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Assessment of the Extent and Impact of Barriers on Freshwater Hydromorphology and Connectivity in Ireland (Reconnect)

Authors: Mary Kelly-Quinn, Michael Bruen, Jonathan N. Turner, John O'Sullivan, Jens Carlsson, Craig Bullock, Siobhan Atkinson and Colm M. Casserly

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2021–2030

Assessment of the Extent and Impact of Barriers on Freshwater Hydromorphology and Connectivity in Ireland (Reconnect)

(2015-W-LS-8)

EPA Research Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

The Reconnect project advanced knowledge on the impact of barriers on connectivity in Irish rivers in terms of sediment dynamics and ecology through studies undertaken between 2016 and 2020. As part of the project, a methodology for prioritising selection of low-head barriers for modification or removal was also developed to improve hydromorphology and connectivity. In addition to mapping barriers in 10 sub-catchments, detailed investigations on fish, macroinvertebrates, macrophytes, hydromorphology and environmental DNA (eDNA) were carried out in four core study areas on the Duag, Dalligan and Burren rivers and Browns Beck Brook, which each contained a significant barrier. The research included monitoring responses to the removal of the ford on Browns Beck Brook. Specific investigations were carried out at 35 other locations across 12 river/stream systems.

It was found that the desk study largely eliminated the need to walk entire river catchments to locate barriers, allowing more focused site visits, especially in remote locations, where walkover surveys may be especially difficult and time-consuming. The catchment barrier density ranged from 0.02 to 1.2 structures per kilometre of river. Coupling barrier density with the dendritic connectivity index (DCI) can highlight where removal or modification of a large number of barriers may be required to significantly improve connectivity. For example, connectivity for diadromous species is affected by barriers located near the mouth of the river or on the mainstem.

The fish studies highlighted issues with upstream fish migration in the River Dalligan, where there is a vertical barrier (2.3 m high) about 2 km from the sea. In the other catchments, brown trout and Atlantic salmon fry and parr were absent, or in low abundance, in the impounded reaches. The impounded reaches did not always hold the highest density of 1+ and older fish. In some of the impounded reaches, fish-carrying capacity is limited by the more lentic conditions. Removal of the ford on Browns Beck Brook resulted in the detection of salmon fry further upstream in 2020 as a result of improved connectivity. Macroinvertebrate habitat loss or change is the key threat. The macroinvertebrate communities identified in impounded reaches were similar to those found in natural pools and were generally significantly different from those of riffle habitats, especially in terms of community structure, taxon richness and Ephemeroptera, Plecoptera and Trichoptera (EPT) richness. In effect, impoundments are elongated pool habitats. Thus, inundation of riffle/run habitat due to impoundment could be significant for macroinvertebrate biodiversity in river reaches. This will depend on the length of the channel that has been inundated. The limited macrophyte investigations did not reveal a consistent pattern with respect to the impact of the impoundment. Species-specific eDNA quantitative polymerase chain reaction (qPCR) assays were found to be highly effective in assessing the distribution of target species, and they provide a valuable, non-invasive method for determining the effect of barriers on target species.

The hydromorphology assessment focused on sediment connectivity and showed that all bed size fractions are capable of passing over both study weirs, suggesting these structures are not currently acting as complete barriers to sediment conveyance. However, results do suggest that they can continue to disrupt hydrosedimentary processes through the temporary storage and later release of material, resulting in bed sediment coarsening downstream, an impact which may possibly lead to altered habitat potential. Suspended sediment monitoring revealed the importance of the impoundment as a secondary source of fine sediment, leading to an amplification of sediment supply extremes, which may have implications for sediment-sensitive biota downstream. Morphodynamics at Browns Beck Brook following barrier removal was characterised by incision and bank erosion. Bed changes were rapid, restoring the pre-barrier gradient within 18 months. Lateral adjustments, while localised and ongoing, emphasise the importance of post-removal monitoring and the possible need for “freedom space” as channels adjust to these changes. Suitable low-cost tools for hydromorphological assessment include unpiloted aerial vehicle imagery surveys and the multi-Modular River Physical (MoRPh) method. The Hydrologic

Engineering Center's River Analysis System (HEC-RAS) one-dimensional hydraulic/sediment models were prepared for the study sites and used to simulate high-flow peaks to examine their relationship with sediment mobilisation.

Seven criteria were proposed for a multi-criteria framework for ranking barriers for removal or modification (cost, flow regulation, heritage value, recreation benefits, sediment, angling/connectivity and river rewilding). The analytical hierarchy process (AHP) was proposed for weighing the importance of the different criteria. In a survey of technical stakeholders, rewilding, flow regulation and sediment were considered the most important criteria; cost and recreation were considered the least important. Further details of economic considerations are provided. This shows an appreciation of the broad range of issues involved in barrier removal decisions. In any future, practical application of this methodology, assessing the weights applicable to a full range of stakeholders, is advised. Recommendations arising from the findings are provided at the end of the report.

1 Introduction

The Water Framework Directive (WFD; 2000/60/EC) requires Member States to achieve at least good ecological and chemical status in all surface water bodies. Hydromorphological quality elements sit in a supporting role, but they must be taken into account when assigning high status or when downgrading from high to good status. The WFD recognises that physical habitat is critical in terms of aquatic community structure and functioning (Elosegi *et al*., 2010). The key elements of hydromorphological quality supporting the biological elements include hydrological regime, condition of geomorphic elements (e.g. channel morphology, substrate composition, bank condition and sediment transport) and river connectivity.

Barriers to freshwater connectivity can negatively impact aquatic fauna, and therefore status classification, either directly or through their effects on hydrological and morphological elements. The *National Characterisation Report for Ireland* (EPA, 2005), produced during the first WFD management cycle, first drew attention to significant hydromorphological pressure on rivers, including impoundment by various barriers. In a later report, Gargan *et al*. (2011) highlighted the risks to hydromorphological status caused by barriers to fish movement. They described how rivers in Ireland have been extensively regulated to improve navigation, and to obtain stream power for milling, with many barriers having been in place for several hundred years. The extent of the problem was highlighted in the Nore catchment, where an inventory of 497 artificial and 11 natural barriers was generated (Gargan *et al*., 2011). More recently, alteration of hydromorphological condition has been reported as the third most prevalent significant pressure on surface waters in Ireland, affecting 24% of water bodies (O'Boyle *et al*., 2019), updated to 16% in the Draft River Basin Management Plan 2022–2027 (P. Morrissey, EPA, personal communication, March 2021). This issue was reiterated in Wall *et al*. (2020), as was the need to address knowledge gaps on the impacts on river ecology.

Hydromorphology describes the physical condition of surface waters. Flow regimes, the condition of geomorphic elements (e.g. channel morphology, substrate composition, bank condition and sediment transport), channel mobility, the dynamic nature of channel form and connectivity are all elements of riverine hydromorphology and are intricately linked (Elosegi *et al*., 2010). Habitat structure is a key factor influencing the biodiversity of rivers; the maintenance of connectivity between these habitats is vital for maintaining natural river processes (e.g. movement of biota, organic and inorganic material) (Kondolf *et al*., 2006; Winkowski and Zimmerman, 2018). In addition, river channels continually change as a result of discharge, sediment yield and landscape features, which results in highly dynamic ecosystems that change through time (Elosegi *et al*., 2010). This natural spatial and temporal heterogeneity is vital for maintaining the functioning, biodiversity and integrity of river ecosystems (Poff *et al*., 1997; Elosegi and Sabater, 2013).

Connectivity is a vital element of all ecosystems. Pringle (2001) defines hydrological connectivity as the "water mediated transfer of matter, energy, and organisms within or between elements of the hydrologic cycle". Ward (1989) and Grill *et al*. (2019) conceptualised connectivity in a four-dimensional framework; in addition to longitudinal, lateral and vertical dimensions, they explicitly include time as a fourth. Longitudinal connectivity controls the movement of sediment, organic matter, water and biota along the river network (Elosegi *et al*., 2010). This has been well described for fish. Lateral connectivity describes the relationship between the river channel and its floodplain, and is important for floodplain productivity, dispersal of aquatic biota and the recycling of organic matter and nutrients (Junk *et al*., 1989). Vertical connectivity describes the exchanges between groundwater, surface water and the atmosphere, and is important for maintaining the physical transfer of water, nutrients and dissolved oxygen (Brunke and Gonser, 1997; Winter *et al*., 1999).

Many river networks are naturally fragmented by waterfalls, cascades, rapids and log jams, which are typically found in steep mountain channels. The nature and impact of these structures vary spatially and temporally (Burchsted *et al*., 2010) and are not generally of concern. In fact, they are thought to increase the hydrological and geomorphological heterogeneity of a river system as a whole despite the barrier posed by waterfalls, for example to the upstream movement of fish such as salmon and trout.

1.1 Anthropogenic River Fragmentation and Potential Impacts

Rivers have been modified throughout human history. Dams are probably the best-known anthropogenic agents of river fragmentation (Fuller *et al*., 2015) and, although their construction accelerated in the 20th century (Malmqvist and Rundle, 2002), they can be dated to approximately 5000 years ago (Schmutz and Moog, 2018). In Ireland, smaller low-head structures, such as fish weirs (stone or wooden barriers constructed in rivers or estuaries to deflect the fish into a net or basket), can be dated to approximately 8000 years ago (6100–5700 BC) (Historic England, 2018). However, the structures rarely spanned the entire width of the channel (Historic England, 2018). In coastal or estuarine waters, ebb weirs and flood weirs were constructed to catch fish moving with the ebbing and flooding tides (Lucey, 2020).

Lehner *et al*. (2011) estimated that there are over 16 million barriers in river systems worldwide. According to Grill *et al*. (2019), 63% of the world's rivers that exceed 1000 km in length are no longer free flowing because of damming; this value is actually likely to be much higher, as the authors did not include smaller structures (weirs, culverts, etc.). When low-head structures are taken into account, the figures are much higher. For example, in the UK, it is estimated that only 1% of rivers are free of artificial structures (Jones *et al*., 2019). According to the EU Adaptive Management of Barriers in European Rivers (AMBER) project, there are at least 1.2 million instream barriers in Europe, 68% of which are low-head structures (AMBER, 2020). This amounts to a mean density of 0.74 barriers/km.

The impacts of barriers, from dams to culverts, on the movement/dispersion (both upstream and downstream) and genetic diversity of a range of fish species have been widely reported (e.g. McCarthy *et al*., 2008; Lucas *et al*., 2009; Nislow *et al*., 2011; Hansen *et al*., 2014), and it is known that even low-head structures and impounded reaches can affect some species (Gowans *et al*., 2003). The ability of a fish to surmount a barrier depends on the species, its swimming/leaping ability and the life stage in question, the time of the year (as this influences flow over the barrier) and the physical characteristics of the barrier (Kemp *et al*., 2008; Bourne *et al*., 2011; Barry *et al*., 2018). For example, sea lamprey [*Petromyzon marinus* (L. 1758)] cannot jump (King, 2006) and instead swim using lateral undulatory movement (Sigvardt, 1989). In effect, assessment of impact will be specific to the site and species and will be influenced by barrier type/dimensions and flow conditions.

