Glengarry and Glen Quoich, but they comprise only one of a number of changes which account for how landscape changed.

We are becoming better equipped to meet these issues, sometimes head-on. One or two historians of Highland Historical Studies have opened up new dimensions and awarenesses, I would argue, because they are equipped with a fluency in the language. Here I am considering the work of the late Dr John Bannerman of Edinburgh University and of Dr Martin MacGregor and Dr Aonghas MacCoinnich, both of Glasgow University. Here Highland history is moved into cross-disciplinary modes and the practitioner approaches the subject with premises built on two or more disciplines such as history, languages and linguistics, and with a questioning of the material deriving from different disciplines.

An economic determinist model of enquiry and analysis would not deny the Highland Clearances, but too often fell short of what was needed for a fuller understanding of the circumstances of the dispossessed. The voice of the Gael would be ritually dropped into the account but, until too recently, drew on an excellent but strictly limited article on 'The Poetry of the Clearances' written by Sorley Maclean in 1938 and 1939. The school of Highland history is better equipped now with major contributions to the repertoire of potential sources such as Donald Meek's *Tuath is Tighearna. Tenants and Landlords*, an anthology of 44 poems and songs of social and political protest from the Clearances and the 'Land Wars'. The editor shows that the authors were factually accurate about the events they described and that the collection offers an important source for the historian. This touches on (and challenges) an argument that rejected literature and oral tradition as legitimate historical source material.

When Calum Maclean was writing in the late 1950s, oral tradition was not in the syllabus of the mainline historian. For Highland and Hebridean history, he was making a pitch for the voice of the folk. Amongst the people he recorded for the emergent School of Scottish Studies was John MacDonald of Highbridge - or 'John the Bard' as he was called locally. He gave 524 folktales to Calum Maclean. 'His father knew everything that ever happened in Lochaber', he had commented as he agreed to be recorded and a lengthy process ensued: '…… We continued to meet once weekly for a whole five months. Day after day he came and poured out the unwritten history of Lochaber. Everything that ever took place there seems to have left some imprint on his memory. ……. I regret that lamentably little of the fine traditions of Lochaber are being passed on to the younger generations. Men like John MacDonald of Highbridge, Archie MacInnes of Achaluachrach, and the late Allan Macdonell of Inverlochy could stand anywhere on the highway between Fort William and Roy Bridge and name every valley, every stream, every copse and every peak in an absolute sea of mountains as far as the human eye could reach. Their knowledge did not, however, stop at mere names. They knew the why and wherefore of them all' (Maclean 1960, 42-43, 58).

Cultural studies and a material turn

In an area that had suffered such catastrophic loss of population over two hundred years, has depopulation removed all our evidence for human ecology? Has a recent 'material' turn in academic studies anything to offer? If there is potential in 'material culture' enquiry, is there an acceptable intellectual position? Drawing material culture into interdisciplinary studies seems an acceptable and realistic option in the shifts in cultural history and widening of the discourse. In this context, Glengarry and Glen Quoich seem to offer ready opportunities for fresh investigation and alternative research pathways.

The evidence of objects augments our view of people in their absence, and prompts the development of new skills such as how to 'read' objects and, equally, how to 'read' the landscape. The combination of the passage of time since the clearance of, for example, Glen Quoich, the part-flooding of the landscape and the spread of forestry make it more difficult to spot the marks of settlement and occupation on the landscape. Sometimes countryside interpretation picks up on a dilemma such as this and adopts a site to explore for public access, for example with the former township of Daingeann. Marks on the landscape - what is sometimes termed the 'cultural landscape' - can add a vital dimension to what has been written down or otherwise recorded. In like measure, if we can identify former township sites, we can be guided to the voices that coalesced to create them - the *sluagh gun ghuth* ('people without a voice') of conventional history.

With a limited literature to hand, can we develop a satisfactory intellectual case? If we can engage with the materiality of the Glengarry past with its multiplicity of sites and structures, and a diversity of available evidence, we seem to have a rich cultural landscape and a mass of data. But for academic Highland history, this has not generally or conventionally been an accessible or acceptable raw material. Historians have been reluctant to imbue objects with the same authority as written texts and the study of material culture has been most obviously the domain of archaeology, anthropologists, folklorists, and museum curators. Here we have a range of allied and overlapping disciplinary perspectives, and drawing language onto the disciplinary palette, we have the opportunity to evolve methodologies that are interdisciplinary, multidisciplinary and / or cross-disciplinary.

Glengarry and Glen Quoich present a testing ground for a fresh methodological approach, in creating a field of study where we can observe the interplay of objects and texts. How we understand or interpret objects or the material conditions of life requires an additional interpretive level, so long as what information we have to hand has come in the first instance through the textual record. In addition, the survival of objects may possibly be random and the question can be posed as to what is gained in having a meaningful, direct, hands-on knowledge of objects and would this familiarity equip historians to gain insights into the past that might not otherwise be gained? And in considering linguistic evidence in this mass of data, are we in danger of embarking on emotive arguments?

For our purposes here, our concern is for everyday life and the material circumstances of people, and particularly those people and groups less evident in, or completely absent from the historical record. Among those so clearly disenfranchised were women and this is an issue highlighted today in gender studies.

In terms of written history and documentary evidence, a standard source for any enquiry of this sort is the late-eighteenth and early-nineteenth centuries' collection of descriptions of parishes in the 'Statistical Accounts'. This is a series of printed reports from all the 938 parishes of Scotland, gathered together under a scheme instigated by Sir John Sinclair of Ulbster in the 1780s. The first series to be published appeared in 21 volumes between 1791 and 1799, and can be considered as a 'primary source' for the history of Scotland and an exceptional record by international standards. This is a treasure-trove of historical data on living communities, with studies of cultivation methods, animal husbandry, fishing, diet, population structure and growth, wages and price movements. Other topics appear such as antiquarian subjects and ancient monuments, language and literature. The scheme was based on a questionnaire circulated to parish ministers to gather in statistical data typifying the Enlightenment imperative to advance what was termed 'improvement' and to build what we would understand as political economy. This is not a monolithic source and the quality of information in each parish account depended critically on its author. As it happens a helpful illustration is in the accounts of the neighbouring parishes of Kilmonivaig and Kilmallie. The 64-year old minister of Kilmallie, Rev Alexander Fraser, produced a highly detailed 28-page essay while his neighbour preferred brevity!

A sense of place

The historical and political landscape of Glengarry and Glen Quoich can be briefly traced. The territories of Clan Donald stretched from the Western Isles to the Great Glen and beyond and, as events demonstrate, offered a significant threat to the emergence and consolidation of the Scottish nation state in the medieval period. This was the era when we enter into documentary history following a shift towards kingship under the Stewart dynasty built on feudalism and the introduction of written charters. Henceforward, the written word on parchment was the sole means of establishing and maintaining rights to lands occupied. In the Gàidhealtachd, of course, this precept was often challenged and the rights of parchment overturned by the sword. This era of 'The Lordship of the Isles' is an aspect of Highland and Hebridean history largely unrecognised or undefined before I F Grant's *The Lordship of the Isles* published in 1935. The 'Lordship' or *Tighearnas nan Eilean*, was a confederation of powerful and successful families or kindreds which included the MacDonalds of Sleat, the MacDonalds of Clanranald, Glengarry, Keppoch and Glencoe, claiming descent from Somerled and, further back in time, descent from the kings of Ireland.

Typically, within what amounts to a tribal society, lines of descent were chronicled in detail and celebrated continuously. This is immediately evident in the patronymic label attaching to the Glengarry family, *Mac 'ic Alasdair*, that is, 'Son of the son of Alexander', immediately identifying the ancestral family and the line within the web of relationships which comprised the wider family and the power structure that was 'Clan Donald'. The eponymous Alasdair or Alexander was the younger of the two sons of Donald who was the second son of Ranald, the eldest son of John, son of Angus Òg, the supporter of Bruce in the Wars of Independence. Genealogy tied the elite together.

The Glengarry family emerges about 1400 in the Lochaber and Knoydart districts and, according to their own 'clan history', a line of 16 chieftains followed descending until 1840 and the sale of the ancestral territories (see MacDonald 1995). The domain of the MacDonnells of Glengarry stretched an impressive 45 miles from east to west, from Aberchalder halfway between Fort Augustus and Invergarry, along the length of Glen Garry, through Glen Quoich to Barrisdale on Loch Hourn, and out to the western tip of Knoydart with Loch Hourn as the northern boundary and Loch Morar as the southern boundary.

A recent past

Defining features of the Glengarry MacDonnells were their adherence to Roman Catholicism and Jacobitism. These facts come out strongly in official papers and have left a strong mark on stories and traditions in the district (see also **Appendix I** for *SSPCK Minute Books*). The MacDonnells were involved in all the Jacobite wars from 1689 to 1745 and decisively attracted the hostility of the government. A detail (amongst many) serves to illustrate this aspect. About 1650, the Chief of Glengarry sent over to Ireland to find two priests for his people and immediate neighbours. Two Irish priests, Mr Francis White (a Lazarist) and Mr Dermid Grey, came from Spain. They entered their charge in the Glengarry estates in 1654. Mr Grey died in 1657 but Mr White laboured in the mission for much longer and died in 1679. His ministry was successful in gaining converts and confirming Catholics and his name was remembered in the district he served. His portrait was kept in a room in the Castle called 'Mr White's Room' ('Glengarry Notes' NLS MS 15169/23).

Their adherence to the Roman Catholic church worsened their situation in government eyes and their 'head house', the Castle of Invergarry, was continually being occupied by government troops or alternatively attacked and demolished. This is the building whose ruins stand on the site known as 'The Raven's Rock' on the north bank of Loch Oich. Much of what can be seen today is not ancient but is of seventeenth-century construction. The aspect of today's 'romantic ruin', beloved of the guidebooks, elides detailing such as very grand principal rooms and a former scale-and-plat staircase that indicate the *palazzo* scale and style of the building. The chief of Glengarry re-occupied the castle when he could, and rebuilt and refurbished it on separate occasions. The Duke of Cumberland and his forces blew up the castle on 29 May 1746 as part of a campaign of looting, burning and destruction that engulfed Lochaber following the Battle of Culloden.

An sluagh gun ghuth ('The people without a voice')

The changing fortunes of those not of the élite of the clan are not so readily mapped. Detecting a Gaelic voice was of course the aim of fieldwork by the School of Scottish Studies in Glengarry in 1963.

The Sound Archive includes interviews with Donald Robertson and Donald Macaskill, in the form of a conversation with the School's fieldworkers. The focus was on place names and place-name lore. There is a selection of stories such as on the historical *Blàr na Lèine* at the head of Loch Lochy, events such as murder, supernatural experiences, the inevitable tales about witchcraft, and other more mundane but none the less so interesting accounts of daily life, working the land, food and diet.

Other areas of research have included place names and the district is exceedingly fortunate to have the fruits of research of earlier proprietors and the remarkable *Place-Names of Glengarry and Glenquoich* (1898, 1931) (see Ellice 1931). Place names generally produce a comparatively rich tapestry of information on the occupation of land and its uses. On the OS maps there is a wealth of names and any number can be selected which offer insights into how the land was occupied and who lived there - Meall an Tagraidh, Teanga gun Urra, Coire Bo Chailein, Lochan na Diota, Allt na Caillich, Cnocan na h-Osnaich, Poll nan Con, Taigh 'an Mhic Dhughail, Creagan nan Gobhar, Bealach Streap, Bealach na h-Imrich, Rathad Fhionn, Creag Gilleasbuig, Mam a' Chroisg, Eilean na Cloinne, Creag a' Choit, Bac na Ceannaiche, Eilean Mhic Phee, Maol Cheann Dearg, Teanga Mhic an Aba, A' Ghurr Thionail Sron, and so on. Some names may also preserve local idioms or usages such as *Caochan* for a stream, *Cadha* for a pass. In a district which has suffered serious population depletion, place names preserve the names of former townships and areas of settled populations – with inferences for former land use and ecology. Former townships are known at Badantoig, Bolinn, Slios Min (including the lands of Faicheam Ard), Munerigie, Daingeann, and in Glen Quoich, Bail' Alasdair, Shian, Achaluachrach, Ardnabi and Dal Ruairidh.

Piquant evidence can sometimes be drawn from place names. The country is divided into regions and districts which are generally recognised and understood. For the observer, regional identity or personality might be vaguely evident but, apart from topography, one township is much like another. For the indweller by contrast, each is quite different from its neighbour. Perception of this and how it might be expressed might become the stuff of folk lore and is a well-recognised phenomenon in Scottish Gaelic, the term *frith-ainm* standing for 'bye-name' (see 'Taobh-tuath Earraghaidheal' 1963). Examples of this sort of characterisation have survived for Glengarry and Glen Quoich; for example, the farm townships of Glengarry such as Polnonachon were described thus, Poll an Aonachoin, 's am bi 'n fhorfhais air na h-eich; Gleann Laoigh, 's am bi 'n t-saothair a mach; Bo-Linn, 's am bi 'n t-im geal; Ladaidh riabhach nam ban boidheach.

All change and retreat from a traditional past

The clan lands were lost, not by military conquest but by the accumulation of debt which built up through the eighteenth century. Alexander MacDonnell of Glengarry died in 1761 and his heir was a minor. The estate was in the hands of lawyers. These debts had built up through the eighteenth century, resulting in the sale of North Morar in 1768 to General Simon Fraser of Lovat. Known traditionally as 'The Little Morar', this may have been the original patrimony of the Glengarry family and so its loss carried symbolic meaning (MacDonald 1995).

In 1772, Duncan MacDonnell of Glengarry married Marjory Grant, daughter of Sir Ludovic Grant of Dalvey. She came to be known as *Marsalaidh Bhinneach* (or 'Light-headed Marjory') and to be recognised for her personal aspiration to raise rents, clear debts and aggrandise the position of the Glengarry family. A further irony lies in the marriage of her daughter Eliza to the Chisholm of Strathglass in 1795, and, managing the estates for a weakly husband, Eliza instigated the clearance of Strathglass in 1801.

Marsalaidh Bhinneach raised the rents of the wadsetters and most emigrated. The people as a whole were facing higher rents and were unable to pay, and this is a consistently heard complaint through the 1780s. In addition, 'services' i.e. rents in kind such as 'carriages', peat cutting, fowls, butter and cheese, were converted to money payments, placing an extra burden on the people.

1782 was a notorious year of scarcity. As a consequence, in 1783-1784, those in debt were pursued, and 'hornings' and 'poindings' were issued for arrears. A watershed was passed in 1782 when the first sheep farmer from the Borders came into Glengarry. The Gillespie family applied for a lease of the lands of Glen Quoich, then in the proprietor's hands. This moment is well recorded in a letter from Mr Thomas Gillespie and Mr Henry Gibson dated Caplegill, 16 April 1782:

> 'Mr Gibson and I return you our joint thanks for the kindness and civility shown to Mr Gibson, junior, in recommending him in such strong terms to Mr Macdonell of Glengarry, with whom he has made a bargain – the articles transmitted to us for our approbation which we have agreed to and wrote Mr Macdonell so, begging of him to write us as soon as he received our letter, that we may take the proper measures for building houses for the reception of our herds against Whitsunday first, which is the term of entry'('Glengarry Notes' NLS MS 15169/115).