The consequences of river fragmentation for macroinvertebrates have received considerably less attention than the consequences for fish. Impacts on movement are likely to be more important for species that spend their entire lives in the river than for those with aerial life stages. It is likely that the main effects will be on changes to habitat, particularly in relation to substrate, water temperature and flow conditions. As Jones *et al*. (2020) pointed out, knowledge of the impacts of low-head barriers on macrophytes is at present quite lacking.

Similarly, the impact of low-head barriers on sediment movement in rivers is relatively poorly studied compared with the impact of large dam structures, and has relied on conceptual and numerical models, largely unsupported or lacking empirical data. Although the backwater effect that promotes sediment deposition upstream of the structure is widely reported (Vanoni, 2006; Csiki and Rhoads, 2010; Pearson and Pizzuto, 2015) and clearly observed behind many low-head dams, the hydrosedimentary dynamics of sediment conveyance and the temporal and spatial impacts downstream are poorly understood. Research on the geomorphic impacts of low-head dams, which until a few years ago had been limited and largely confined to catchments in the USA (e.g. Skalak *et al*., 2009; Csiki and Rhoads, 2010, 2014; Pearson *et al*., 2011; Pearson and Pizzuto, 2015), suggests that local scour, bed material coarsening and the formation of downstream riffles are potential issues (Csiki and Rhoads, 2010). None of these studies, however, measured bedload or suspended sediment transport directly or provided a detailed investigation into the degree of, or mechanism for, transport over these structures.

1.2 Reconnect – Aims and Objectives

The overall aim of the Reconnect project is to advance knowledge on the impact of low-head barriers on connectivity in Irish rivers in terms of sediment dynamics and ecology, and to develop a methodology for prioritising the selection of barriers for modification or removal to improve hydromorphology and connectivity. Specific research tasks included:

1. evaluation of the effectiveness of desk and field techniques to create a geo-referenced layer for freshwater barriers in Ireland (Chapter 3);
2. mapping and characterisation of barriers in selected catchments/sub-catchments and production of a geo-referenced layer (Chapter 3);
3. investigation of macroinvertebrate and fish communities upstream and downstream of various types of barriers to assess their potential impact (Chapter 4);
4. testing the feasibility of using environmental DNA (eDNA) to examine the catchment-wide impact of barriers on key fish and macroinvertebrate species (Chapter 5);
5. characterisation of the hydromorphological context for barrier emplacement and the physical form of selected barriers and associated attributes of channel boundaries (upstream and downstream of the barrier sites) (Chapter 6);
6. evaluation of existing tools to predict the effect of barriers on hydromorphology and implications for ecology (Chapter 7);
7. economic analyses of the cost of barrier removal (Chapter 8);
8. production of a multi-criteria decision-making methodology to facilitate practical management decisions (Chapter 9).

Chapter 2 presents details of the range of sites where the various elements of the research were undertaken, while the final chapter (Chapter 10) brings together the findings from all of the work packages to draw conclusions and make recommendations for policy and practice.

1.3 What is a Barrier?

The Reconnect project focused on artificial barriers and adopted the definition used by the EU AMBER project, which defines an artificial instream "barrier" as "any built structure that interrupts or modifies the flow of water, the transport of sediments, or the movement of organisms and can cause longitudinal discontinuity". This recognises that these structures may be barriers for certain hydromorphological and ecological elements, either permanently or for only certain short periods. We have concentrated on low-head structures and excluded large reservoir and storage dams (> 5 m in height).

Excluding storage/reservoir dams, four broad categories of low-head artificial barriers (Figure 1.1) can be defined in addition to natural barriers such as waterfalls. These include weirs, bridge aprons, culverts and fords (Figure 1.1). The weirs were generally built to harness the flow of the river to power mills in the 18th and 19th centuries and are no longer needed to serve this purpose. Some weirs, such as the one on the River Glendasan in Co. Wicklow, were built for electricity generation. A bridge apron is a concrete slab under the bridge that protects the bridge pillars from being undermined by the river. This creates an area of low flow and is often accompanied by a step. Culverts are of variable design and are present at road crossings that do not carry a wide span bridge. Fords are equally variable and are generally concrete structures used to enable river crossing. Most are located on small streams, often in agricultural settings.

Figure 1.1. Four broad categories of low-head barriers on Irish rivers. (a) Weir on the River Dodder, Dublin city; (b) bridge apron on the River Dodder, Dublin city; (c) culvert on the River Owenboliska, Co. Galway; and (d) ford on Browns Beck Brook, Co. Wicklow.

2 Site Selection

2.1 Site Selection

Four core and 35 non-core sites were selected for the research undertaken in this project. The four core study sites included the Shanrahan Weir on the River Duag (Co. Tipperary), the Dalligan Weir on the River Dalligan (Co. Waterford), an unnamed ford crossing on Browns Beck Brook (Donard, Co. Wicklow) and Hanover Weir on the Burren River, Co. Carlow (Figure 2.1). At the time of project commencement, the barriers in the core study sites had been identified for removal over the course of the project such that pre-removal (baseline) and post-removal monitoring would be facilitated.

Catchment and study area details, together with some information pertaining to the weir structures, are summarised in Table 2.1. Further site details, together with the research activity undertaken, namely aquatic biota (fish, macroinvertebrates and macrophytes), eDNA and hydromorphology (water flow, bed substrate and suspended sediment flux), in the study areas upstream and downstream of the structures at these core sites are included in Appendix 1. Alpha-numeric codes are included in Appendix 1 to identify each monitoring site, with the first three letters of each code defining the river (DUG for Duag, DAL for Dalligan, BBB for Browns Beck Brook and BUR for Burren), with

Figure 2.1. Locations of core study areas in the Reconnect project. Sub-catchments of the four sites are highlighted.

Table 2.1. Details of study catchments, study areas within catchments and barrier structures in the study areas

	River Duag	River Dalligan	Browns Beck Brook	River Burren
Drainage area above weir/ford (km^2)	59.3	17.7	13.03	136.62
Basin elevation above weir/ford (m OD)	52.8–651.2	31.7–602.4	165–379	51–444
Stream order	4th	3rd	2nd	4th
Channel slope for study area (m/m)	0.003	0.013	0.011	0.0014
Main channel slope for catchment (m/m)	0.004	0.03	0.028	0.0011
Sinuosity (catchment)	1.17	1.14	1.42	1.5
Dominant land uses	Pasture/peat bog/forestry	Pasture/peat bog/forestry	Pasture/forestry/ heathland	Pasture/arable
Annual precipitation recorded on site (mm) (1 February 2018 to 31 January 2019)	1081	1043	–	–
Structure type	Stone weir with approximate crump-type profile	Weir with contracted ogee spillway	Non-standard, broad crested ford	Concave/broad crested weir
Structure height (m)	1.0	2.3	1.5 (old ford crossing)	–
Structure width (m)	30 (maximum width)	6.5 (notch width), 57.7 (maximum width)	5.5 (old ford crossing)	–
Year constructed	Pre-1840s	1967/1968	1960s	1800s

OD, ordnance datum.

sites upstream and downstream of the studied weirs being referred to as US and DS, respectively, and the further upstream and downstream sites being denoted by F (FUS and FDS) and with a numeric identifier reflecting instances where more than one further upstream or further downstream site was included in the study. Reference sites in the study areas are defined by a reference reach (REF).

2.1.1 River Duag catchment and Shanrahan Weir

The River Duag in Co. Tipperary, Ireland, is a tributary of the River Tar, which, in turn, is a tributary of the River Suir. The River Duag rises in the Kilworth Mountains along the Cork–Tipperary border before discharging to the River Tar between Clogheen and Ballyporeen. The river offers spawning potential for Atlantic salmon (*Salmo salar*; hereafter referred to as salmon). The core study area, extending for a distance of *c.*430 m on a fourth-order stream, was situated in the lower part of the catchment and comprised four monitoring stations (Figure 2.2a), three of which were located upstream of Shanrahan Weir.

Shanrahan Weir (Figure 2.2b) is a lateral weir, 1 m high and *c.*30 m long, with a stone crump structure dating back to the 1840s. It presently serves to direct water along a small race to a nearby farmyard. Although it was anticipated that Shanrahan Weir would be removed in the course of the project, this removal had not yet occurred at the time of writing this report.

2.1.2 River Dalligan catchment and Dalligan Weir

The River Dalligan rises in the southern tip of the Monavullagh Mountains and flows in a southerly direction to where it discharges to the Irish Sea just west of Ballyvoyle Head in Co. Waterford. Dalligan Weir, located 2.2 km upstream from the sea outfall on a third-order stream, is a 2.3-m-high contracted ogee structure (Figure 2.3b) that was built in 1967/1968. Seven monitoring sites over a stream length of approximately 4.2 km were studied. Four of these sites were located upstream of Dalligan Weir, with the remaining three being downstream of the structure (Figure 2.3a). Although it was anticipated that this weir would be removed during the project, this removal has yet to occur. The river upstream of the weir has the potential to support salmon and sea trout (*Salmo trutta*).

2.1.3 Browns Beck Brook catchment

Browns Beck Brook (also known as Donard Stream) rises north-east of Donard, Co. Wicklow (Figure 2.4).

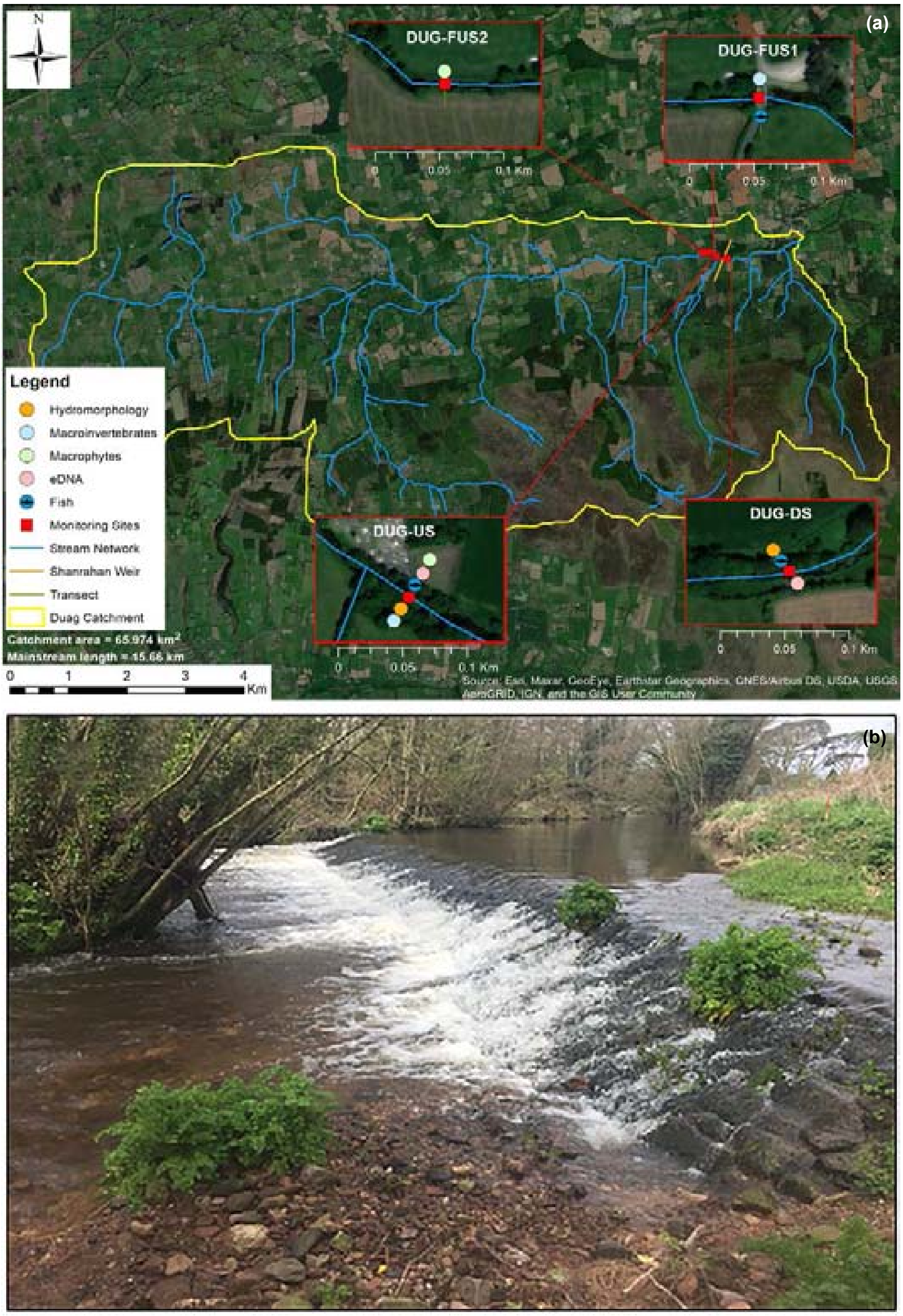

Figure 2.2. (a) Catchment map of the River Duag, showing locations of the monitoring sites and the research activities undertaken at these sites. (b) Shanrahan Weir on the River Duag.

It is a second-order tributary of the River Carrigower, which, in turn, discharges into the River Slaney system. The study area included an (unnamed) ford crossing, built originally in the 1960s, that was designated for replacement/modification by Inland Fisheries Ireland (IFI). The old ford crossing (Figure 2.5a) was a non-standard broad-based structure that extended 1.5 m vertically above the channel bed grade. It contained no fish pass and represented a potential barrier for fish, including

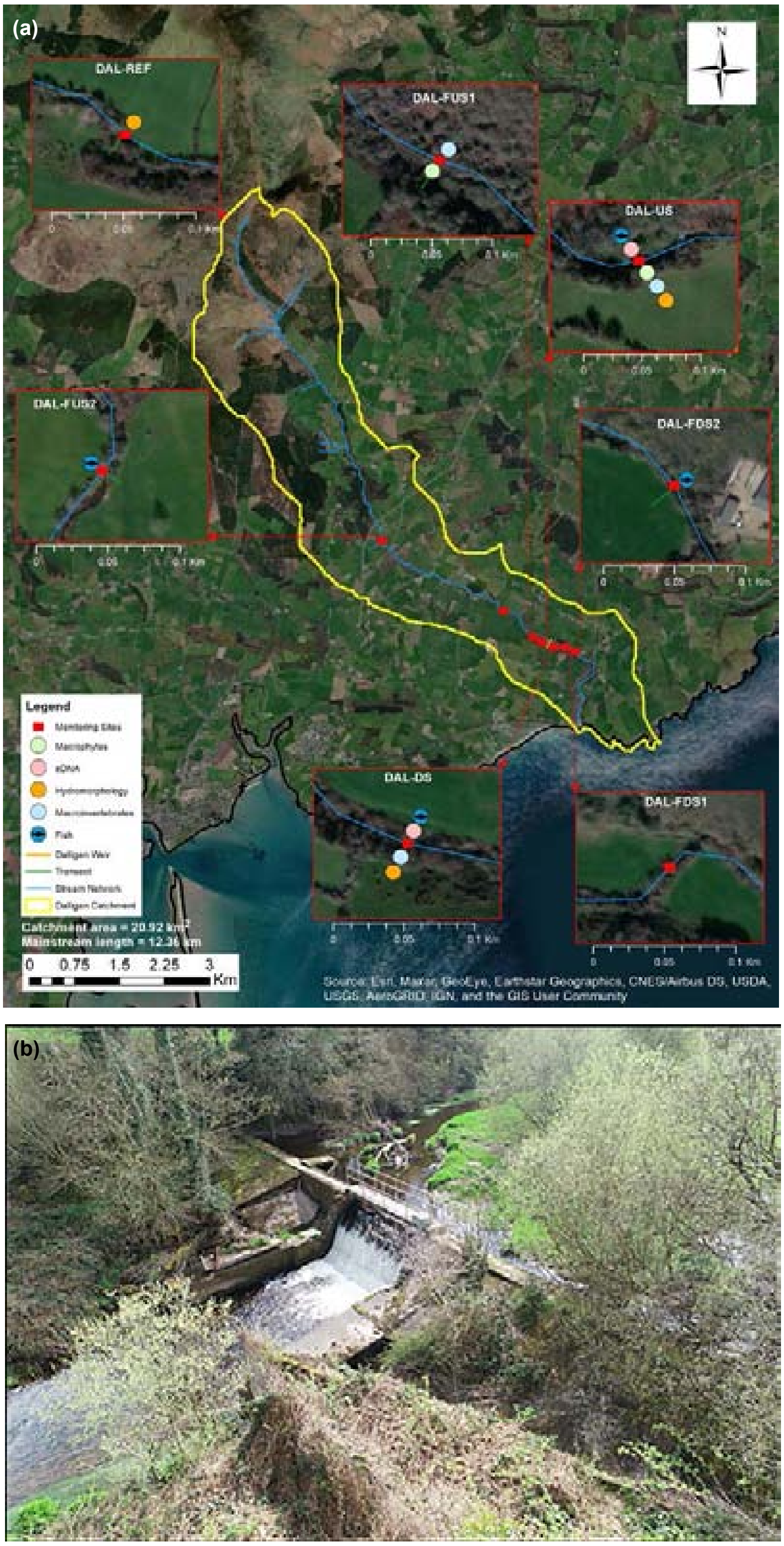

Figure 2.3. (a) Catchment map of the River Dalligan, showing locations of the monitoring sites and the research activities undertaken at these sites. (b) Dalligan Weir.

salmon. The river in the vicinity of the ford crossing had also undergone localised channelisation, which involved major realignment and re-sectioning of the channel (Figure 2.5b). Demolition of the ford crossing and construction of a replacement culvert structure were carried out in the summer of 2019. The replacement concrete box culvert (Figure 2.5f) is essentially a single-span structure that serves to

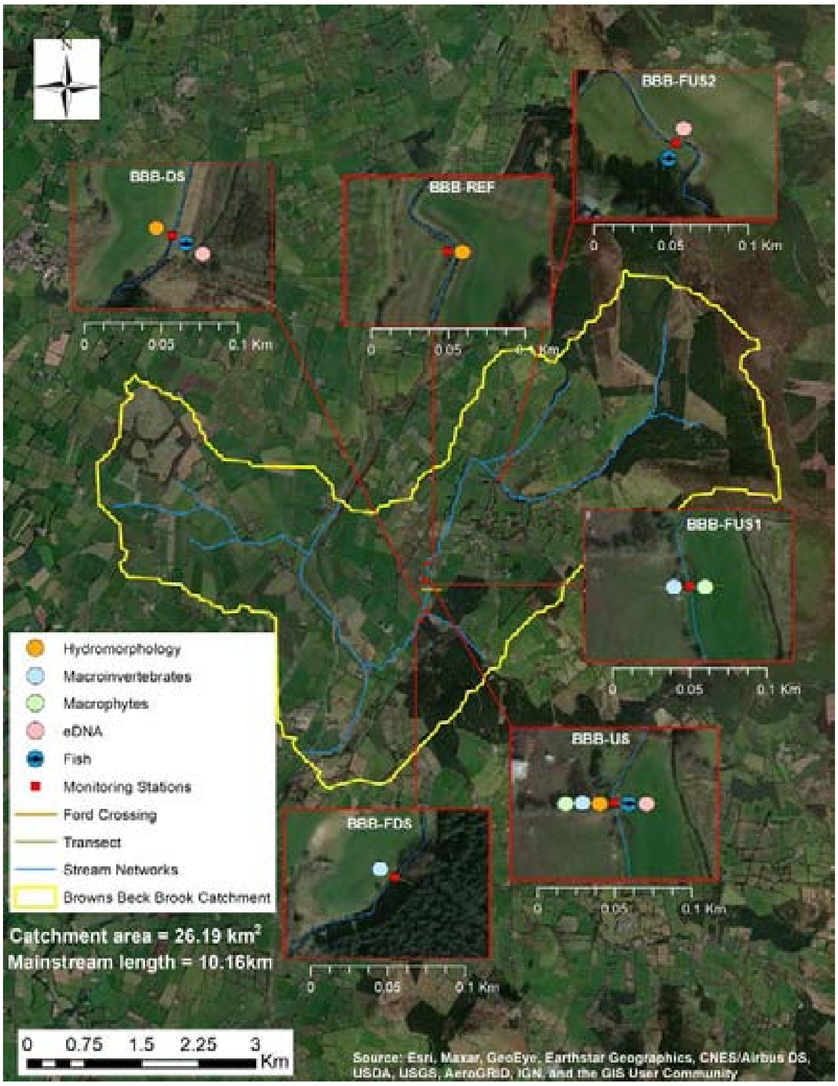

Figure 2.4. Browns Beck Brook catchment map showing locations of monitoring sites and the research activities undertaken at these sites.

restore river continuity between the reaches upstream and downstream of the crossing. The work was carried out in three phases over two summers as follows: first, the stream channel was temporarily diverted around the ford structure to allow access for removal (October 2018); second, the ford was demolished and removed (July 2019); and, third, the new box culvert was installed, the original position of the channel was reinstated and the temporary diversion channel was cut off and back-filled (August 2019).