In 1785, the axe of removal fell on Glen Quoich. Fifty-five tenants, crofters and cottars were warned and decrees of removal and ejection served. They included an expected list of local names, MacDonnell, Macphee, Kennedy, MacLellan, Cameron, Stewart, MacCalkan, Macmillan, Gillies and Macintosh. Fifty-five heads of families amounted, say, to a local population in the region of 300 people. Another estimate put the numbers of cleared at over 500 (Chisholm 1877, 181). At the present stage of research, we can assume a distribution of the Glen Quoich population between Bunchosaidh, March Burn or Glashcullen, Aultbeath, Carn Ban, Bunchaoilie, Glenquoich, Doire Mhorgail, Poulary or Poll-àirigh, Tom Donn and Inshlaggan. A hundred years on, there was a settled population of only about 57, and a further 19 servicing the Ellice's Lodge and the Inn at Tom Donn, possibly no more than a population of between 70 and 80.

The raising of rents which had disgusted the Glengarry wadsetters or tacksmen and led to emigration has been treated by modern historians as a relatively benign phase of the Clearances, conventionally referred to as the 'tacksmen emigrations'. The settlement of 'Upper Canada', now Ontario, between 1785 and 1802 has been studied by Marianne McLean who challenged the position of Eric Richards and J M Bumsted that the clearances and sheep farms did not have a central role in provoking mass emigration (McLean 1994). Bumsted for example maintained that the early Highland emigrants were not the impoverished victims of the Clearances. A song (surviving in Nova Scotia) by a Knoydart man who left Loch Nevis on an emigrant ship in 1786 paints a different and bleak picture of coercive circumstances and deep reluctance to leave.

The Glengarry clearances proceeded in 1786 with removals from Ardochy and Munerigie on the north shore of Loch Garry, and the 1786 emigration from Knoydart and further emigration in 1802. In 1804, evictions notices were served in Knoydart on 11 heads of families. This was followed by the 1806 evictions of 19 families from Auchagirnach, Portban, Letterfearn, Laggan, North Laggan, Leek and Invervigar, and the 1808 evictions of 24 families from Letterfearn, Laggan, Shian, Auchagirnach, 'Old Ground' or Seann Talamh, Mandally, Invergarry, Skiary, Sandaig and Airor ('Glengarry Notes' NLS MS 15169/120-137).

The great-grandson of Glengarry of the '45, Alasdair Ranaldson MacDonell of Glengarry, succeeded in 1788 aged fifteen to his estates which were managed under a trust and the principal trusteeship of his mother, *Marsailidh Bhinneach*. Glengarry was known colloquially as *Alasdair Fiadhaich* ('Wild Alexander' or 'Alexander the Untamed'), and his career more than lived up to this epithet. He was known for his arrogance and a fierce temper as well as for an extravagant lifestyle. He was under the burden of legal cases including trial for murder and harassing the workforce constructing the Caledonian Canal and stealing their boats and materials (although he profited from land sales and provision of timber). He was referred to by the Canal Commissioners as 'our arch-enemy Glengarry'.

Work on the Canal was begun in 1803 and it was opened in 1822. Through these years Glengarry kept up his personal 'war' with the Commissioners with claims that he was underpaid for the lands purchased for the Canal, claims for injury to the fishings and damage to fishing rights, claims for loss of amenity and exclusive navigation of Loch Oich, claiming exclusive ownership of the Loch and seeking compensation for 'the rude and unceremonious visits of strangers and the public at large'. Glengarry was on his way to Edinburgh to consult his lawyers, but the steamer on which he was travelling on the first leg of his journey, *Stirling Castle*, was wrecked near the Corran Narrows in Loch Linnhe on 14 January 1828. Glengarry fell getting off the ship, struck his head and died that night. His debts and outstanding lawsuits it was said amounted to £80,000, possibly around £5m in today's prices. His legal battle against the Canal Commissioners carried on after his death and a conclusion was reported in the *Inverness Courier* on 9 June 1830:

> 'We understand that the important cause betwixt Glengarry and the Caledonian Canal Commissioners, which has been for some years in the Court of Session, was decided in favour of the Commissioners on Saturday last. The case related to the possession of Loch Oich, which is surrounded by lands belonging to Glengarry, and for the use of which, in the formation of the Canal, he claimed compensation from the Commissioners.' (Barron II, 80)

Another major enterprise in 'opening' up the district was the 'Glengarry Road' from Loch Oich to Loch Hourn. A contractor from Perth, who began work on a road in 1804, contracted to finish in 1806. He had estimated too low and weather conditions hampered progress. The road was finally completed to Loch Hourn about 1812. From then it was reported to be in constant use by drovers from Skye and timber traffic for the building of the Caledonian Canal (Haldane 1973).

The estates remained in the hands of their traditional owners until the 1830s. In a state of chronic indebtedness, they began to be sold. In 1839, the Glengarry estate was sold to the Marquis of Huntly for £80,000 and Glen Quoich to Mr Edward Ellice for £32,000. Huntly sold on Glengarry within a year, in October 1840, to Lord Ward for £91,000, who sold the estate for £160,000 to Edward Ellice in 1860. In 1879, the combined estates of Glengarry and Glen Quoich were recorded as totalling 99,500 acres. In terms of Highland landownership – and 'untainted' by any involvement in the Clearances – the Ellice family is remarkably interesting, and accessible through their family papers in the National Library of Scotland. Edward Ellice (1783-1863) was a merchant and politician, with mercantile interests in the West Indies and North America. He became MP for Coventry in 1818, standing on a Whig and radical platform. As a Whig, he was a forceful influence behind the passing of the first Reform Act in 1832.
On his Glen Quoich property, Ellice built a lodge on the shores of Loch Quoich. It was described as large but spartan. Here he entertained many of the leading political, literary and artistic figures of the day. As a matter of curiosity, Sir Edwin Landseer's iconic *Monarch of the Glen*, completed in 1851, was modelled it is said on the stags and landscape of Glen Quoich; besides his fame as artist, Landseer earned a reputation in deer stalking as a terrible shot. Sport was the main incentive for visiting

Glengarry and Glen Quoich and the Ellice Papers in the National Library offer copious evidence for this. Sport was not covered in the talk (or in this paper, but see **Appendix II**).

The estates descended from Edward Ellice, known as 'The Old Bear', to his son, Edward Ellice (1810-1880), Liberal MP for the St Andrews Burghs. In the 1840s and 1850s he took a strong interest in reform of the Scottish Poor Law. As critic of the existing system of Poor Relief and following the Knoydart evictions in 1853- 1854, he mounted an attack on the administration of the Poor Law in the West Highlands. In 1855, he published *A Letter to the Rt Hon Sir George Grey Bart MP in a Reply to a Report upon the Administration of the Poor Law in the Highlands of Scotland*. In 1857, the Knoydart portion of the former Glengarry Estate, containing 67,400, acres was put up for sale. Edward Ellice bid £90,000 for it but it was bought by James Baird who bid £90,200.

Edward Ellice junior built the Scots baronial-style mansion at Invergarry which was completed in 1869. When the house was acquired by the family of Cameron of Glen Nevis in 1959, it was converted into the Glengarry Castle Hotel. Ellice junior died in 1880 and was buried at Tor-na-Cairidh near Loch Garry. The estates passed to his first cousin, Edward Charles Ellice (1858-1934), who published *Place-Names of Glengarry and Glenquoich* in 1898 and expanded it, as has been mentioned, into a second edition in 1931.

This text is part of work-in-progress and makes no claim to a comprehensive history of Glengarry and Glen Quoich; rather, it offers a critique and number of thoughts and working tools for continuing research.

Sabhal Mòr Ostaig
An t-Ògmhios 2018]

Appendix I
'You were the salmon in freshwater …'
Rivers and Lochs Institute, Inverness College, UHI, 13 March 2018.
SPCK Minutes Volume III Fol. 68, 24 May 1721.
The Clerk presented and read a Petition from the Minister and Elders of the Parish of Kilmonivaig in the Braes of Lochaber, shewing that the said Parish being twenty-four miles in length from south west to north east and sixteen in breadth from west to east, ………. that the Parish again divides itself by a ridge of mountains into two countries very populous, but the people most ignorant and rude, and withal so poor, that few of them are in condition to give education to their children at schools; in this Parish are two great glens and Keppoch lyes in the centre, the one is called Glenroy, being ten miles in length belonging to McIntosh, belonging to the Duke of Gordon, consisting of twelve miles, and more than half of the inhabitants are papists, who apostasized to popery of late years, a list of their names and times of their apostacie is sent with the said Petition and produced, and as to such as yet profess themselves Protestants are far from being stable that way. That in the west and north side of the foresaid mountains are Dochanassie and Glengarry, the first is six miles long, inhabited by Camerons, all protestants, Glengarry consists of eleven miles, but full of woods and mountains, not very populous, but the inhabitants are all papists, the Reformation never took place among them, a list of their names are produced also, that in this Parish, ignorance, prophaneness, popish idolatrie and well worship have arrived to a great height, darkness prevails very much, Godliness ridiculed, and there was never a school settled therein, and were there one in it, not only would protestants, but even papists send their children thereto, and the Petitioners engage themselves to give all the encouragement and countenance in their power, and to use their utmost endeavours to get a considerable number of schollars, and propose Keppoch as the place for it, there being upward of

fourty children within two miles thereof fit for the school and no watter to hinder their attendance. The Petition also represents that two popish priests viz:- Peter McDonald an Irishman, and Grigor McGgrigor a Scotsman, resides there, and of late three more have joined them, and that these priests travel openly from place to place, say mass in every house publickly and frequently even within four miles of Fort William, and therefore craving that the Society would grant their Petition, and lay the lamentable case of the said Parish before these in Government, that orders may be given to the Garrison either to terrifie these priests or apprehend them.

SPCK Minutes Volume II Fol. 350: General Meeting, 4 November 1725.
English and Irish Vocabulary ordered.
The Committee further overtured as a means to extirpate the Irish language, that the Schoolmasters should oblige their Schollars every Saturday to turn a certain number of Irish words into English, and for their help herein that there be printed an English and Irish Vocabulary, and that it be sent to schools where Irish is spoken.

Appendix II
Inverness Courier 10 February 1841
An English gentleman, Mr Bainbridge, MP for Taunton, was lessee of the Glengarry shootings previous to the purchase of the property by Lord Ward; and annoyed by the loss of game, this gentleman set about a vigorous system of war and extermination against all the vermin intruders. He engaged numerous gamekeepers, paying them liberally, and awarding prizes to those who should prove most successful. These rewards varied from £3 to £5 each, and the keepers and watchers pursued the slaughter with undeviating rigour and attention. The result was the destruction, within three years, of above four thousand head of vermin, and a proportional increase in the stock of game. Having been furnished with a complete list by Mr Scott, manager of the Glengarry Estates, the list of the vermin destroyed at Glengarry from Whitsunday 1837 to Whitsunday 1840 is subjoined:

> 11 Foxes, 198 Wild Cats, 246 Marten cats, 106 Pole cats, 301 Stots and weasels, 67 Badgers, 48 Otters, 78 House cats, going wild, 27 White-tailed sea eagles, 15 Golden eagles, 18 Osprey or fishing eagles, 98 Blue hawks or peregrine falcons, 7 Orange-legged falcons, 11 Hobby hawks, 275 Kites, commonly called salmon-tailed gledes, 5 Marsh harriers or yellow-legg'd hawks, 63 Goshawks, 285 Common buzzards, 371 Rough-legged buzzards, 3 Long buzzards, 462 Kestrel or red hawks, 78 M artin hawks, 83 Hen harriers or ring-tailed hawks, 6 Ger falcon toe-feathered hawks, 9 Ash-coloured hawks, 1,431 Hooded or carrion crows, 475 Ravens, 35 Horned owls, 71 Common fern owls, 3 Golden owls, 8 Magpies.

Inverness Courier 15 September 1841
A Highland gathering, promoted by Lord Ward, was held in Glengarry. It was regarded as a novelty, and attracted a large attendance. A fuller notice of the gathering appears in the following issue, and a notice is given of the sport enjoyed by Lord Ward and his friends during the season. They had killed about a thousand brace of grouse, besides ptarmigan, roe and red deer, and black game. One fine stag was killed weighing 27 stone 3 lbs.

Bibliography and further reading
Beyond secondary sources listed below, the principal sources of information are the Ellice of Invergarry Papers in the National Library of Scotland, NLS MSS 15001-15195, and the collection of papers, references and resources held in the Glengarry Visitor Centre, Invergarry.

Barron, James (1913). *The Northern Highlands in the Nineteenth Century: newspaper index and annals*. Volumes I-III. Inverness 1903-1913.

Bumsted, J M (1982). *The People's Clearance. Highland Emigration to British North America, 1770-1815*. University of Manitoba Press and Edinburgh University Press.

Chisholm, Colin (1877(. The Clearances of the Highland Glens. *Transactions of the Gaelic Society of Inverness* Volume 6 (1876-1877), 174-188.

Dieckhoff, H C (1932). *A Pronouncing Dictionary of Scottish Gaelic based on the Glengarry Dialect according to oral information obtained from natives born before the middle of last century*.

Dwelly, Edward (1930). *The Illustrated Gaelic-English Dictionary 1901-1911*. Third Edition.

Ellice, Edward C (1931). *The Place-Names of Glengarry and Glenquoich*. London.

Haldane, A R B (1973). *New ways through the Glens. Highland road, bridge and canal makers of the early nineteenth century*. Edinburgh.

MacDonald, Norman H (1995). *The Clan Ranald of Knoydart and Glengarry*. Edinburgh.
Mackay, Iain (2004). *The Last Highland Clearance*. Inverness: Bidean Books.

Maclean, Calum (1973). *The Highlands*. New Edition. Inverness: Club Leabhar.

McLean, Marianne (1994). *The People of Glengarry. Highlanders in transition, 1745-1820*. McGill-Queen's Studies in Ethnic History.

Meek, Donald Ed. (1995). *Tuath is Tighearna. Tenants and Landlords*. Scottish Gaelic Texts Society.
Richards, Eric (1985). *A History of the Highland Clearances*. London.

[Ross, Donald] *The Glengarry Evictions, or Scenes at Knoydart*. 1853

'Taobh-tuath Earraghaidheal' (1963). Frith-ainmean, *An Gàidheal*. Leabhar LVII, Aireamh 8 (An Lùnastal 1963), 91-92.

Watson, William J (1932). *Bàrdachd Ghàidhlig*. Glasgow.

Figure 7.1.1. Neart nan Gleann: Gaelic advert for hydropower development (1954)

The advert shown in **Figure 7.1.1** was published on the Scottish Gaelic quarterly periodical *Gairm*, created in Glasgow in 1952, No. 8, Summer 1954, p.296. The advert was run through the 1950s in 3 or 4 versions and in a mixture of Gaelic and English. The curious detail in this, possibly the earliest of the adverts, is the clear note of nostalgia in the brief couplet that faces the Cruisie lamp, and it may be that this aspect of the message was dropped in later adverts in favour of a longer piece of explanatory text with a more direct message.

Power from the Glens
'The light of the cruisie, half the cèilidh,
The fragrance of the peat, a wee bit of the story ……..'
[Are you still a slave] to the old black kettle?
Housewife, are you still struggling with your grandmother's cooking equipment? You wont surely be wearing clothes that are out of fashion. Why then is your kitchen old-fashioned? Get yourselves involved in electricity and be shoulder-to-shoulder with other women who have every comfort in their housework.