The study reach, covering a length of 2.8 km, had six monitoring sites, four of which were upstream of the stream crossing and two were located downstream (Figure 2.4).

2.1.4 Burren River catchment

The River Burren is a tributary stream in Co. Carlow that rises in the townlands of Raheenleigh and Coolasnaghta, and flows from there in a northerly direction to where it discharges into the River Barrow system, below the town of Carlow. The core study reach (Figure 2.6) was located in the lower part of the Burren catchment and extended for almost 5 km from the furthest upstream to the most downstream monitoring site.

Included in the study reach was Hanover Weir, a concave structure that dates back to the 1800s (Figure 2.7a). This weir has always contained a fish

Figure 2.5. Restoration phases on the Browns Beck Stream: (a) before the ford removal, (b) creation of a diversion channel (October 2018) and (c and d) removal of the concrete ford structure (July 2019), (e and f) installation of the culvert (August 2019).

pass to facilitate the migration of salmon, but it was identified for removal/modification by IFI, as it did not provide for the free movement of all fish at all times of the year, as required under the provisions of Section 116 of the 1959 Fisheries (Consolidation) Act and the requirements of the European Habitats Directive. A modification, rather than a removal, was ultimately sanctioned. This included the construction of a rock ramp-type fish pass in front of the existing weir (Figure 2.7b), the transverse and longitudinal

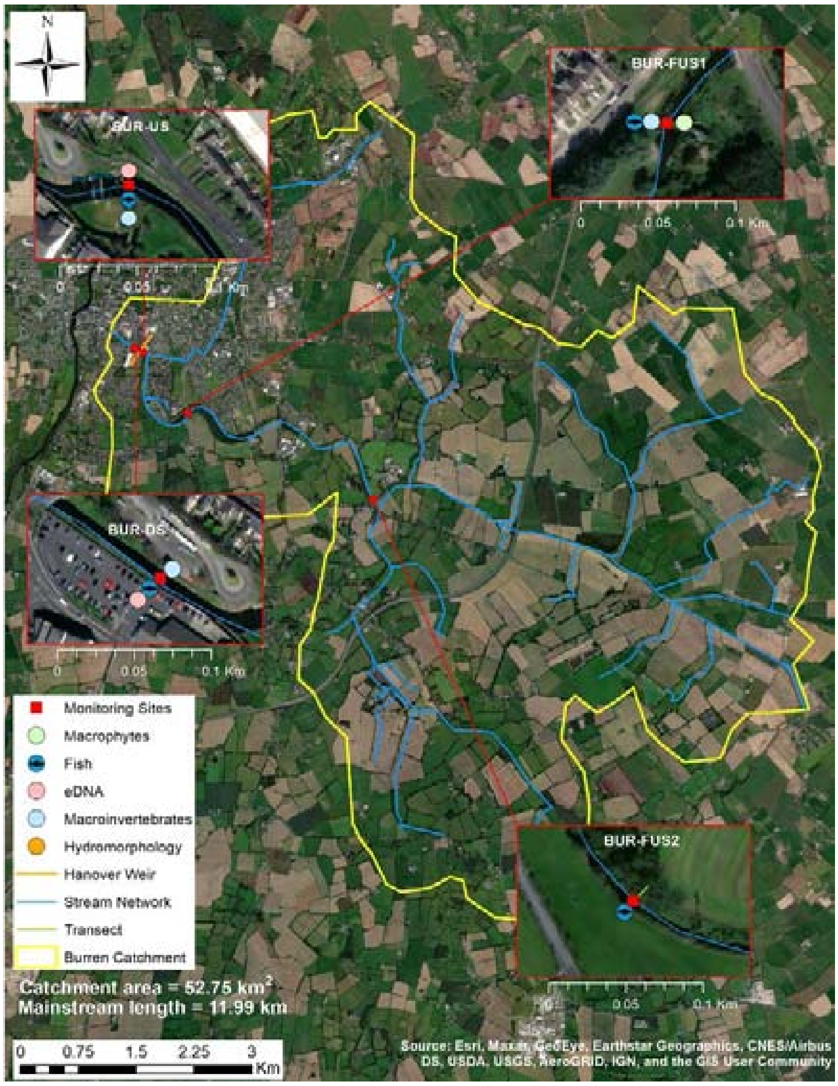

Figure 2.6. River Burren catchment map showing locations of monitoring sites and the research activities undertaken at these sites.

dimensions of which are *c.*13 m and *c.*50 m, respectively. The weir crest was also lowered by 0.6 m. The rock ramp has eight steps at 5 m intervals, each dropping 130 mm at each step. There are pools between the ridges.

2.2 Non-core Study Sites

The locations of the 35 other locations across 12 river/stream systems are shown in Figure 2.8, with the activities undertaken summarised in Appendix 2. A similar coding to that used for the core study areas applies to these non-core study sites.

Figure 2.7. Hanover Weir (a) viewed downstream on River Burren prior to remedial works and (b) viewed downstream following the construction of the rock ramp fish pass. Images: Inland Fisheries Ireland.

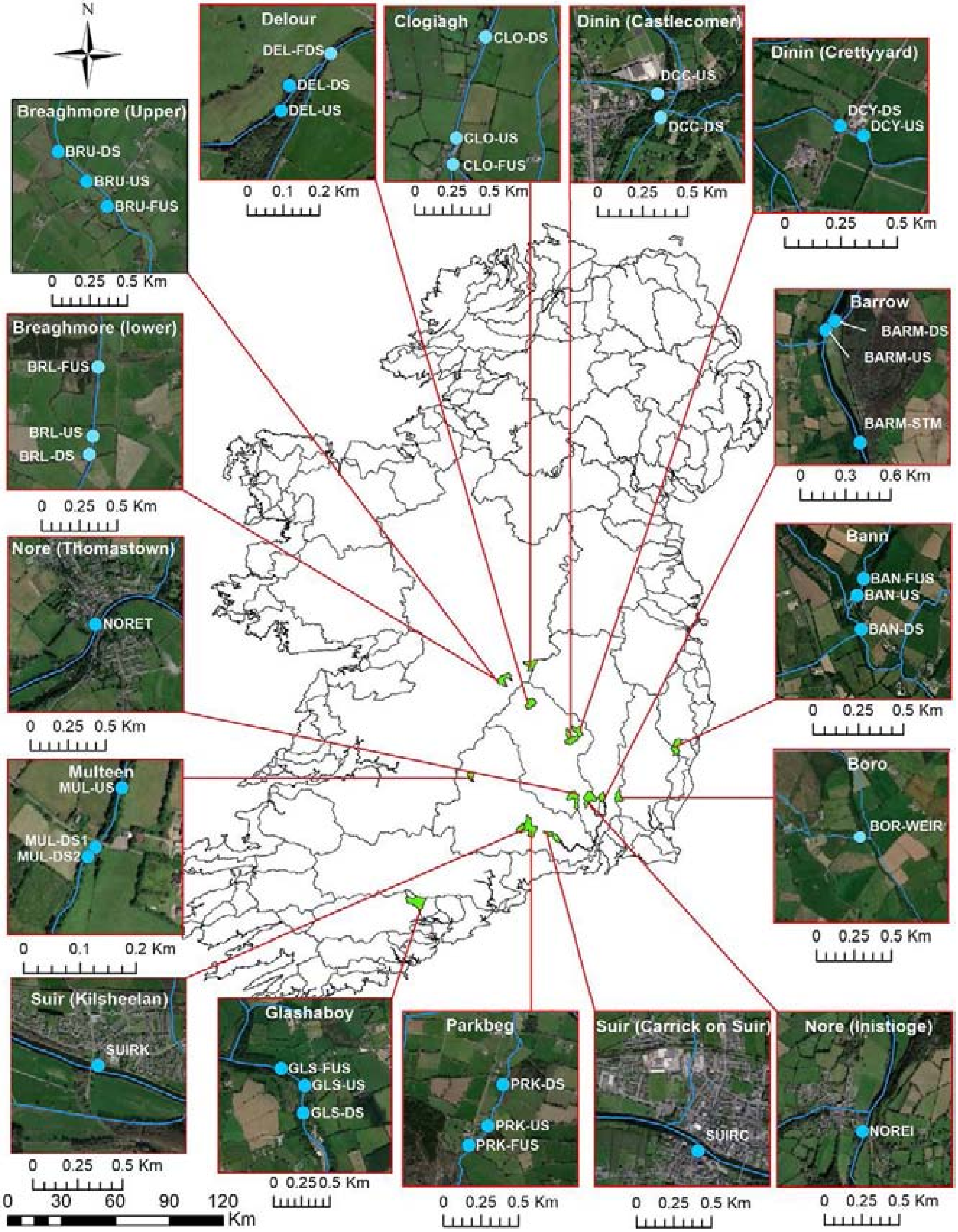

Figure 2.8. Locations of non-core study sites in the Reconnect project. The sub-catchments are shown in green. DS, downstream; FDS, further downstream; US, upstream; FUS, further upstream.

3 Mapping and Characterisation of Barriers in Selected Catchments/Sub-catchments

The research undertaken here involved two tasks. First, an assessment was carried out on the value of a desk-based approach for locating barriers on rivers (section 3.1; published in Atkinson *et al*., 2018a). Second, field mapping of 10 selected catchments/sub-catchments took place to capture both location and the physical diversity of the structures (section 3.2) and assess risk to fish movement (published in Atkinson *et al*., 2020).

3.1 Assessment of the Value of a Desk Study for Building a National River Barrier Inventory

The desk study was based on one catchment in the east (Dodder, a sub-catchment of the River Liffey) and one in the south-east (Nore) of Ireland. The River Nore, a designated Special Area of Conservation (SAC) under the EU Habitats Directive, is an important salmon river and has previously been the focus of river barrier research (Gargan *et al*., 2011). Water from the mainstem of the river was historically used to power watermills (Hamond, 1990). The River Dodder had numerous industries that relied on this river as a source of stream power and this resulted in it being heavily regulated in the 18th and 19th centuries through the construction of weirs (McEntee and Corcoran, 2016). Although the river does not have SAC status, it is an important recreational angling river.

Two approaches were adopted. The first (method 1) utilised maps and satellite imagery, displayed in a geographical information system (GIS) platform (Table 3.1 and Figure 3.1). The second approach (method 2) was also underpinned by a GIS analysis and involved identifying intersections of the transport network (roads and railway tracks) with river systems and recording each intersection as a potential barrier (NRA, 2008). The effectiveness of both desk studies was assessed and compared by cross-referencing the "potential" desk-located barriers with those actually recorded in a walkover survey of the rivers. The River Nore was walked in winter 2007/2008 by IFI (Gargan *et al*., 2011). The Dodder catchment was walked in summer 2016 by the Reconnect team. Full details of the methods and data analysis are given in Atkinson *et al*. (2018a). For clarity, the term "actual barrier" is used when referring to those identified in the field survey. The term "potential barrier" refers to the structures located using the desk-based methods.