7.1.2 eDNA field collection and lab processing methods

Field collection and filtration
Water samples were collected in 2L bottles, and then ~600 ml were filtered in triplicate from the same 2L bottle, to assess reproducibility and potential contamination issues. The filter chosen was a 0.45 cellulose nitrate filter, and filtering took place in the laboratory in a PCR-Free room using a vacuum manifold. Samples were initially collected and processed with enclosed filters and water filtered

through with a syringe, but long-term it was not deemed a satisfactory methodology if an option existed to filter in the lab the next day.

DNA extraction

Samples were extracted in our eDNA laboratory. This room is separated from the main laboratory that contains PCR products. Separate lab coats and gloves are used in the eDNA room. All samples were extracted inside a UV cabinet. Benches and equipment were treated with 10% bleach before extractions and the UV cabinet was left on for 30 minutes to destroy any DNA on the surfaces.

Samples were extracted using the Qiagen DNeasy powersoil kit following the standard protocols except that the samples were eluted in 50ul rather than 100ul to increase their concentration. Samples were DNA extracted in batches of 24 including one extraction blank.

Library preparation

Briefly, the library preparation workflow was carried out according to the 16S Metagenomic Sequencing Library Preparation Protocol by Illumina. The workflow follows a two-step polymerase chain reaction (PCR) that includes a primary PCR amplification (Amplicon PCR), where the selected fragment is amplified using specific primers, with Illumina overhang adapters attached to the 5' end of the primers. A second PCR (index PCR) attaches Illumina-specific sequencing adapters and indices to the first PCR product according to the dual indexing strategy. A combination of 8 forward and 12 reverse indices allow for up to 96 samples to be uniquely identified by the combination of these tags. Demultiplexing of samples after sequencing allowed the sequences to be connected to their samples.

Amplicon PCRs were carried out in triplicate and triplicate PCR negatives were added to each plate. Negative controls used nuclease free water instead of DNA. Field, filtration, and extraction blanks were added throughout the pcr plates. Amplicon PCRs were carried out using the following protocols found in Appendix 2

Samples were quantified using a QIAxpert System (Qiagen) and normalized with 10mM Tris pH 8.5 to 5ng/µl using a QIAgility System (Qiagen). Then 5µl of each normalised library were combined into a single pool containing all individual sample libraries.

The final pooled library was quantified by quantitative PCR (qPCR) using the KAPA Library Quantification Kit for Illumina (Roche). This assay specifically quantifies the amount of Illumina-adapter ligated DNA (rather than total DNA in the sample) as only ligated fragments will get sequenced. Prior to the qPCR reaction the final pooled library was diluted twice according to the KAPA Library Quantification Kit Technical Data Sheet. Reactions were also run in triplicate. The qPCR reaction and thermal cycling conditions were as follows:

Reaction volumes

	Volume
Final pooled library/ DNA standards	4 µl
KAPA SYBR Fast qPCR Master Mix (2X) combined with Primer Mix (10X)	12 µl
ROX Low(50X)	0.4 µl
Nuclease Free H_2O	3.6 µl
Total	20 µl

Thermal cycling conditions

95° C for 5 minutes

35 cycles of:

95° C for 30 seconds

60° C for 45 seconds

For COI a Version 3 (V3) chemistry MiSeq cartridge was used with runs of 600-cycles. For RBCL and 12S a version 2 (V2) MiSeq cartridge was used with runs of 300 cycles.

PCR conditions for eDNA marker amplification

RbcL Amplicon PCR

Primer sequences:

RBCL_705F	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAG	AACAGGTGAAGTTAAAGGTTCATAYTT
RBCL_808R	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAG	TGTAACCCATAACTAAATCGATCAT

(Stoof-Leichsenring et al., 2012)

Expected amplicon size (Ex primers) 76bp

Mastermix	X1
KAPA	6.25µl
Forward primer (10µm)	0.25 µl
Reverse primer (10µm)	0.25 µl
H20 (nuclease free)	4.5 µl
DNA	1.25 µl

Thermal cycling conditions

94°C 2mins

94°C 30s	X45
49°C 30s	
72°C 30s	

72°C 10min

4°C hold

12s Amplicon PCR
Primer sequences:
MiFish_U_F TCGTCGGCAGCGTCAGATGTGTATAAGAGACAG GTCGGTAAAACTCGTGCCAGC
MiFish_U_R GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCATAGTGGGGTATCTAATCCCAGTTTG
(Miya et al., 2015)
Expected amplicon size (ex primers) 125bp

Mastermix	X1
KAPA	6.25µl
Forward primer (10µm)	0.25 µl
Reverse primer (10µm)	0.25 µl
H20 (nuclease free)	3.75 µl
DNA	2 µl

Thermal cycling conditions
94°C 2mins

98°C 10s	X35
72°C 30s	
68°C 30s	

68°C 5min
4°C hold

COI Amplicon PCR

mclCOIintF	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAG	GGWACWGGWTGAACWGTWTAYCCYCC
NexR-JGhco2198N	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAG	TANACYTCNGGRTGNCCRAARAAYCA

(Geller et al., 2013; Leray et al., 2013)

Mastermix	X1 µl
Buffer (10x)	1.25 µl
MgCl2 (25mM)	1 µl
dNTPs (10mM)	0.25 µl
Bsa 920mg/ml)	0.5 µl
Forward primer (10µm)	0.75 µl
Reverse primer (10µm)	0.75 µl
Amplitaq Gold	0.1 µl
H20 (nuclease free)	5.9 µl
DNA	2 µl

Thermal cycling conditions
95°C 10mins

95°C 20s	X40
49°C 30s	
72°C 60s	

72°C 7min
4°C hold

7.1.3 Water quality analysis results

Laboratory analysis of samples

A wide range of water quality parameters were measured in the laboratories of the Environmental Research Institute (ERI; Table 2). Measurement of many of these parameters required pre-filtration, which was carried out using 0.45 µm Nylon syringe filters (Fisherbrand®, 33mm diameter). Three filter blanks (Milli-Q) were also prepared and analysed as samples to account for any contamination during the filtration process (as an internal QA/QC process).

Table 7.1.1: Water quality parameters measured and relevance of each to case study. Key water quality parameters for salmonid health are highlighted in blue.

	parameter	*field / lab*	*method*	*relevance*	*ref*
	pH	*field*	*Hanna HI 991300*	**low pH can negatively impact salmonids**	**1,2**
EC	**electrical conductivity**	*field*	*Hanna HI 991300*	**general water quality indicator**	
	temperature	*field*	*Hanna HI 991300*	**high temperature can negatively impact salmonids**	**3**
	turbidity	*lab*	*Hach turbidity meter*	**high turbidity can negatively impact salmon redds**	**1,4**
SS	**suspended solids**	*lab*	*Gravimetric; GFC filters*	**high SS can negatively impact salmon redds**	**1,4**
DOC	**dissolved organic carbon**	*lab*	*Shimadzu TOC-L (HTCC)*	**general water quality indicator, may interact with metals to reduce availability/toxicity**	
DIC	**dissolved inorganic carbon**	*lab*	*Shimadzu TOC-L (HTCC)*	**general water quality indicator**	
NH_4^+	**dissolved ammonium**	*lab*	*SEAL AQ2 discrete analyser (colorimetry)*	**juvenille salmonid sensitive to nutrient pollution**	**1,4**
TON	**total oxidised nitrogen**	*lab*	*SEAL AQ2 discrete analyser (colorimetry)*	**juvenille salmonid sensitive to nutrient pollution**	1,4
PO_4^{3-}	**dissolved phospate**	*lab*	*SEAL AQ2 discrete analyser (colorimetry)*	**juvenille salmonid sensitive to nutrient pollution**	1,4
SO_4^{2-}	**sulpahte**	*lab*	*SEAL AQ2 discrete analyser (colorimetry)*	**general water quality indicator**	
Al	**dissolved aluminium**	*lab*	*Varian ICP-OES 720ES*	**toxic to juvenille salmon in combination with low pH**	**1,2**
As	**dissolved arsenic**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Ca	**dissolved calcium**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
Cd	**dissolved cadmium**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Cr	**dissolved chromium**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Cu	**dissolved copper**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Fe	**dissolved iron**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
K	**dissolved potassium**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
Mg	**dissolved magnesium**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
Mn	**dissolved manganese**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
Na	**dissolved sodium**	*lab*	*Varian ICP-OES 720ES*	**general water quality indicator**	
Ni	**dissolved nickel**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Pb	**dissolved lead**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**
Zn	**dissolved zinc**	*lab*	*Varian ICP-OES 720ES*	**potentially toxic element in watercourses**	**3**

[1] Krogland, F. and Staurness, M. (1999). Water quality requirements of smelting Atlantic salmon (Salmo salar) in limed acid rivers, Canadian Journal of Fisheries and Aquatic Science, 56, 2078-2086, [2] Mills, D. (1989) Ecology and Management of Atlantic Salmon, Chapman and Hall, London, 337pp, [3] The Scottish Government (2014) Environmental Protection - The Scotland River Basin District (Standards) Directions 2014, [4]Hendry, K., Cragg-Hine, D., O'Grady, M, Sambrook, H. and Stephen, A. (2003). Management of habitat for rehabilitation and enhancement of salmonid stocks, Fisheries Research, 62, 171-192

Key water quality parameters

pH in water quality sampling sites ranged between pH 5.5 and 7.95 across the study. In general, there was little difference between sites, suggesting the loch and river water (upstream and downstream of the dams respectively) were similar. There were some exceptions, notably in the August 2019 sampling, where some loch and river sites differed somewhat. This was likely a consequence of the weather and river discharge conditions (and flow through the dam). The results suggest that dams generally had little effect on the water pH.

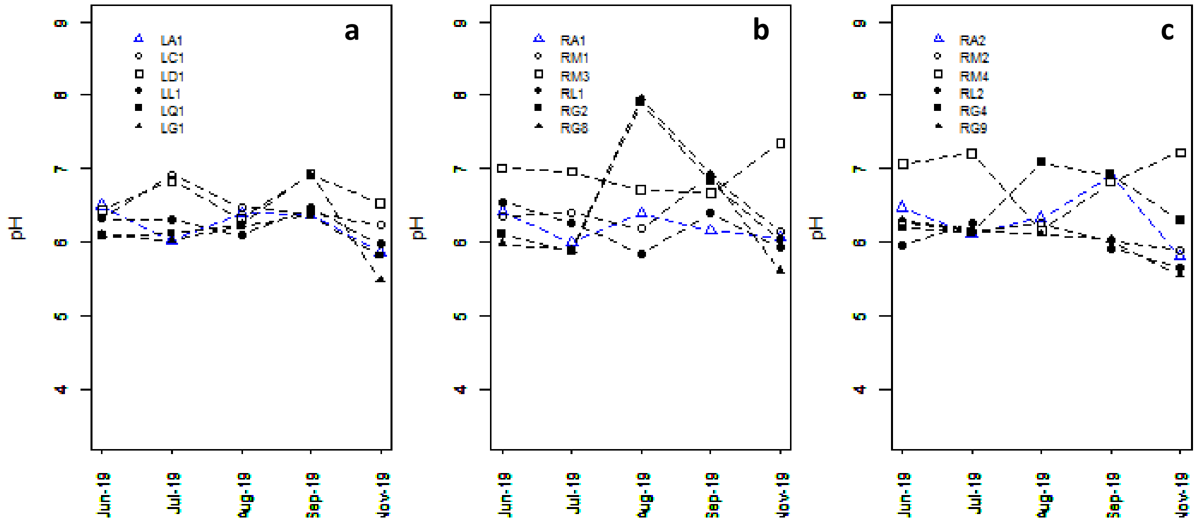


Figure 7.1.2: pH of AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Electrical conducutivty was similar between loch and river type sites and between the control system (Arkaig) and the other five loch-river systems in the GGHS. In general EC values were mostly around 30 µS cm^{-1}, with all values < 70 µS cm^{-1}. This is considerably lower than rivers in other parts of Scotland, i.e.Caithness (Gaffney, 2016), indicating that the GGHS watercourses contain low total concentrations of dissolved constituents such as metals and major ions.

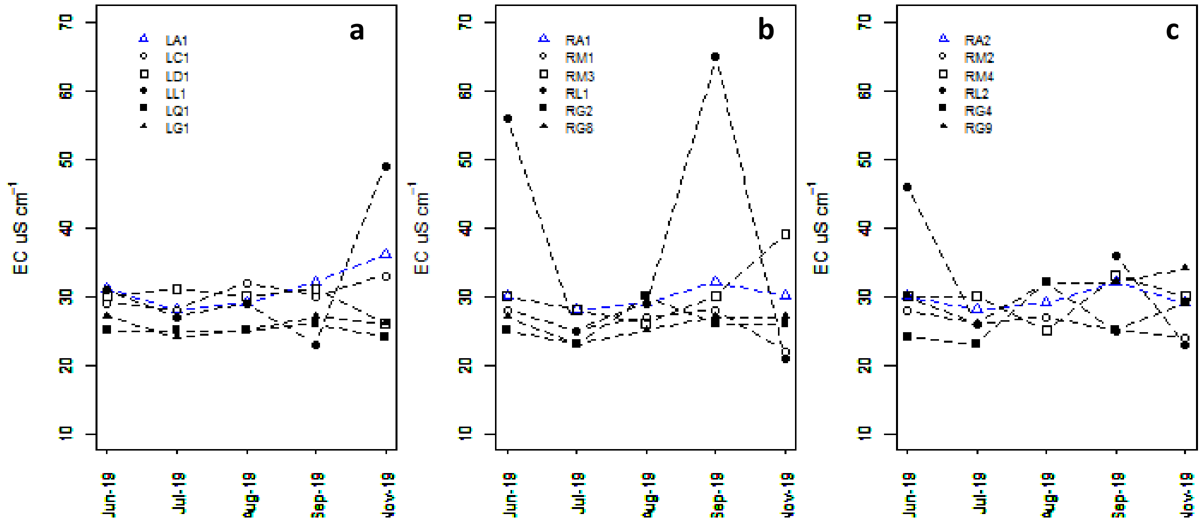


Figure 7.1.3: Electrical conductivity (EC) of AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Turbidity was generally low during the study with maximum levels of 3.2 NTU measured, which represents very low turbidity levels (and was lower than the UK drinking water standard of 4 NTU; (DWI, 2010). Small differences were observed between different loch and river sites, with values generally lowest on the Arkaig. Little difference was observed upstream and downstream of the dams within each system.