3.2 Output of the Desk and Field Mapping

In total, 508 barrier structures were recorded in the Nore catchment in the walkover survey

Table 3.1. The various map layers and data sources used for the desk studies

File type	Source	Link	Description
Raster Map Layer	Ordnance Survey Ireland (OSI)	https://www.osi.ie/	1:50,000 Discovery Series map (OSI, 2019a)
			Historic 25" map (1897–1913) (mapped at 1:2500 scale) (OSI, 2019b)
	Environmental Systems Research Institute (ESRI)	Available in ArcMap base layers	World imagery, high-resolution satellite and aerial imagery (2011+) (ESRI, 2009)
Shapefile	Environmental Protection Agency, Ireland (EPA)	http://gis.epa.ie/	"WFDRiverWaterbodies" (mapped at 1:50,000 scale)
			"WFDSubcatchments"
	© OpenStreetMap contributors	https://www.openstreetmap.ie/resources/data/	Open-source data on road and rail network

Reproduced from Atkinson *et al*. (2018a).

Figure 3.1. Examples of the map layers used in the desk study. (a) Historical 25" map layer, (b) satellite image, (c) Discovery Series map and (d) weir. The weir on the Owendoher River, tributary of the River Dodder (d), indicated with a star (a–c), was visible only on the historical 25" map layer (a). The satellite image (b) and Discovery Series map (c) did not indicate this structure. Reproduced from Atkinson *et al.* (2018a).

(Gargan *et al.*, 2011). Both the detailed desk study (method 1) and the rapid desk study (method 2) overestimated this number (data are available in Atkinson *et al.*, 2018a). Over 90% (2697) of the potential barriers identified using method 1 were road–river crossings (bridges, culverts, fords). The probability of detection (POD) rates achieved in the 21 sub-catchments of the Nore and its mainstem by the detailed mapping study undertaken using method 1 (96% over the entire catchment) were consistently equal to or higher than those achieved using method 2. Using method 2, a 100% POD was achieved in only two of the sub-catchments, and five barriers on the mainstem were missed. When method 1 was used, only 19 barriers, all on first- to third-order streams, were missed in the entire Nore catchment, compared with 77 barriers missed using method 2.

A total of 189 actual barriers were recorded in the field survey of the Dodder. Here, again, both method 1 and method 2 overestimated this number (Table 3.2).

Table 3.2. The total numbers of actual barriers in each of the 10 study catchments

Catchment	Potential barriers	Actual barriers						
		Road crossing	Weir	Dam	Sluice	Waterfall	Other	Total
Dodder	242	51	117 (23)	2	6 (1)	12 (4)	1	189
Erriff	135	21	2	–	–	24 (9)	1	48
Bann	171	36	3 (1)	–	–	1 (1)	–	40
Moynalty	135	9	5 (2)	–	–	–	–	14
Kinnegad	47	1	–	–	–	–	–	1
Nanny	139	7	7 (1)	–	–	–	–	14
Dromore	184	19	5 (2)	–	–	1	–	25
Glashaboy	96	18	5	–	–	–	–	23
Owenboliska	61	3	1	1	–	1	–	6
Clodiagh	108	7	4	–	–	1 (1)	–	12
Total	1318	172	149	3	6	40	2	372

Numbers in parentheses indicate the number of actual barriers located during the field survey that were not located using the desk study. For example, in the Dodder catchment, a total of 117 weirs were recorded; however, of these, 23 had not been found using the desk study.

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However, differences between the two desk study methods were more notable in the Dodder catchment, with the POD obtained using method 2 (43.4%) being almost half of that achieved using method 1 (85.2%). Satellite imagery and historical maps were particularly important for locating barriers in the Dodder: 30% of the barriers were located using satellite imagery alone (25 weirs and 19 road crossings) and 21% of the barriers were located using historical 25" maps alone (27 weirs, three waterfalls and four road crossings). The remaining barriers were visible on two or more maps. Of the 392 potential barriers located using method 1, over 60% (242) were road–river crossings.

Both desk studies overestimated the true number of river barriers, so ground-truthing the potential barriers is required. However, a desk study largely eliminates the need to walk entire river catchments to locate barriers, allowing more focused site visits. It is also important to note that a large number of the potential barriers were road–river crossings (over 60% in the Dodder and over 90% in the Nore). The subsequent ground-truthing associated with these structures can be rapid, as the sites can be readily accessed by road.

While there is clear value in having a complete river barrier inventory, the extent of the desk study and resultant field study research could be further reduced by carrying out an initial characterisation of headwater streams and eliminating from further consideration those that are unsuitable for sustaining fish and those that have no impact on flow or sediment movement (e.g. high gradients, presence of natural barriers).

In summary, the desk studies described here can help guide the field survey, making it more efficient and targeted. In particular, the desk study lends itself to remote locations, where walkover surveys of the river network may be especially difficult and time-consuming.

3.3 Field Mapping of Barriers in 10 Selected Catchments

Five inland and five coastal catchments/sub-catchments (hereafter "catchments") with different land use characteristics and ranging in area from 93 km² to 296 km² were surveyed for the presence of barriers (Figure 3.2). The desk study identified 1589 potential barriers in the 10 study catchments, and 1401 structures were visited. Road crossings that did not interfere with natural stream conditions in terms of gradient, width and substrate were not considered barriers to fish migration. In addition, backwatered culverts with water depths comparable to that of the natural stream and weirs that were breached or washed out (such that their impact on fish movement was deemed to be insignificant), as well as dry intermittent streams and ditches, were also excluded from the assessment.

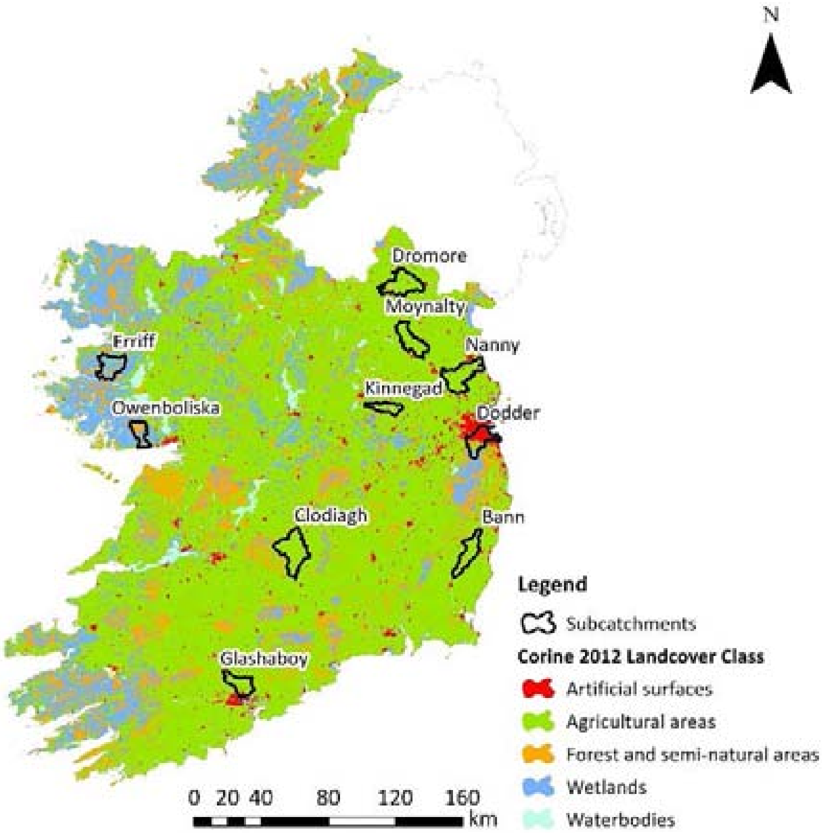

Figure 3.2. Map of Ireland showing CORINE 2012 level 1 landcover classes and the location of each sub-catchment.

A level 1 IFI barrier risk assessment (Gargan *et al*., 2011) was carried out on each structure in low-flow conditions between 2016 and 2018, which included taking measurements of the features of each structure (Figure 3.3). For example, in the case of weirs and sluices, these included weir or sluice height, drop height, total height of the structure, plunge pool depth, downstream apron length, sill length (measured on the horizontal) and slope (gentle, moderate, steep and vertical).

The degree of fragmentation in each catchment was calculated using two metrics: river barrier density and the dendritic connectivity index (DCI) (Cote *et al*., 2009). The DCI scores were calculated for diadromous species (DCI_D – salmon, sea trout, sea lamprey) and potadromous species (DCI_P – European eel and potamodromous trout) and for two activities. DCI_D and DCI_P took account of spawning and feeding and included both natural and anthropogenic barriers. The DCI_D calculation is based on the probability of a fish moving in both upstream and downstream directions between the mouth of the river and another segment of the river network. Wetted area (McGinnity *et al*., 2003) was the best proxy for spawning/feeding habitat that could be readily accessed at a large scale. Estimates of spawning habitat excluded lakes. Details of the calculation steps are provided in Atkinson *et al*. (2020).

3.3.1 Barrier counts and degree of fragmentation

A total of 372 structures that were deemed barriers to fish movement, under the conditions at the time of surveying, were recorded. Three of these were dams and the remainder were low-head weirs/sluices, barriers associated with road or rail crossings of rivers and natural structures (Table 3.2). Approximately 14% of road crossings presented barriers to the movement of fish. Extrapolating this to a national scale, there are possibly approximately 9000 road crossings in Ireland that are barriers to fish migration (intersecting the national road and river network layers in a GIS generates a total of 64,387 crossings).

There was considerable variability in the numbers and density of actual barriers between the catchments, from just one in the River Kinnegad

Figure 3.3. Photographs showing varying barrier types and some of the physical measurements recorded. (A). Bridge apron with a drop (H) at the downstream end of the apron (D. A. L.). (B) Sloping weir (S.L. and H) with a downstream apron (D.A.L.) and a downstream drop (D.H.). (C) Culvert with a drop (H). D.A.L., length of apron; D.H., height of drop; H, height; S.L., sill length measured on the horizontal. Reproduced from Atkinson *et al.* (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Table 3.3. Barrier types defined based on physical dimensions, number of each type encountered and slope characteristics

		Physical attribute			Slope/nature of apron (count)			
Barrier category		Apron	Drop	*n*	Gentle	Moderate	Steep	Stepped
Bridge/culvert		+	+	44	38	4	2	
Bridge/culvert		+	–	11	3	3	1	4
Bridge/culvert		–	+	81				
Bridge/culvert		–	–	33				
Ford				3				
Weir	Sloping	+	+	8			8	
Weir	Sloping	–	+	6	2	2	2	
Weir	Sloping	–	–	26		10	16	
Weir	Vertical			78				78
Weir	Stepped			31				
Sluice				6				
Natural				40	1	4	25	10
Dam				3				

+, present; –, absent. Full details of structure dimensions are given in Atkinson *et al.* (2020).