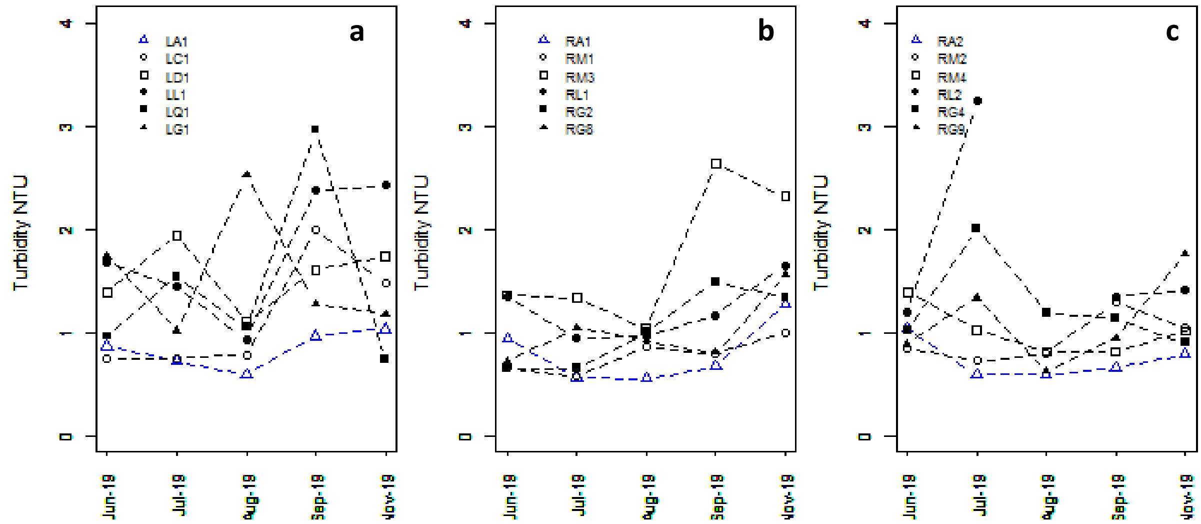


Figure 7.1.4: Turbidity of AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Suspended solid (SS) concentrations varied between the different loch and river sites, and over time. Concentrations were highest at Loch Quoich (site LQ1), in the Jul and September samples but generally lower downstream in the River Garry (sites RG2, RG4), although these sites were sometimes higher in SS concentration than other river sites. At all timepoints concentrations were generally lowest in the River Arkaig (control system). The higher SS concentrations in lochs was likely related to wave disturbance of sediment near the shore during sampling, and may not be as representative of the SS in the deeper waters.

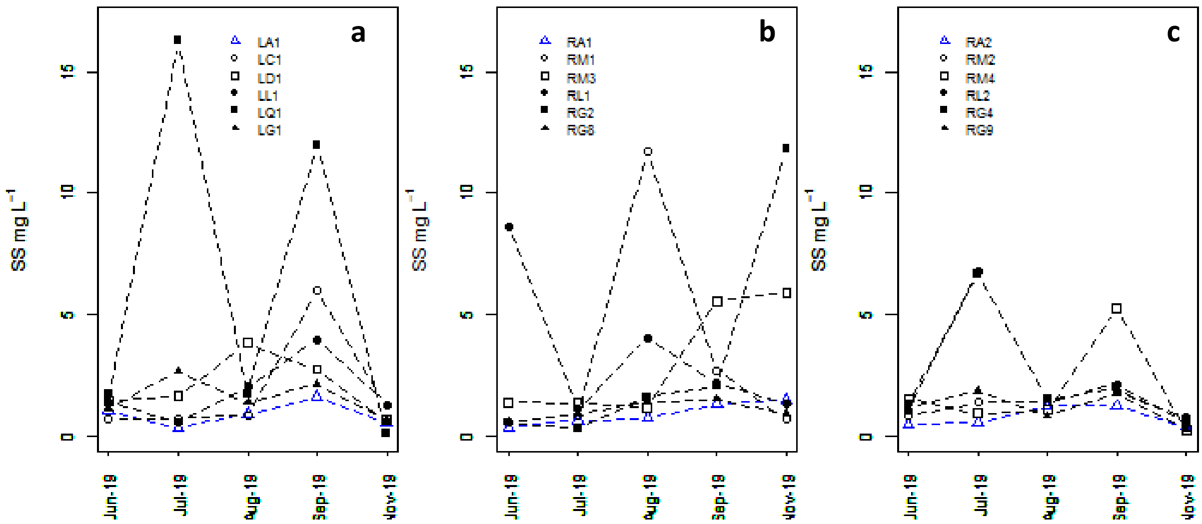


Figure 7.1.5: Suspended solid (SS) concentrations in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Concentrations of dissolved organic carbon (DOC) were generally similar upstream and downstream of dams, with some differences between sites. Concentrations everywhere were less than 14 mg L^{-1}, which represents fairly normal concentrations for upland rivers. DOC concentrations varied seasonally and with discharge conditions, which can be seen across the study. The main differences in DOC concentration were between catchments, and there were no measureable effects of dams.

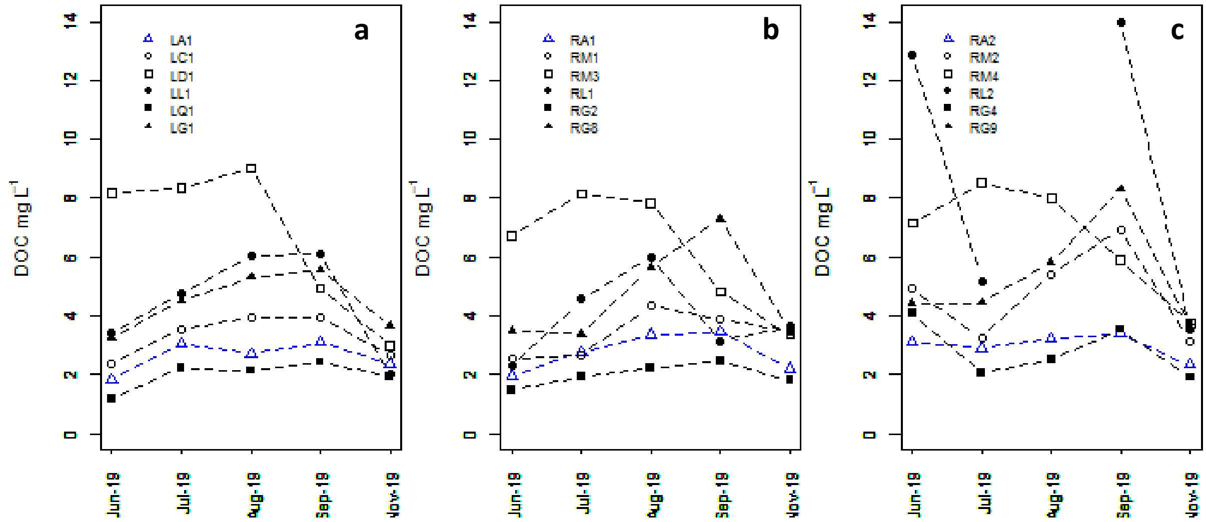


Figure 7.1.6: Dissolved organic carbon (DOC) concentrations in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Dissolved ammonium (NH_4^+) concentrations varied over time across the water quality sites and there were differences between the various loch and rivers sites. There were also differences within some catchments i.e. upstream and downstream of dams. This was most apparent in Loch Loyne and the River Loyne sites (Figure 5c; concentrations higher in the River immdiately downstream of the dam) and in Loch Quoich and the River Garry sites (Figure 5d; concentrations higher in the Loch). However, even in the Arkaig control catchment, there were differences between the loch and rivers sites, which shows this was not due to the effect of a dam.

Despite this, the NH_4^+ concentration differences between all sites were still relatively small. In general, NH_4^+ concentrations were low in terms of the Scottish Governments water quality standards (The Scottish Government, 2014), with all sites achieving "high" quality status (<160 µg N L^{-1}). Sites

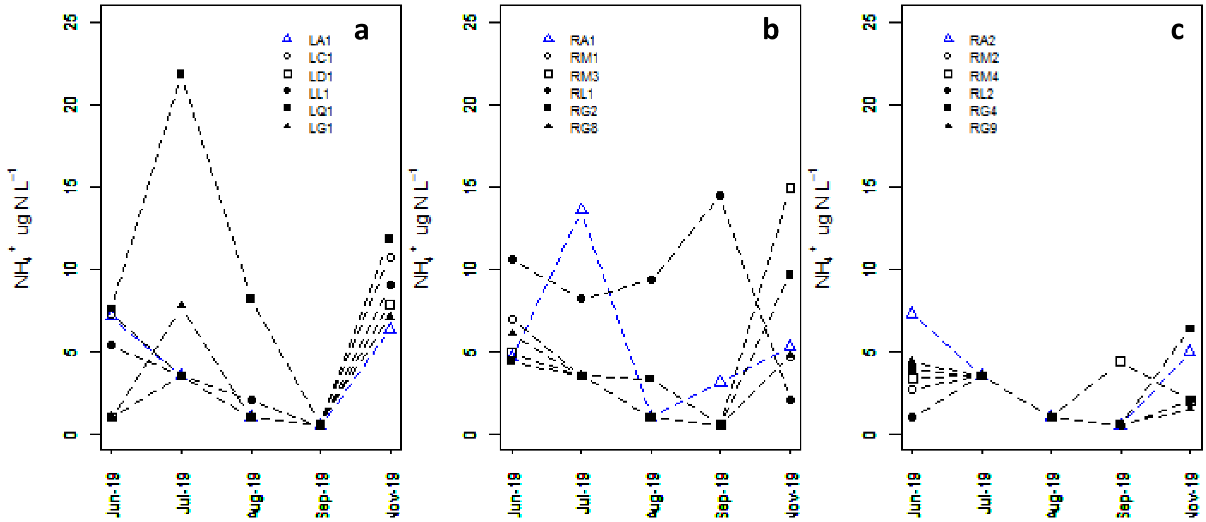


Figure 7.1.7: Dissolved ammonium (NH_4^+) in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Dissolved phosphate (PO_4^{3-}) concentrations were generally very low across all sites during the study and often below the limit of detection; there were no differences upstream and downstream of dams. The only site where higher PO_4^{3-} concentrations were measured (30 µg P L^{-1}) was site RM4 (on the River Moriston) in the September sampling. This may have been associated with human imapcts e.g. domestic septic tanks, but is still a relatively low PO_4^{3-} concentration for rivers. On all other occasions at all sites PO_4^{3-} concentrations achieved “high” quality status under the Scottish Governments water quality standards.

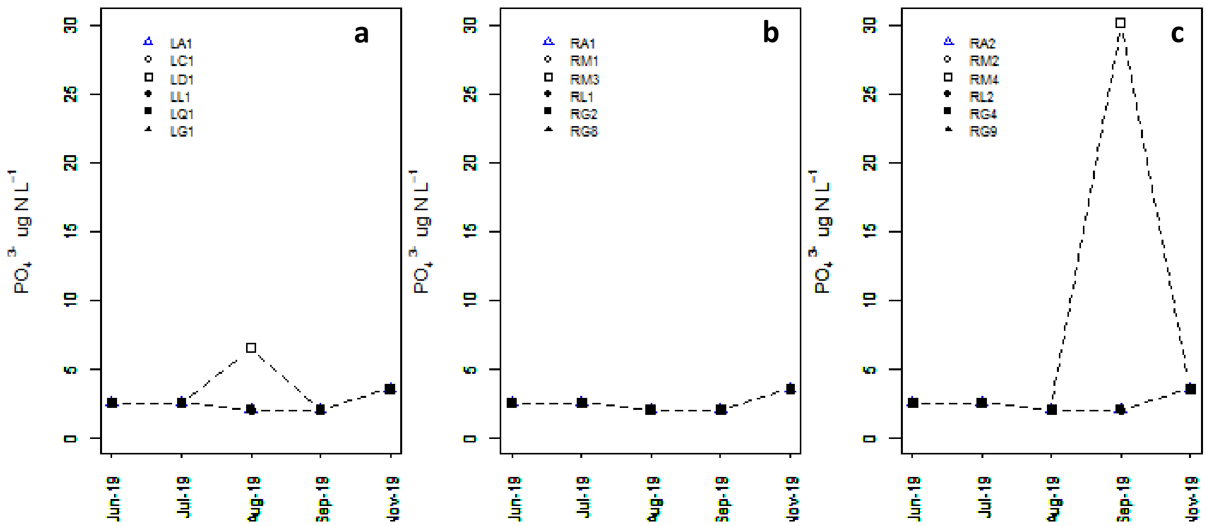


Figure 7.1.8: Phosphate (PO_4^{3-}) concentrations in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Concentrations of total oxidised nitrogen (TON) were generally similar between sites and upstream and downstream of dams and were mostly below 60 µg N L^{-1}, which is considered a low TON concentration. There was temporal variation at all sites and the control catchment (Arkaig) was very similar over time and in concentration to the sites with dams, suggesting no impact of dams on TON concentrations.

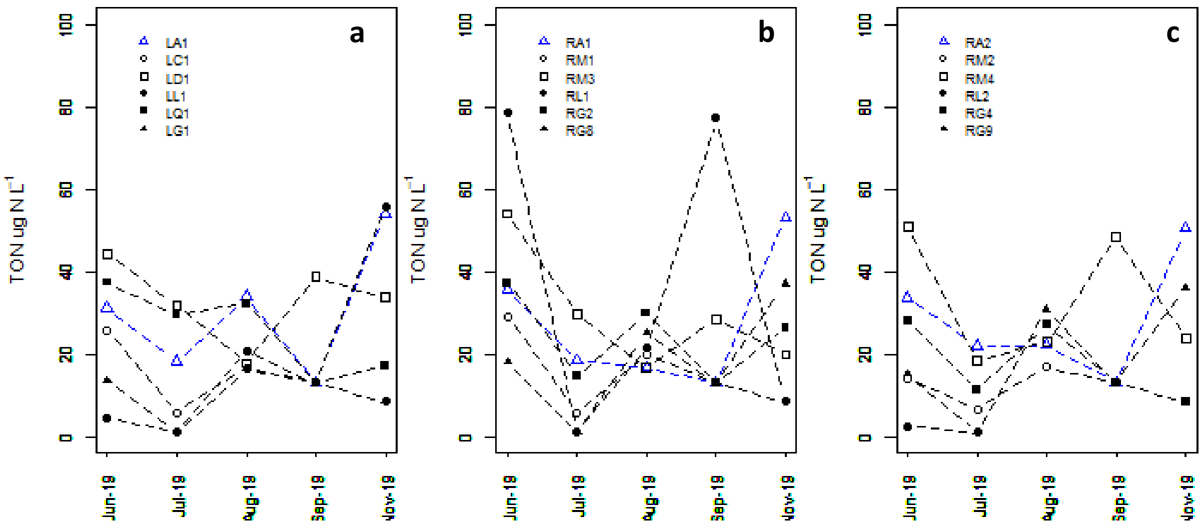


Figure 7.1.9: Total oxidised nitrogen (TON) concentrations in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Dissolved aluminium (Al) concentrations varied over time in the sampling sites, but concentrations were generally lower than the drinking water standard of 200 µg L^{-1}. Generally, there were some differnces between catchments e.g. lower concentrations in the Arkaig cathcment, while slightly higher concentrations in the Dundreggan-Morrison cathcment but in all catchments, Al concentrations were very similar upstream and downstream of barriers, suggesting there were no effects of barriers on Al concentrations. Dissolved Al is a particularly important water quality parameter for salmon in early developmental stages, when high Al concentrations are combined with low pH. However, both the pH and Al results suggest no detrimental effects to the river and loch ecosystem from these parameters.

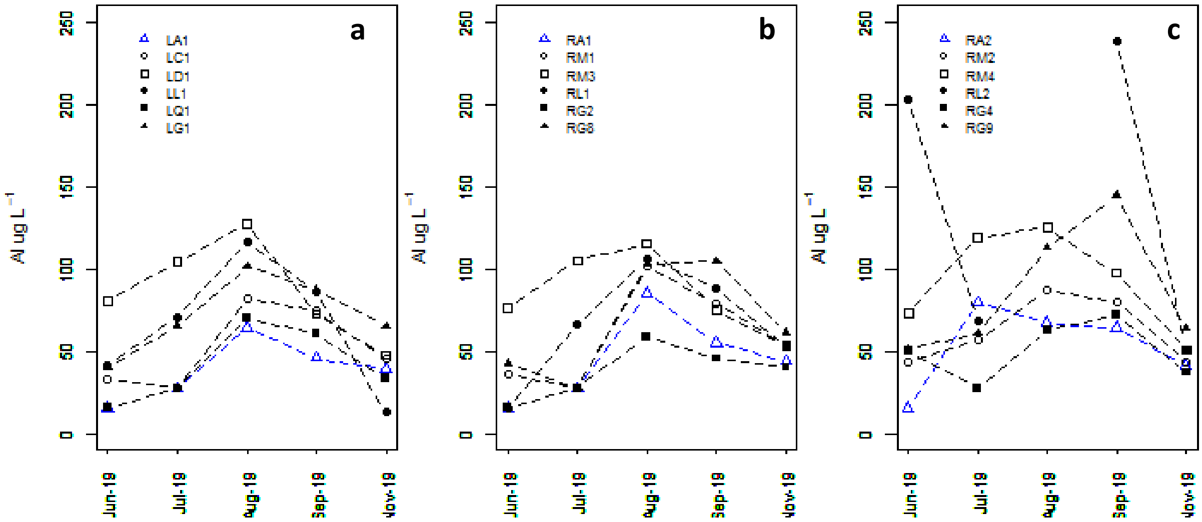


Figure 7.1.10: Dissolved Al concentrations in AMBER sampling sites from June 2019 to November 2019, in (a) loch sites; upstream of dam, (b) river sites; downstream of dam and (c) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Other water quality parameters

Dissolved zinc (Zn), arsenic (As), cadium (Cd), copper (Cu), Nickel (Ni) and lead (Pb) concentrations were generally below the limit of detection on each sampling occasion at all sites. Therfore, there were no differences upstream or downstream of barriers and no effect of dams. Each of these elements are potentially toxic elements which could impact on biota, therefore the fact that they were generally not detected in the Ness River system is a positive outcome for water quality.

Dissolved iron (Fe) and manganese (Mn) concentrations were variable between catchments but similar upstream and downstream of dams in each catchment. Each catchment showed a similar temporal patterns between sites, except the Loyne system, where there were greater variations over time.

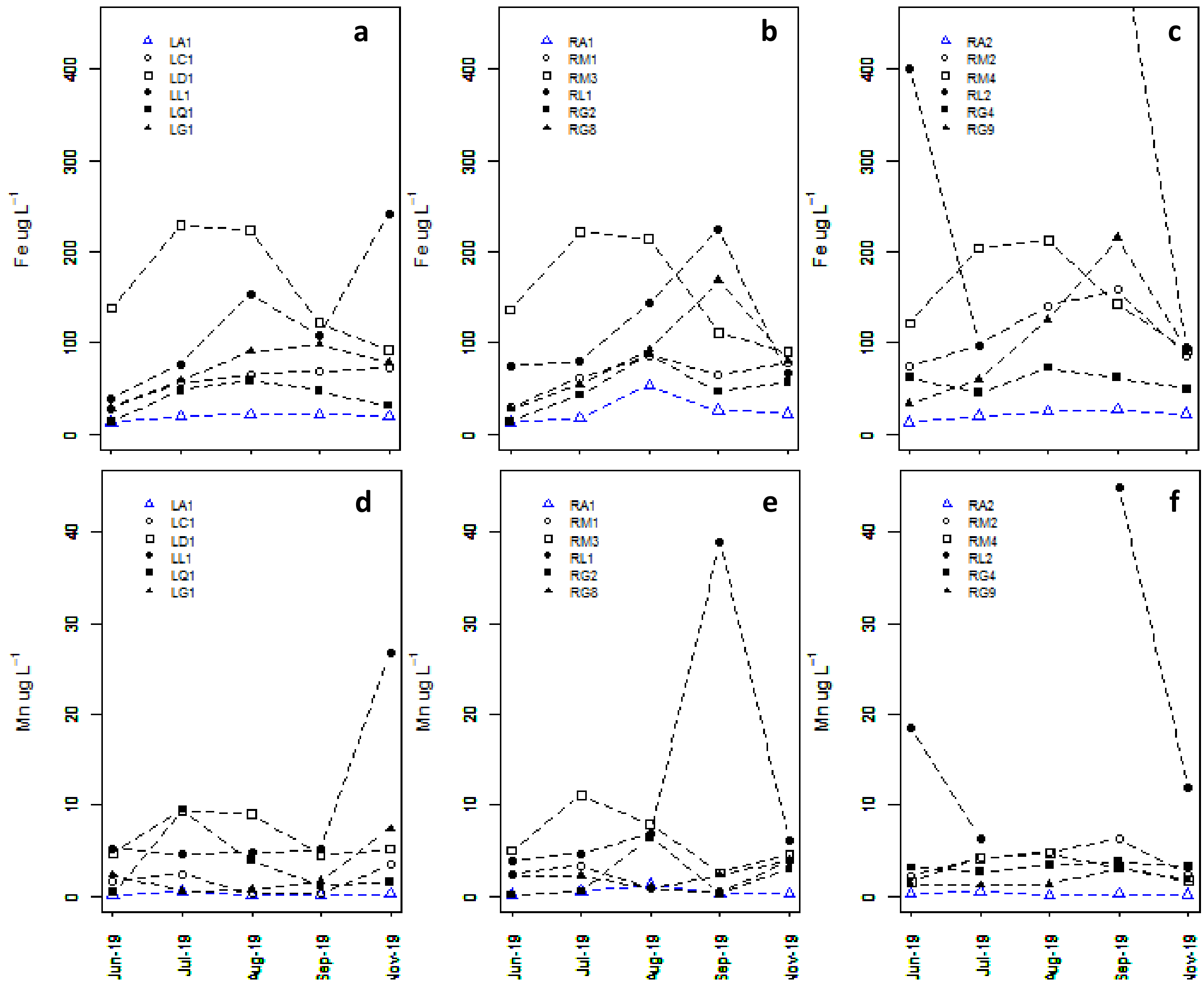


Figure 7.1.11: Dissolved Dissolved iron (Fe; a-c) and manganese (Mn; d-f) in AMBER sampling sites from June 2019 to November 2019, in (a,d) loch sites; upstream of dam, (b,e) river sites; downstream of dam and (c,f) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Dissolved calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) concentrations were similar over time at sites upstream and downstream of dams, showing no obvious effect of dams on any parameter. There were some differences between catchments with the Loyne system showing the greatest variation over time, with some peaks in concentrations in both the loch and river sites at different time points. This may have been related to the flow of water through the dam; on some sampling occasions the dam was in full flow, while in others there was a very low outflow. This may have resulted in a disconnection between the loch and river water in terms of major ion concentrations.

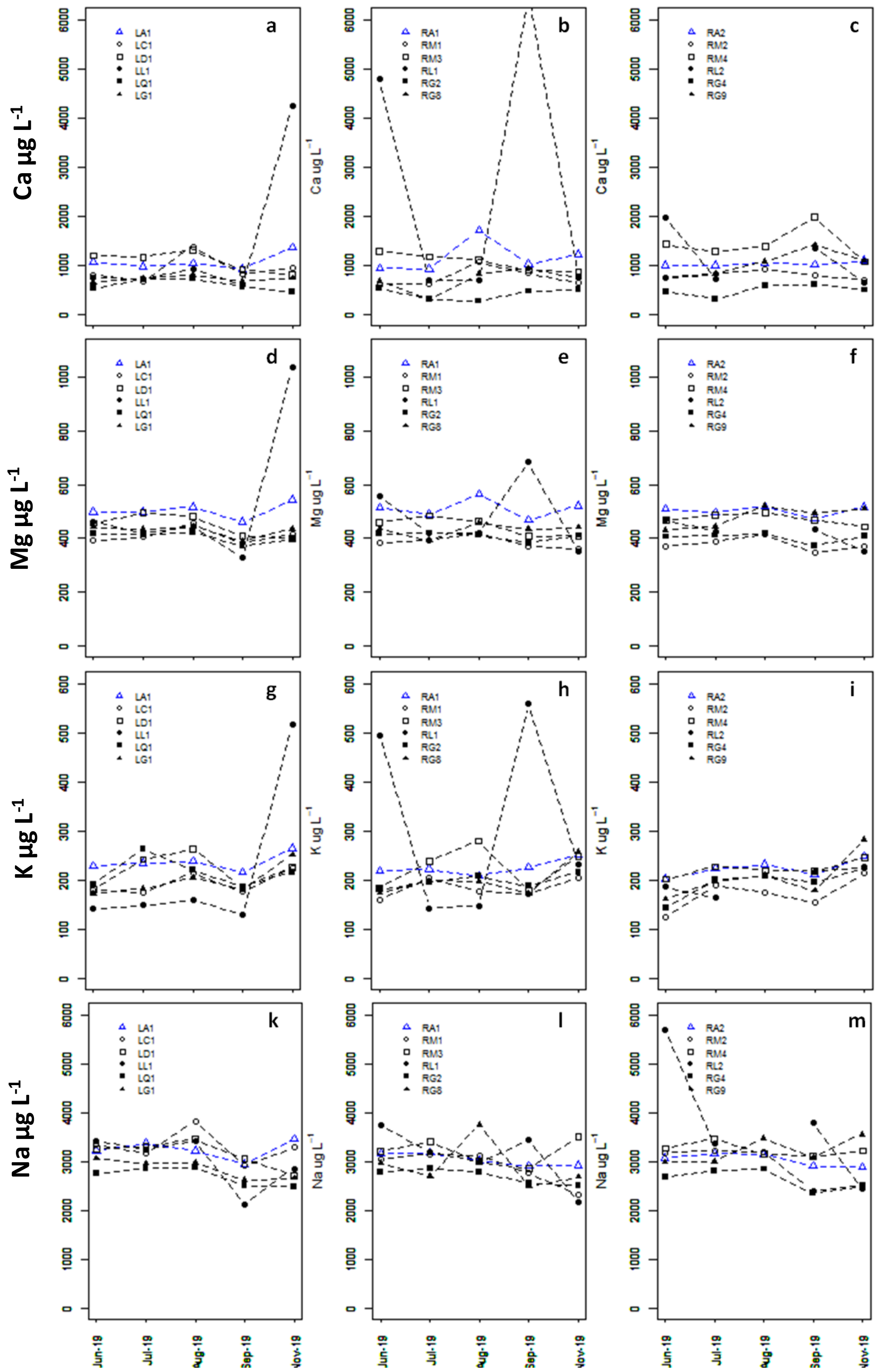


Figure 7.1.12: Dissolved Dissolved calcium (Ca; a-c), magnesium (Mg; d-f), potassium (K; g-i) and sodium (Na; k-m) in AMBER sampling sites from June 2019 to November 2019, in (a,d,g,k) loch sites; upstream of dam, (b,e,h,l) river sites; downstream of dam and (c,f,i,m) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Dissolved inorganic carbon (DIC) and suphate (SO_4^{2-}) concentrations also displayed a similar temporal pattern in water quality between upstream and downstream of dams, showing no effect of dams on either parameter. There were slight differnces between catchments with the Loyne system showing the greatest variation over time.

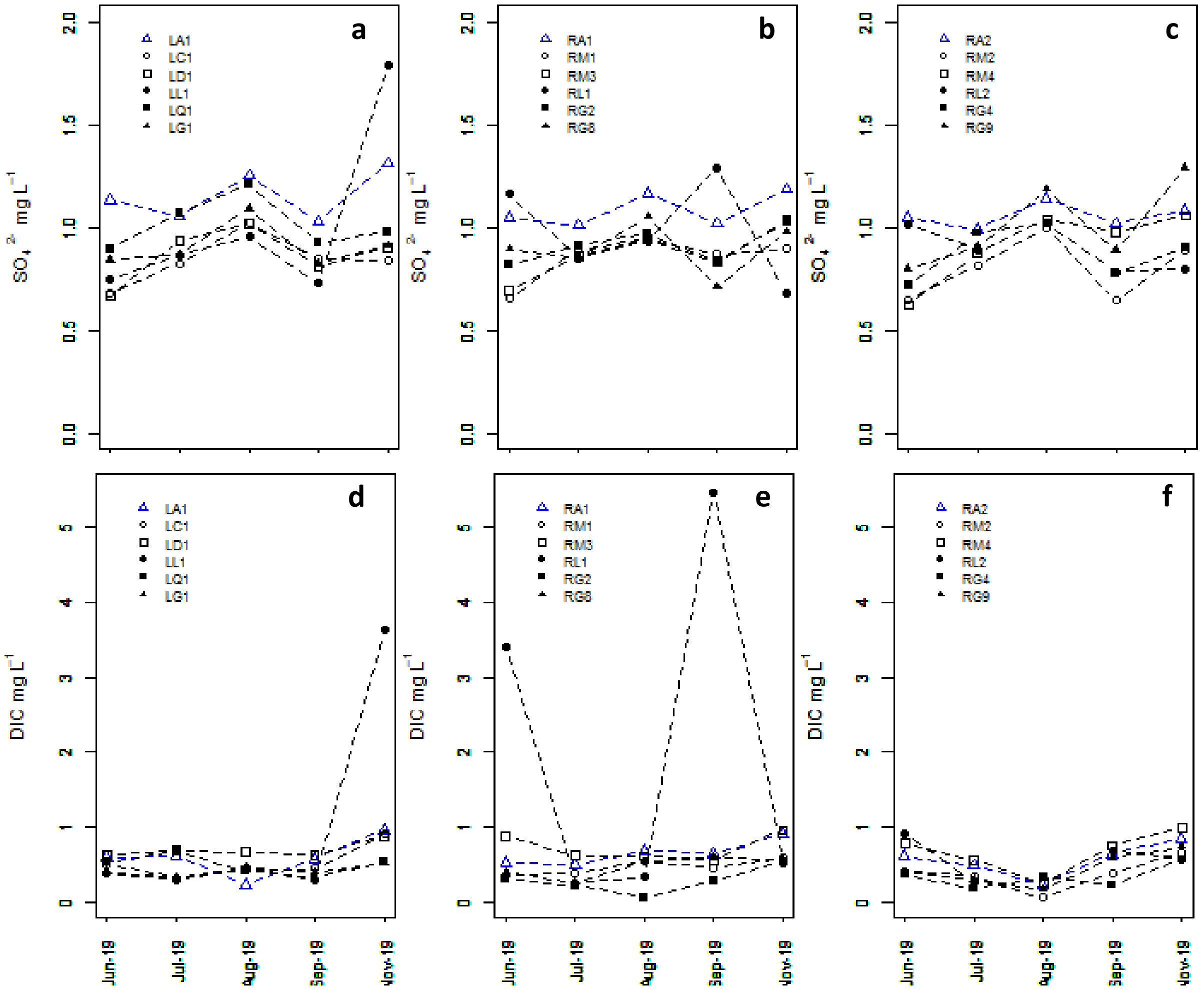


Figure 7.1.13: Sulphate (SO_4^{2-}; a-c) and dissolved inorganic carbon (DIC; d-f) in AMBER sampling sites from June 2019 to November 2019, in (a,d) loch sites; upstream of dam, (b,e) river sites; downstream of dam and (c,f) downstream river sites; ~1 km further downstream. Points in blue are from the Arkaig Loch and River system; which are control sites, as there is no hydroelectric dam between the loch and the river (only a weir – stretching approximately half way across the River Arkaig).