(0.02 structures/km) to 189 in the Dodder (1.2 structures/km). Barriers associated with road–river crossings were typically concentrated in the headwaters (first- and second-order streams) whereas weirs and waterfalls were more widespread in first- to fifth-order streams (Figure 3.4).

In total, 13 river barrier types were defined in this study (Table 3.3), including four types of bridges/culverts and five types of weirs, which captured the physical diversity of the barriers. Barriers associated with road–river crossings (bridges, culverts and fords) were most common ($n = 172$) and were more evenly dispersed across the 10 study catchments. Of the bridges and culverts, those with a downstream drop but no apron (perched structures) were most numerous ($n = 81$). These typically presented both a jump challenge and a depth challenge for fish.

Six catchments (Dodder, Erriff, Glashaboy, Monalty, Nanny and Owenboliska) had at least one barrier located on the mainstem river within 5 km of the mouth/confluence, giving them generally the lowest DCI_D scores, ranging from 0.6 to 44.1. This contrasts with the Bann, Clodiagh and Kinnegad catchments (with only one barrier on a first-order stream), which had high values for all DCI scores.

All connectivity scores were impacted in the Dodder, Glashaboy and Nanny catchments (see Atkinson *et al*., 2020). Results were more variable in the other catchments. For example, the lowest recorded DCI_D scores were in the Erriff catchment, where low scores for sea lamprey and eel were due to the potential unsuitability of the fish pass associated with the Aasleagh Falls for these species. The natural connectivity (DCI_N) for sea lamprey and eel in this catchment were also low because of a series of high-risk/impassable waterfalls/chutes immediately upstream of Aasleagh Falls. The third-lowest DCI_D was in the Owenboliska catchment and here, again, it was for sea lamprey, because of the natural waterfall located on the mainstem of the river ($DCI_N = 10.4$). Further details can be found in Atkinson *et al*. (2020).

In terms of connectivity for potamodromous species, the Dodder ranked worst for trout for both spawning and feeding activities, followed by the Erriff, Glashaboy and Moynalty. The largest differences in DCI_P for spawning and feeding activities within the same catchment were recorded in the Dromore, Owenboliska and Erriff catchments, and this was a result of the number and size of the lakes within these catchments.

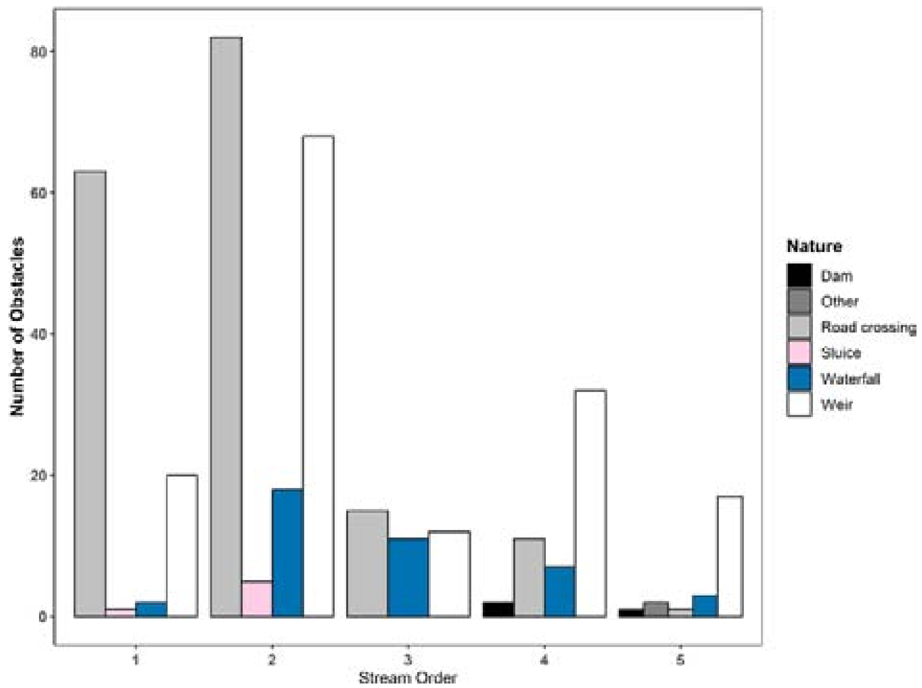

Figure 3.4. The total number of barrier types per stream order across all sub-catchments. Reproduced from Atkinson *et al*. (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

A barrier located at or near the mouth of the river has a greater effect than the density of barriers on connectivity for diadromous fish. This was particularly significant for species with poor swimming/jumping abilities (e.g. sea lamprey), as seen in the Owenboliska, Nanny, Dodder and Erriff catchments. However, barrier density is more relevant for movement within the river; thus, a significant negative correlation between the DCI_P for trout for both feeding and spawning activities and barrier density was detected (feeding: Pearson correlation = –0.76, $p = 0.01$, $n = 10$; spawning: Pearson correlation = –0.82, $p = 0.003$, $n = 10$).

Barrier density could be coupled with the DCI to highlight severely affected catchments, where removal or modification of a large number of barriers may be required to significantly improve connectivity. For example, both the Dodder and Nanny catchments have low DCI_D values. However, the Dodder has one barrier per 0.8 km of river, while the Nanny has one barrier per 19 km. Thus, for salmon, for example, removing the lowermost barriers in the Nanny would probably be more beneficial than removing the lowermost barriers in the Dodder.

4 Investigation of the Potential Impact of Barriers on Macroinvertebrate and Fish Communities

The research in this chapter investigated the potential impact of barriers on fish populations, particularly on salmonid population structure and density, and on macroinvertebrate community composition and structure. Macrophyte surveying was limited to the core study sites.

4.1 Fish Studies

The fish studies were undertaken at the four core sites and at a number of the non-core sites (Delour, Multeen and Dinin; see Appendix 2). The data collected from the four core study areas were used to track changes after barrier removal. For various planning and other related issues, only the ford on Browns Beck Brook was removed, and the Hanover Weir on the Burren was modified with the construction of a rock ramp. Sites on each river were located within the impounded reach, immediately downstream where possible, and in some rivers at other locations upstream and downstream of the impounded reach. Sites in two catchments (Dalligan and Duag) of the core study area were fished in 2 years (2016 and 2017) while the sites on the Burren were also fished in 2019 and those on Browns Beck Brook, where the ford was removed, were fished in 5 years in total (2016–2020). The other sites were fished on one date in 2017 (Appendix 2). In the River Multeen there are two structures that impound water. The lowermost structure is a small rock weir, which creates a small impoundment. Approximately 15 m upstream of this structure is a bridge apron. The rock weir was constructed to backwater the bridge apron; however, the apron remains exposed. Electrofishing was carried out below the rock weir (MUL-DS2), within the impoundment of the rock weir (MUL-DS) and upstream of the bridge apron (MUL-US). The area above the bridge apron was, however, only a relatively shallow pool habitat. Full site details are available in Kelly-Quinn *et al*. (2021).

River reaches were isolated by stop nets (8 mm mesh) and electrofished by experienced operators from IFI using bank-based or boat-mounted electric fishing units. The density of salmon 0+ and parr age classes and 0+ and older trout age classes were estimated separately for each study reach using the methods outlined in Bohlin *et al*. (1989). 0+ fish were considered to be those < 9 cm in length (nose to tail fork), and parr or older fish were considered to be anything greater than this.

4.1.1 Fish species encountered

As expected, salmonids dominated the fish catches at all sites. Juvenile salmon (0+/1+) occurred in all rivers except the Dalligan, but not at all sites (Figures 4.1 and 4.2). Other fish species were encountered in relatively small numbers (Table 4.1). Eels were found in all rivers, generally upstream and downstream of the barriers, except the Burren in 2016 and Multeen in 2017. Most of the eels captured were caught in the Dalligan and 50% (2017) to 60% (2016) of these were captured immediately below the weir.

4.1.2 Salmonid population structure and density

With the exception of the Duag in 2016, trout fry were generally less common (or absent) in the impounded reaches than in the downstream sites and further upstream (Figures 4.1 and 4.2). In 2017, when a larger number of sites were surveyed, the difference was found to be statistically significant for trout fry (Figure 4.3) but not for older trout (all ≥ 1+ combined). The Burren held a lower density of fish in the impounded reach in 2016 and 2017, and this was largely because of the small numbers of 1+ trout (see Figure 4.1). The impounded reach of the other three core sites had a higher density (variable in the degree) of ≥ 1+ trout in 2016, which held true for Browns Beck Brook and the Duag in 2017 (Figure 4.1). However, the size range of ≥ 1+ trout was relatively similar across these sites. At two of the other sites fished in just 2017 (Dinin Crettyyard and Castlecomer), the ≥ 1+ fish were lower in numbers in the impounded reach (Figure 4.3), here also largely because of the low representation of 1+ trout. In the Multeen, the first shallow impounded reach held the highest number of ≥ 1+ trout.