Snapshot River Kingie and Gear Garry water quality comparison

In the September water quality sampling, additional samples were collected from the River Kingie eDNA sampling sites for comparison with the Gear Garry catchment. These results show very similar water quality between both watercourses.

Table 7.1.2: September water quality results for River Kingie and Gear Garry comparison, results for Kingie are average concentrations for sites RK1, RK2, RK3, while Gear Garry results are average for sites RG2, RG4, RG5 (sites upstream of Kingie confluence).

sites	pH	EC (µS/cm)	Turb. (NTU)	SS (mg/L)	DOC (mg/L)	DIC (mg/L)	N-NH_3 (µg N/L)	TON (µgN /L)	PO_4^{3-} (µg P/L)
Kingie	5.53	25	0.5	0.93	2.45	0.85	<LOD	13	<LOD
Gear Garry	6.51	25	1.3	1.94	3.33	0.20	<LOD	13	<LOD
sites		**SO_4^{2-} (mg/L)**	**Diss. Al (µg/L)**	**Diss. Ca (µg/L)**	**Diss. Fe (µg/L)**	**Diss. K (µg/L)**	**Diss. Mg (µg/L)**	**Diss. Mn (µg/L)**	**Diss. Na (µg/L)**
Kingie		1.05	36	831	103	224	466	2	2294
Gear Garry		0.79	59	500	57	188	370	2	2377

Methods of analysis for laboratory measured parameters at Environmental Research Institute

pH - will be measured in the laboratory using a Hannah HI991300 Portable pH/EC/TDS/Temperature Meter calibrated using certified pH 4, 7 and 10 solutions.

Electrical conductivity - will be measured in the laboratory using a Hannah HI991300 Portable pH/EC/TDS/Temperature Meter calibrated with a certified 2013 µS cm^{-1} solution (and dilutions thereof).

Turbidity - will be measured using a Lovibond Turbicheck Meter calibrated using certified NTU standards of <0.1, 20, 200 and 800NTU's.

Total Suspended solids - will be measured gravimetrically – a known volume of water will be filtered through a pre-dried/desiccated/accurately weighed filter paper (to +/-0.00001g). The mass of the solids remaining on the paper after filtration will then be weighed (following drying/desiccation) to obtain a "suspended solids" measurement.

Dissolved organic carbon (DOC) - on a filtered sample, will be quantified using a Shimadzu Total Organic Carbon TOC-L Analyzer (680°C combustion catalytic oxidation method).

Ammoniacal-nitrogen (NH_3 /NH_4^+) - will be measured in filtered water samples using a SEAL AQ2 Discrete Analyzer. Ammonia in the sample reacts at alkaline pH with hypochlorite previously liberated from dichlotoisocyanurate. Formed chloramine reacts with salicylate in the presence of nitroferricyanide to form a blue-green indophenol dye, which is photometrically measured at 670 nm.

Nitrate+nitrite nitrogen (TON) - will be measured together in filtered water samples on a SEAL AQ2 Discrete Analyzer using a copperized cadmium coil to reduce the nitrate to nitrite. Combined quantities of nitrite react with sulfanilamide to form a diazonium compound. This species couples with

N-(1-naphthyl)-ethylenediamine dihydrochloride to form a reddish-purple azo dye which is measured photometrically at 520 nm (nitrate and nitrate was determined as a sum (TON)).

Soluble reactive phosphate (SRP) or orthophosphate - will be measured in filtered water samples using a SEAL AQ2 Discrete Analyzer utilising the antimony-molybdate reaction with ascorbic acid as the reductant. The resultant blue colour will be measured at a wavelength of 880 nm.

Sulphate – will be measured on a Varian 720-ES Series ICP-OES on filtered acidified water samples (as S, then converted back to sulphate).

A suite of DISSOLVED ELEMENTS – (sodium, potassium, calcium, magnesium, aluminium, iron, manganese) - will be measured in filtered water samples on a Varian 720-ES Series ICP-OES on filtered acidified water samples.

7.1.4 Drone flight path summary images

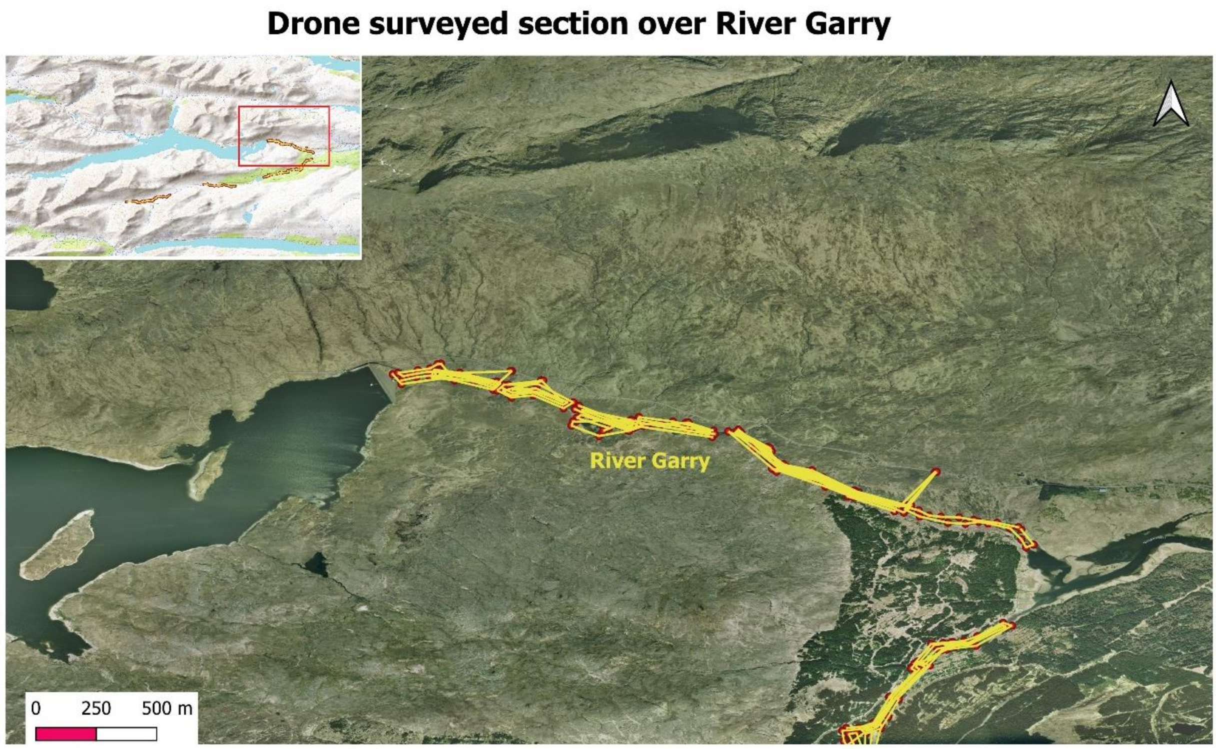


Figure 7.1.1. Drone survey section over the River Garry.

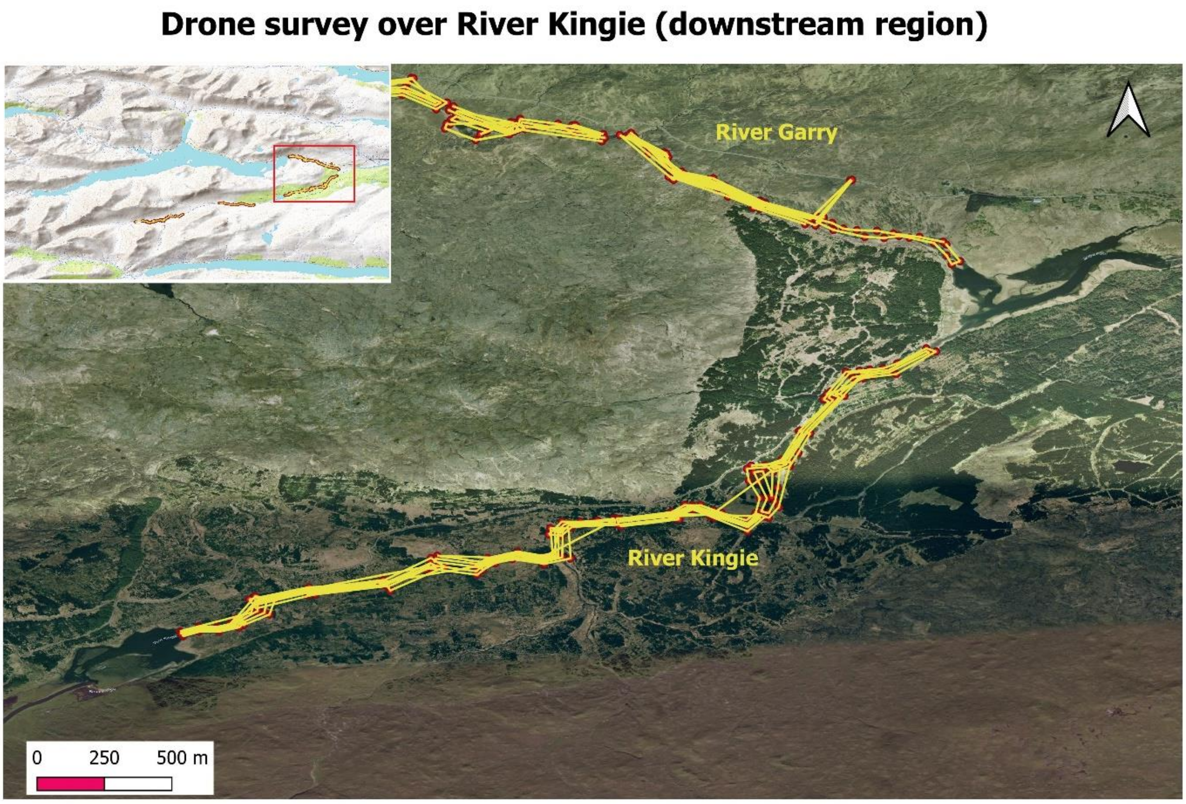


Figure 7.1.2. Drone survey section over the downstream River Kingie.

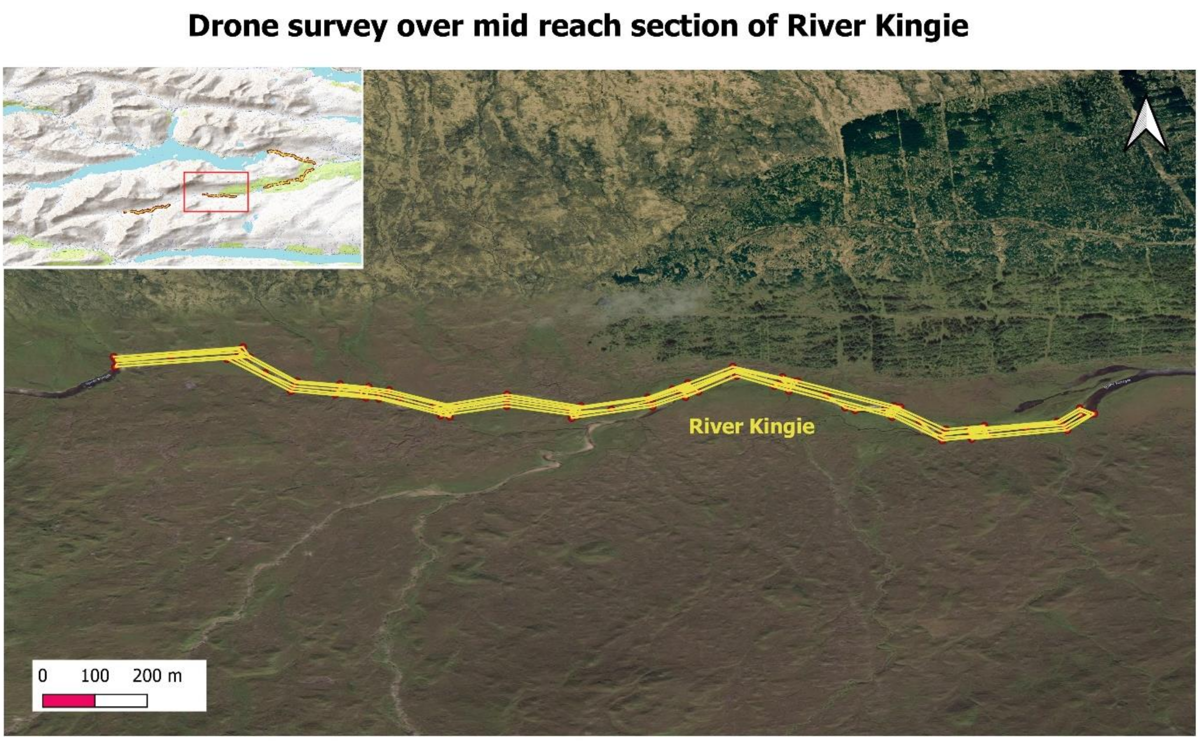


Figure 7.1.3. Drone survey section over the mid-reach of the River Kingie.

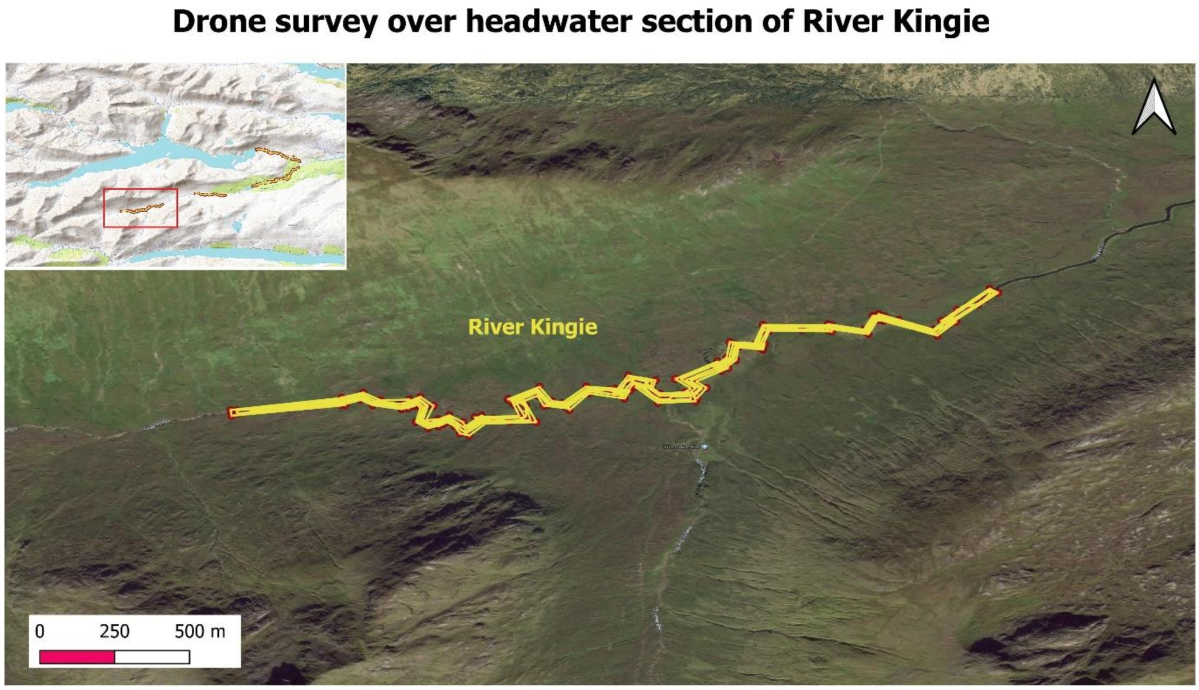


Figure 7.1.4. Drone survey section over the headwaters of the River Kingie.

7.2 A2.3 CASE STUDY 5: Włocławek Dam, River Vistula – ANNEX

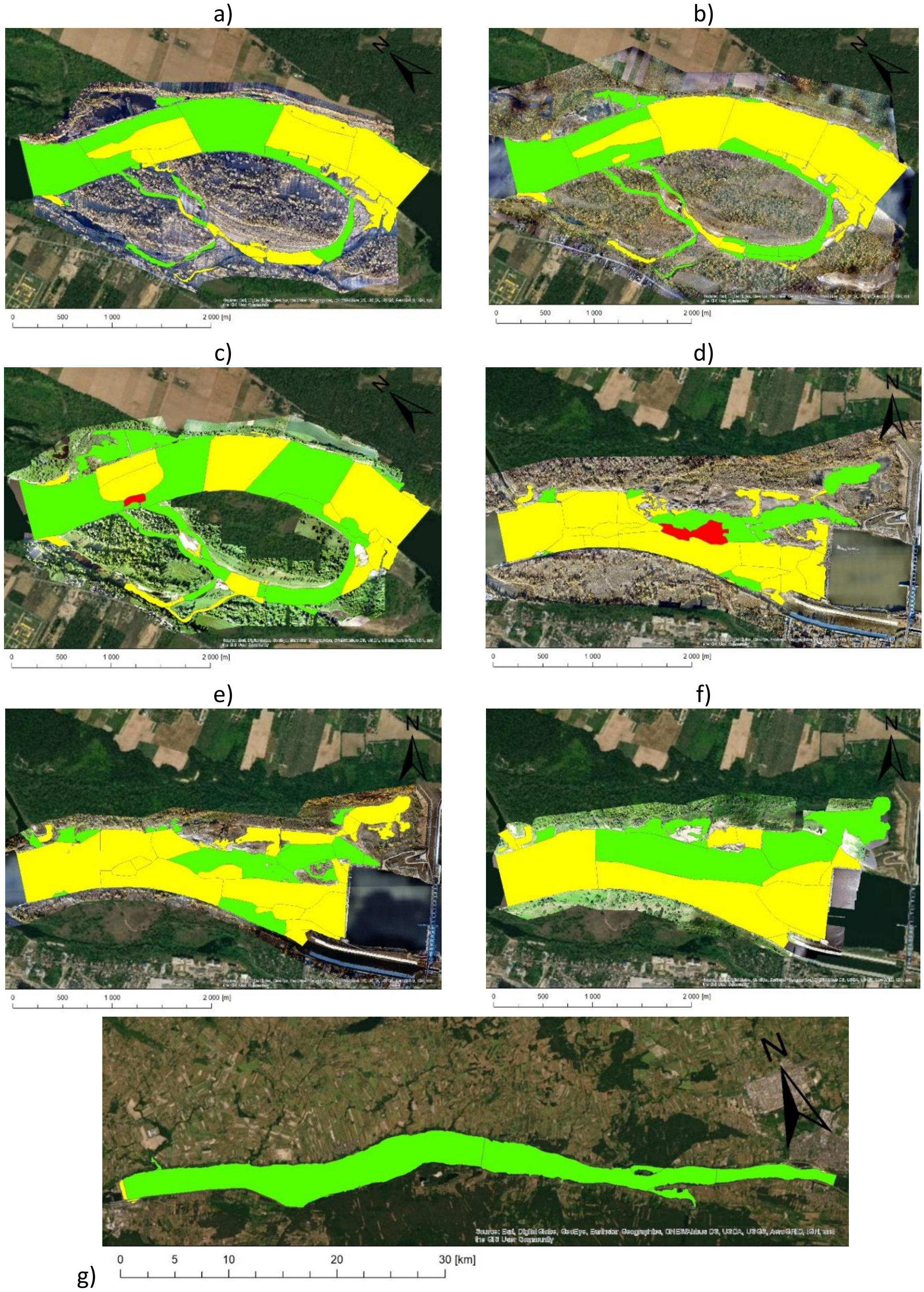


Figure 7.2.1: Benthic moderate tolerant guild in Vistula River: Bógpomóż a) Q=1,6 l/s·km^2, b) Q=2,3 l/s·km^2, c) Q=3,8 l/s·km^2; Wloclawek (below the dam) d) Q=1,6 l/s·km^2, e) Q=2,3 l/s·km^2, f) Q=3,8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

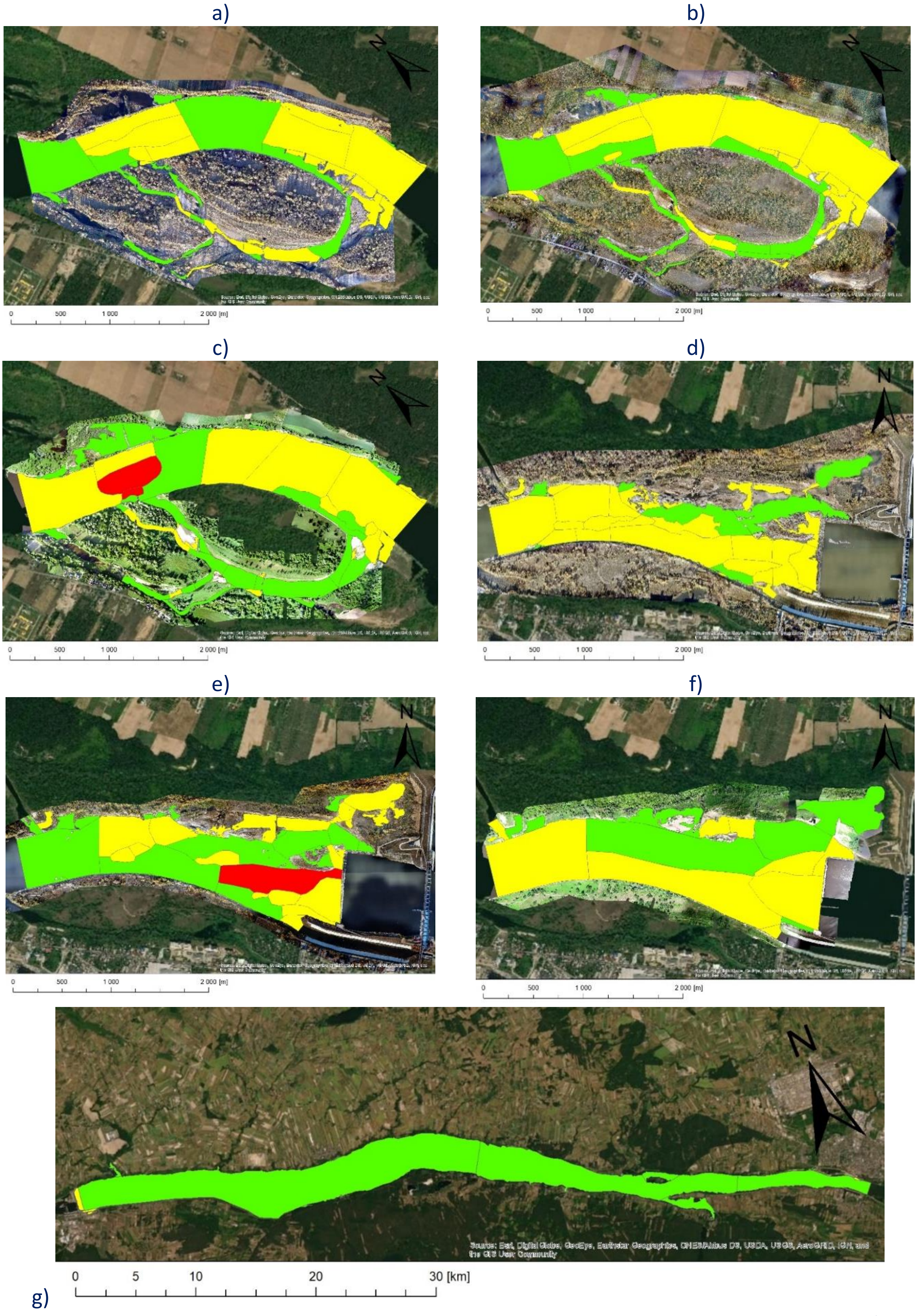


Figure 7.2.1: Limnophilic benthic moderate tolerant guild in Vistula River: Bógpomóż a) Q=1,6 $l/s{\cdot}km^2$, b) Q=2,3 $l/s{\cdot}km^2$, c) Q=3,8 $l/s{\cdot}km^2$; Wloclawek (below the dam) d) Q=1,6 $l/s{\cdot}km^2$, e) Q=2,3 $l/s{\cdot}km^2$, f) Q=3,8 $l/s{\cdot}km^2$; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

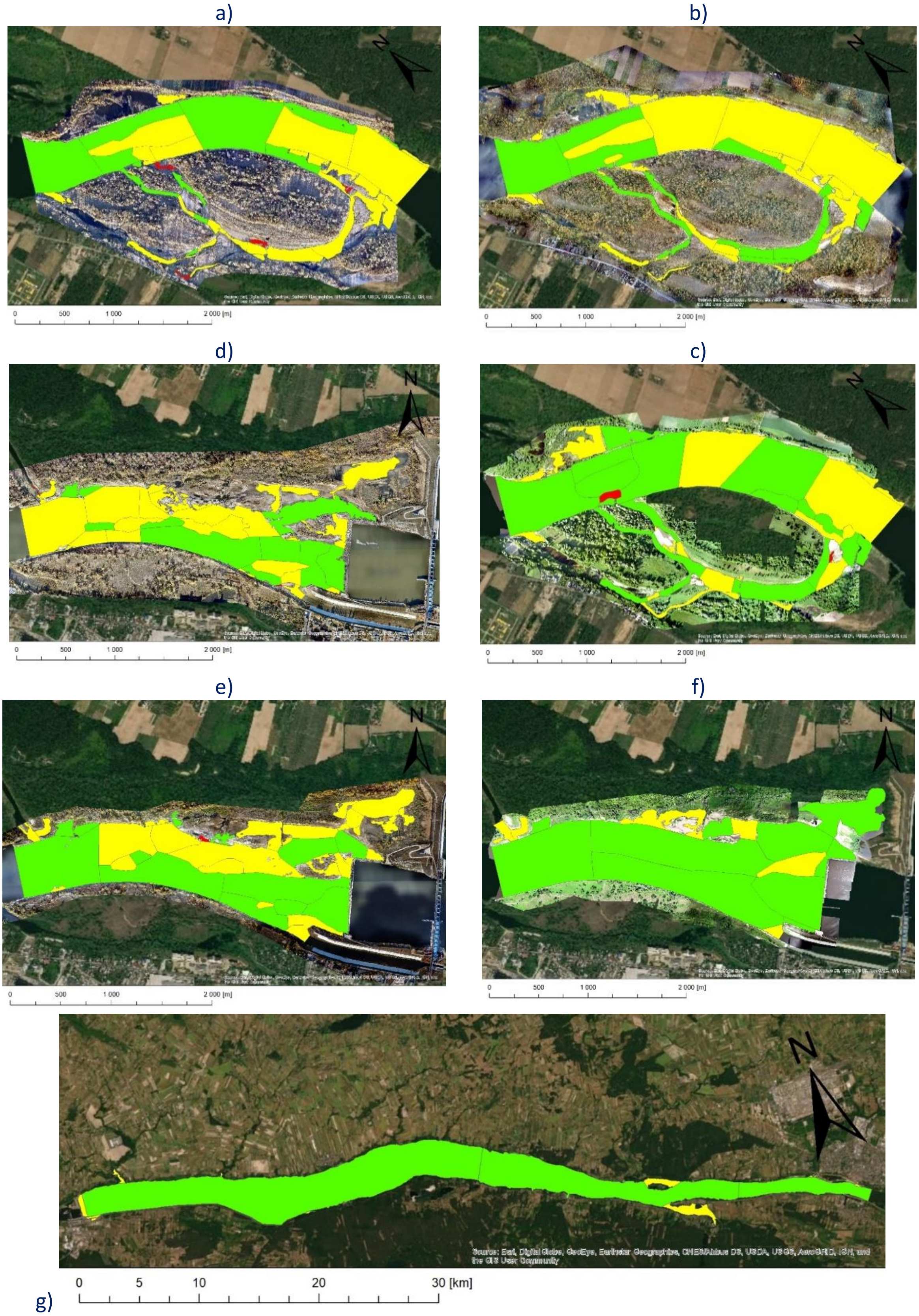


Figure A3. Limnophilic lithophilic moderate tolerant guild in Vistula River: Bógpomóż a) Q=1,6 l/s·km^2, b) Q=2,3 l/s·km^2, c) Q=3,8 l/s·km^2; Wloclawek (below the dam) d) Q=1,6 l/s·km^2, e) Q=2,3 l/s·km^2, f) Q=3,8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable)