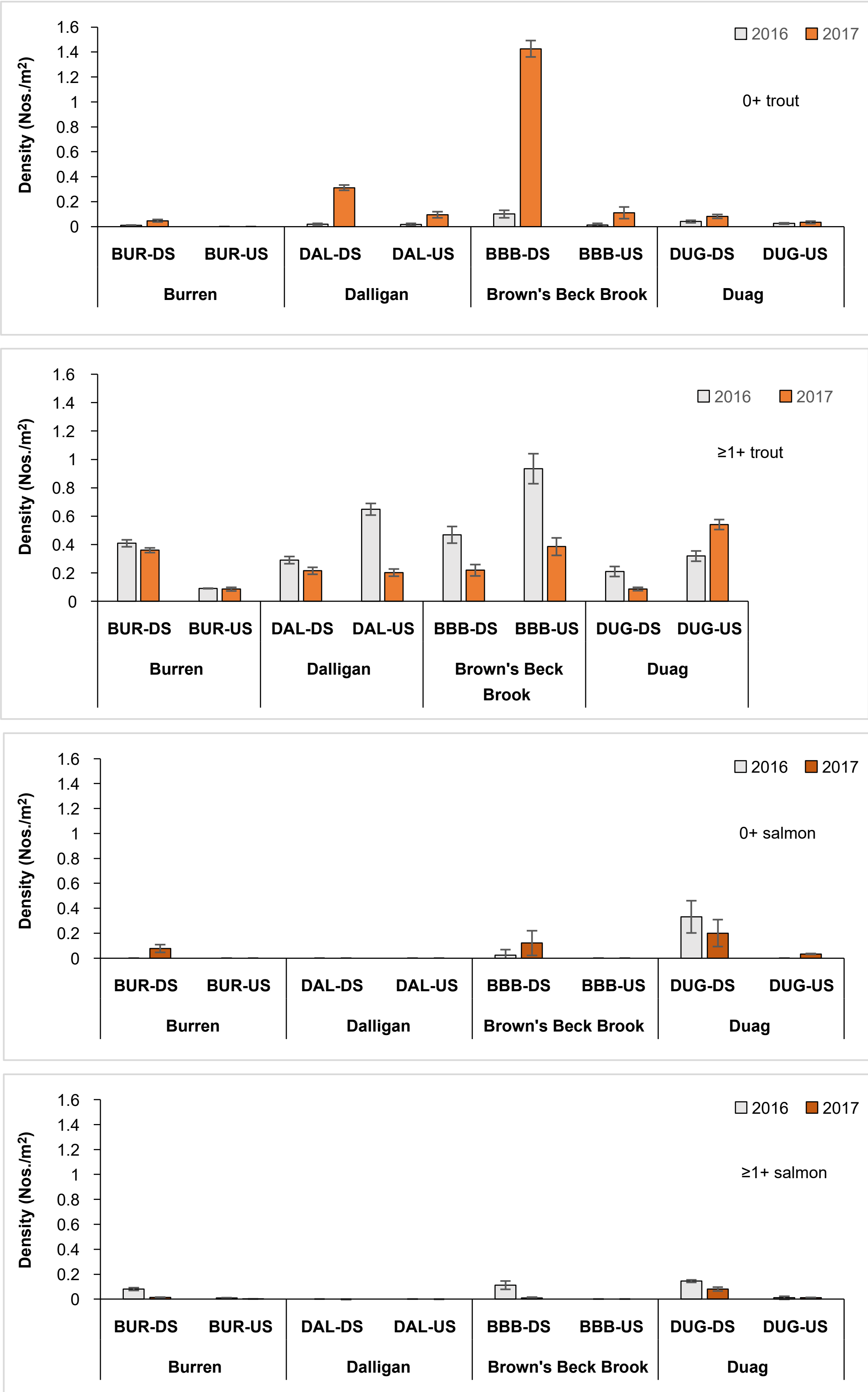

Figure 4.1. Comparison of the density (error bars are 95% confidence intervals) of trout and salmon at sites in the core study areas in 2016 and 2017. DS, downstream; US, upstream.

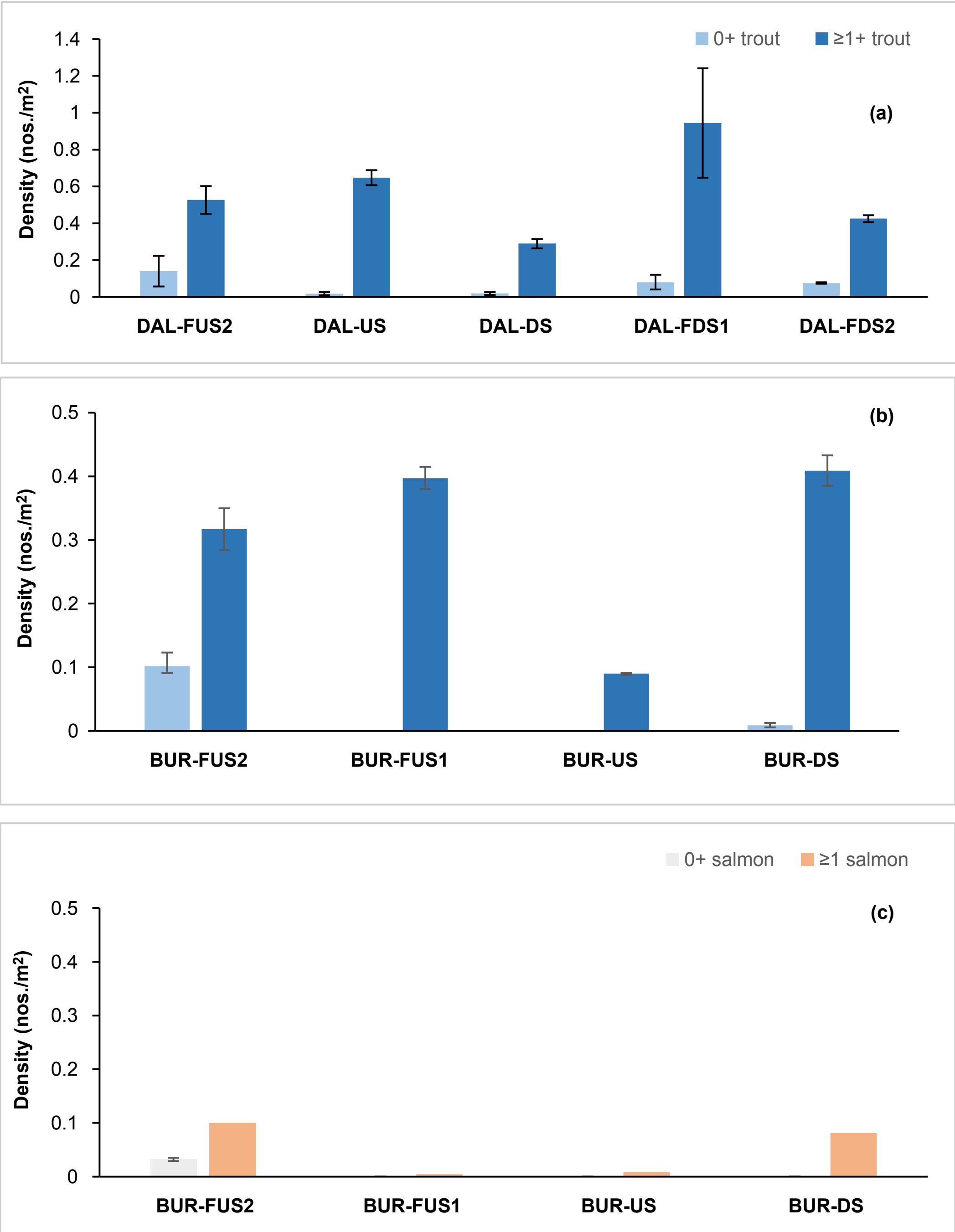

Figure 4.2. Comparison of the density (error bars are 95% confidence intervals) of trout at all sites fished in the Dalligan (a) and Burren (b) in 2016 and of salmon in the Burren (c). The impounded reaches are BUR-US and DAL-US. DS, downstream; FDS, further downstream; US, upstream; FUS, further upstream.

As previously mentioned, salmon were absent from the River Dalligan and at the additional sites. In 2016 and 2017, the three other core sites did not record any salmon fry in the impounded reach (Figure 4.1), apart from a small number in the impounded reach of the Duag in 2017. Sites located downstream or further upstream (Burren and Duag) had salmon fry present. Salmon fry did not appear in the impounded reach of Browns Beck Brook until 2018 and further upstream in 2020 (Figure 4.4). Salmon parr densities were generally low and, apart from a single 17-cm parr, all were 1+ fish. They were absent or in lower densities in the impounded reaches, with the exception of the impounded reach on the Delour and Multeen (Figure 4.3).

Table 4.1. Fish species other than salmonids recorded at the various study sites in 2016 and 2017

River	Site	Year	Eel	Minnow	Stickleback	Stone loach	Lamprey	Roach	Flounder	Perch
Browns Beck Brook	BBB-FUS2	2016	–	–	–	–	–	–	–	–
	BBB-US	2016	–	–	–	–	–	–	–	–
	BBB-DS	2016	–	–	–	–	–	–	–	–
	BBB-FUS2	2017	4	–	–	–	–	–	–	–
	BBB-US	2017	1	–	–	–	1	–	–	–
	BBB-DS	2017	3	–	–	–	–	–	–	–
Dalligan	DAL-FUS2	2016	5	–	–	–	–	–	–	–
	DAL-US	2016	1	–	3	–	9	–	–	–
	DAL-DS	2016	11	–	–	–	13	–	–	–
	DAL-DS1	2016	0	–	–	–	3	–	–	–
	DAL-DS2	2016	0	–	–	–	–	–	–	–
	DAL-US	2017	–	–	17	–	4	–	–	–
	DAL-DS[a]	2017	38	–	–	–	1	–	1	–
Duag	DUG-US	2016	1	–	–	4	1	–	–	–
	DUG-DS	2016	5	–	–	2	–	–	–	–
	DUG-FUS1	2016	3	–	10	5	33	–	–	–
	DUG-FUS2	2016	–	–	1	2	–	–	–	–
	DUG-US	2017	1	–	1	3	–	–	–	–
	DUG-DS	2017	5	–	1	3	–	–	–	–
Burren	BUR-FUS2	2016	–	3	–	5	–	–	–	–
	BUR-FUS1	2016	4	28	1	–	11	–	–	–
	BUR-US	2016	1	–	–	–	1	–	–	–
	BUR-DS	2016	–	9	2	4	4	–	–	–
	BUR-US	2017	1	–	–	1	2	–	–	–
	BUR-DS	2017	3	–	–	5	2	2	–	–
Delour	DEL-US	2017	1	–	–	–	4	–	–	–
	DEL-DS	2017	15	–	–	1	2	–	–	–
	DEL-FDS	2017	15	–	–	1	9	–	–	–
Dinan (Crettyyard)	DCY-US	2017		407	32	6	2	–	–	–
	DCY-DS	2017	2	232	1	33	–	–	–	–
Dinan (Castlecomer)	DCC-US[a]	2017	2	–	–	2	–	–	–	–
	DCC-DS	2017	2	–	–	2	2	–	–	1
Multeen	MUL-US	2017	–	–	–	2	2	–	–	–
	MUL-DS1	2017	–	–	–	–	–	–	–	–
	MUL-DS2	2017	–	–	–	–	–	–	–	–

All sites ending in "-US" are impounded reaches, as is MUL-DS1.
[a]One sea trout was caught below the barrier.