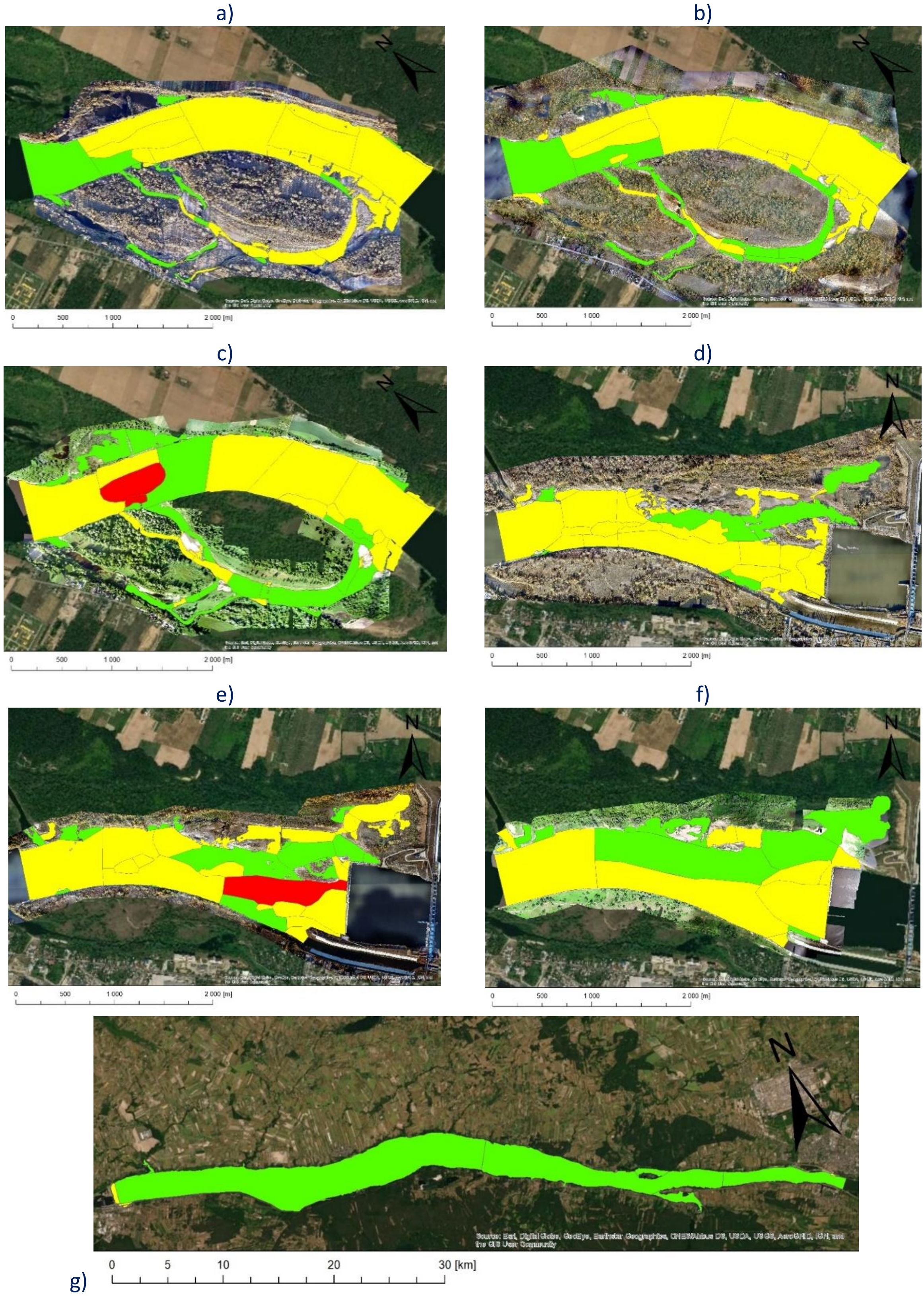


Figure 7.2.4: Limnophilic phytophilic moderate tolerant guild in Vistula River: Bógpomóż a) Q=1,6 $l/s{\cdot}km^2$, b) Q=2,3 $l/s{\cdot}km^2$, c) Q=3,8 $l/s{\cdot}km^2$; Wloclawek (below the dam) d) Q=1,6 $l/s{\cdot}km^2$, e) Q=2,3 $l/s{\cdot}km^2$, f) Q=3,8 $l/s{\cdot}km^2$; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

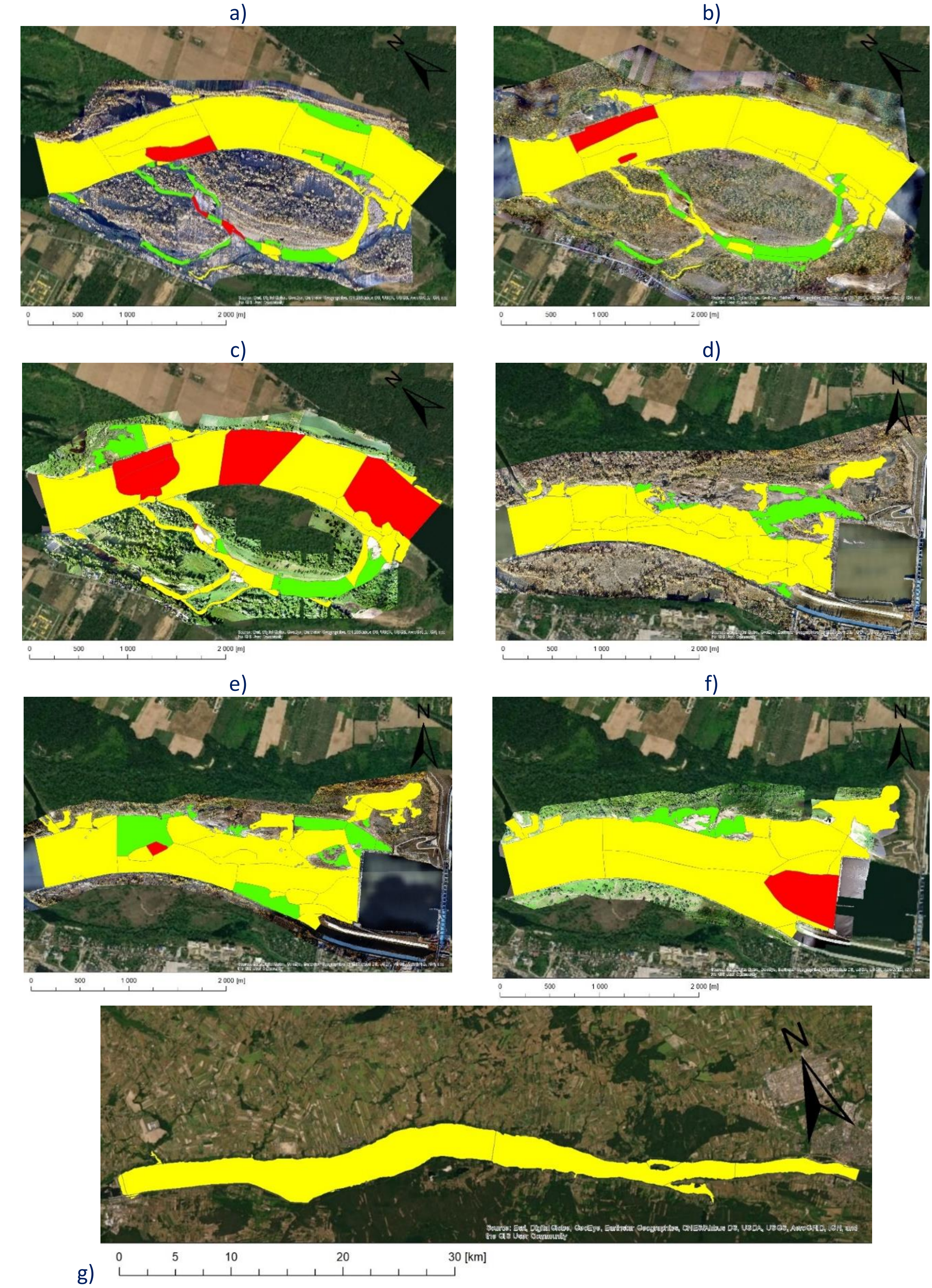


Figure 7.2.5: Rheophilic benthic detritus-pelal intolerant guild in Vistula River: Bógpomóż a) Q=1,6 l/s·km², b) Q=2,3 l/s·km², c) Q=3,8 l/s·km²; Wloclawek (below the dam) d) Q=1,6 l/s·km², e) Q=2,3 l/s·km², f) Q=3,8 l/s·km²; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

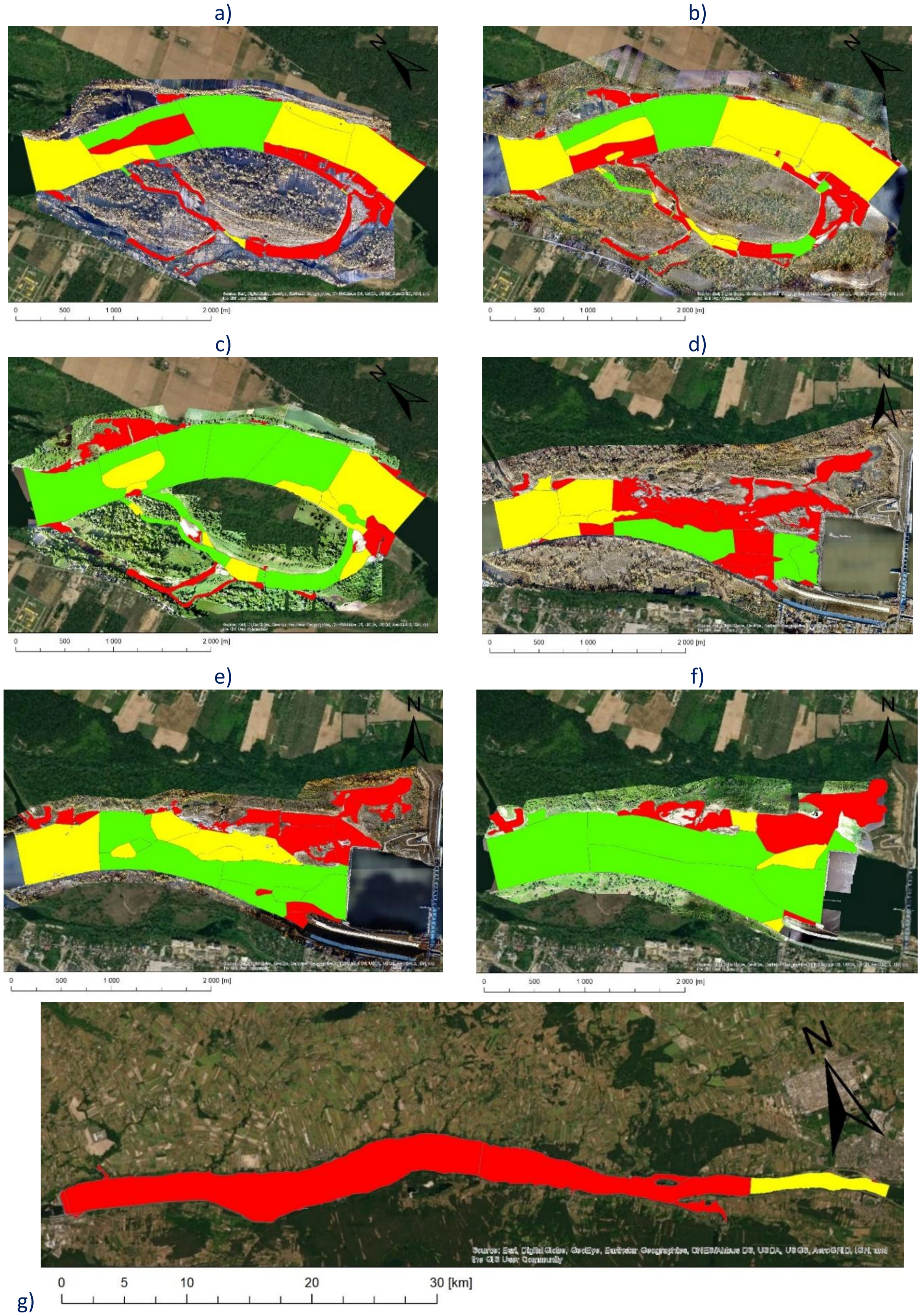


Figure 7.2.6: Rheophilic benthic sand-gravel guild in Vistula River: Bógpomóż a) Q=1,6 l/s·km^2, b) Q=2,3 l/s·km^2, c) Q=3,8 l/s·km^2; Wloclawek (below the dam) d) Q=1,6 l/s·km^2, e) Q=2,3 l/s·km^2, f) Q=3,8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).

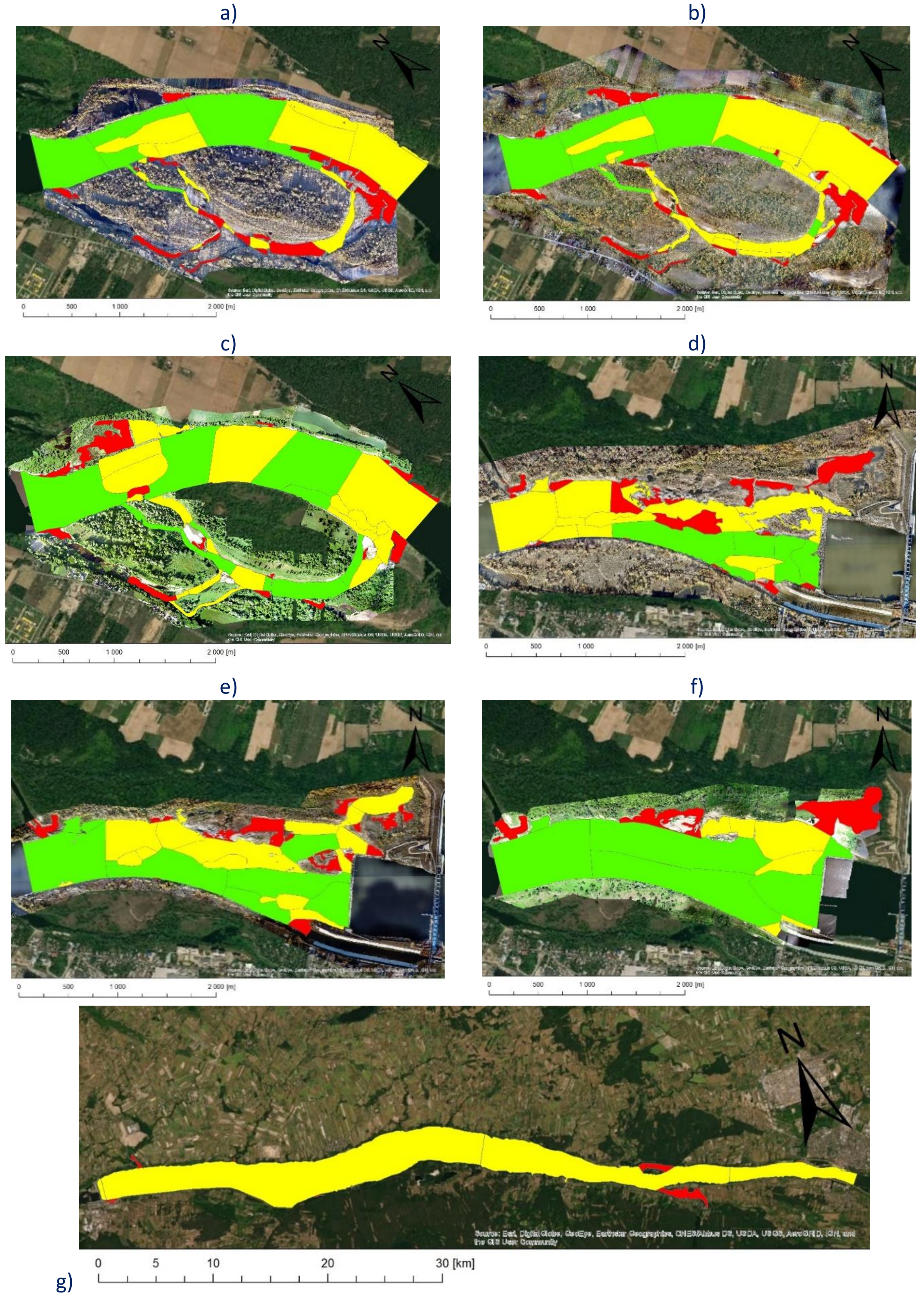


Figure 7.2.7: Rheophilic water column sand-gravel guild in Vistula River: Bógpomóż a) Q=1,6 l/s·km^2, b) Q=2,3 l/s·km^2, c) Q=3,8 l/s·km^2; Wloclawek (below the dam) d) Q=1,6 l/s·km^2, e) Q=2,3 l/s·km^2, f) Q=3,8 l/s·km^2; g) Impoundment. (habitats: green – optimal, yellow – suitable, red – unsuitable).