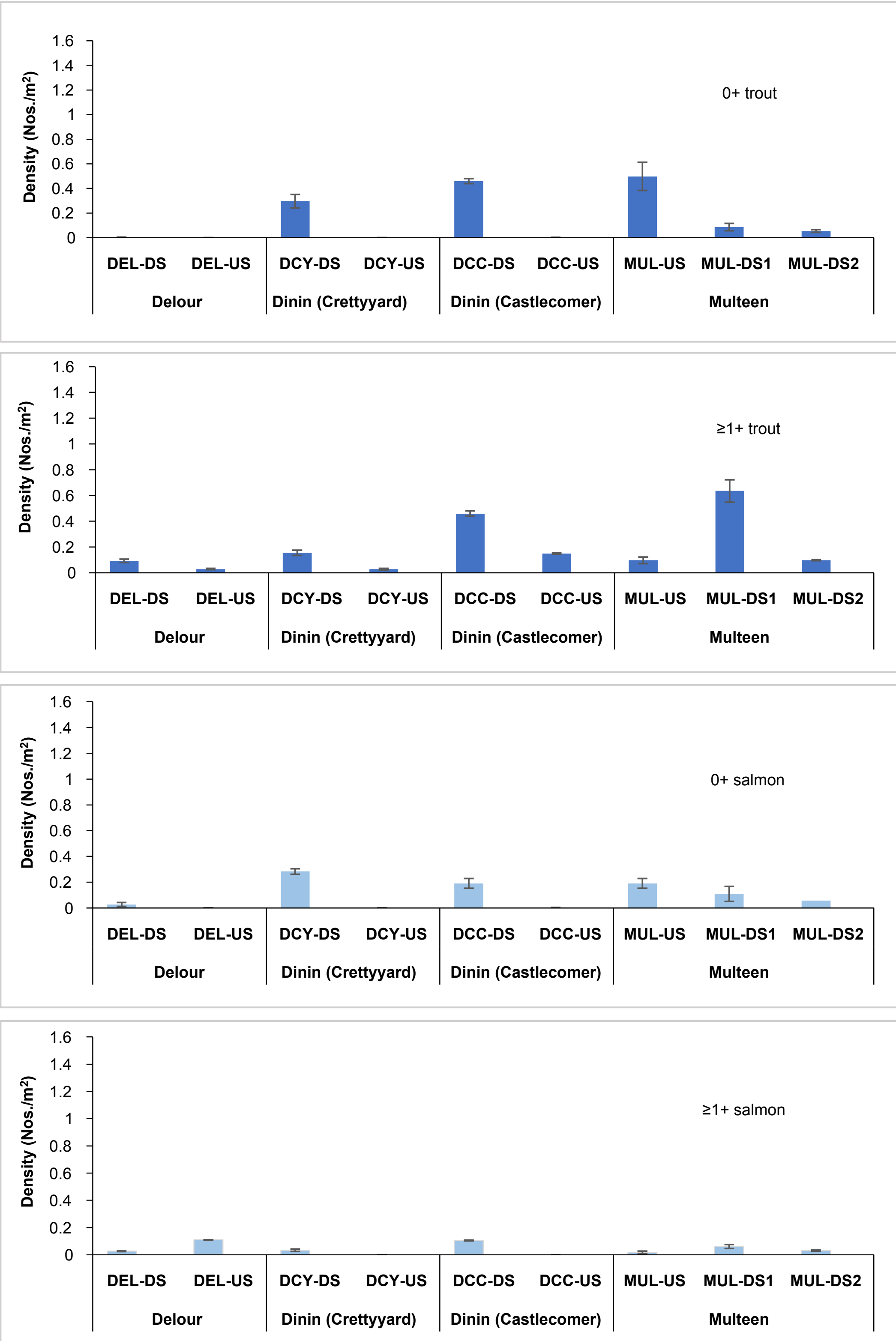

Figure 4.3. Comparison of the densities (error bars are 95% confidence intervals) of trout and salmon in the Delour, Dinin and Multeen in 2017. DS, downstream; US, upstream.

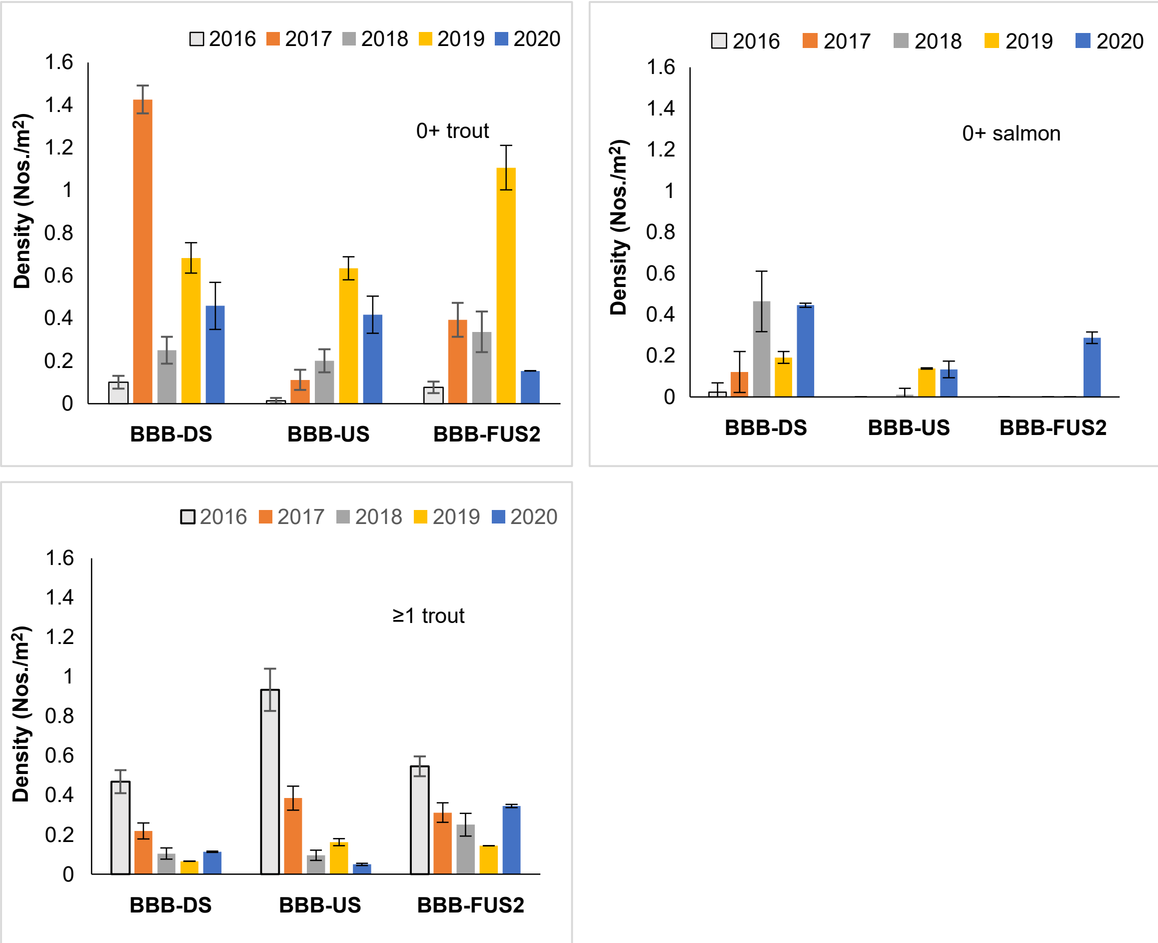

Figure 4.4. Annual variation in the density of brown trout and salmon at sites on Browns Beck Brook. The impounded reach is BBB-US (note that this reach was no longer impounded following the removal of the ford in July 2019). DS, downstream; FUS, further upstream; US, upstream.

Figure 4.4 illustrates changes in the densities of trout and salmon over the period before and after the ford removal on Browns Beck Brook. There was an increase in the density of 0+ trout in 2019 and 2020 in the previously impounded reach and there was an increase in the density of salmon in this reach in both years. Salmon fry were also recorded at the uppermost sites for the first time in 2020.

Following the installation of the rock ramp on Hanover Weir on the Burren in August 2017, there was a striking increase in the density of ≥1+ trout and also of salmon parr in the upstream reach (BUR-US), which was formerly more heavily impounded (Figure 4.5). Furthermore, there was an increase in the density of fish in the 20–24 cm range in the upstream reach in 2019, which, apart from fewer trout around 18 cm, was relatively similar to that in the downstream reach.

4.2 Macroinvertebrate Community

The study on macroinvertebrates consisted of two components (studies 1 and 2). Study 1 investigated the potential impact of the structures on downstream macroinvertebrate communities by comparing the communities in riffles and natural pools upstream and downstream of the impoundments. The second component assessed potential changes in the macroinvertebrate communities within impoundments by comparing the communities in natural pools and riffles upstream of the impounded reach with those from the impoundment (study 2).

To avoid the confounding effect of poor water quality, all sites were chosen on rivers known to be minimally impacted by pollution (good to high ecological status). In total, 10 sites with impounding structures on nine rivers were chosen (Appendices 1 and 2). Five of these structures were in rivers with siliceous geology

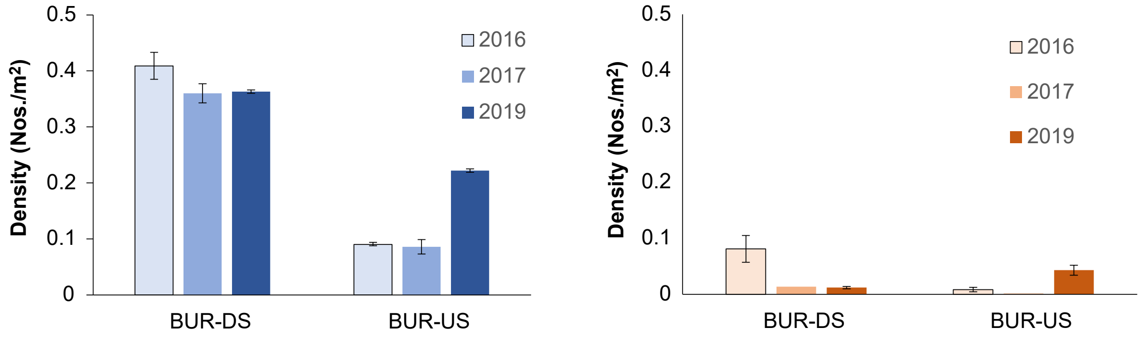

Figure 4.5. Comparison of the density of ≥1+ trout (left) and salmon (right) at the two sites on the Burren downstream (BUR-DS) and upstream (BUR-US) of the Hanover Weir in 2016, 2017 and 2019.

and two were in rivers with calcareous geology. The remaining three structures were located on river segments with calcareous geology; however, in these rivers, a portion of the upstream catchment had mixed and/or siliceous geology. For the purposes of the analysis, however, these sites were considered to be calcareous. Apart from one ford, all structures were weirs with a height of less than 2.5 m (details can be found in Kelly-Quinn *et al*., 2021). The impounded reaches ranged in length from 20 m to 200 m, and all were wadeable, enabling a similar sampling approach in all mesohabitats.

Macroinvertebrate sampling was carried out between 3 and 12 May 2017. A 1-minute kick sampling technique was employed using a standard pond net (mesh 1 mm) from the Freshwater Biological Association. Three kick samples were taken in three habitats, natural pools, riffles (upstream and downstream of the impoundment) and in the impoundment (Figure 4.6).

An additional 20-second hand search (per replicate kick sample) was carried out within riffle habitats, whereas an additional 20-second marginal sweep (per replicate kick sample) was carried out within pool and impounded habitats. Taxa identification was to the lowest practicable taxonomic level. Full details of the statistical analysis can be found in Kelly-Quinn *et al*. (2021).

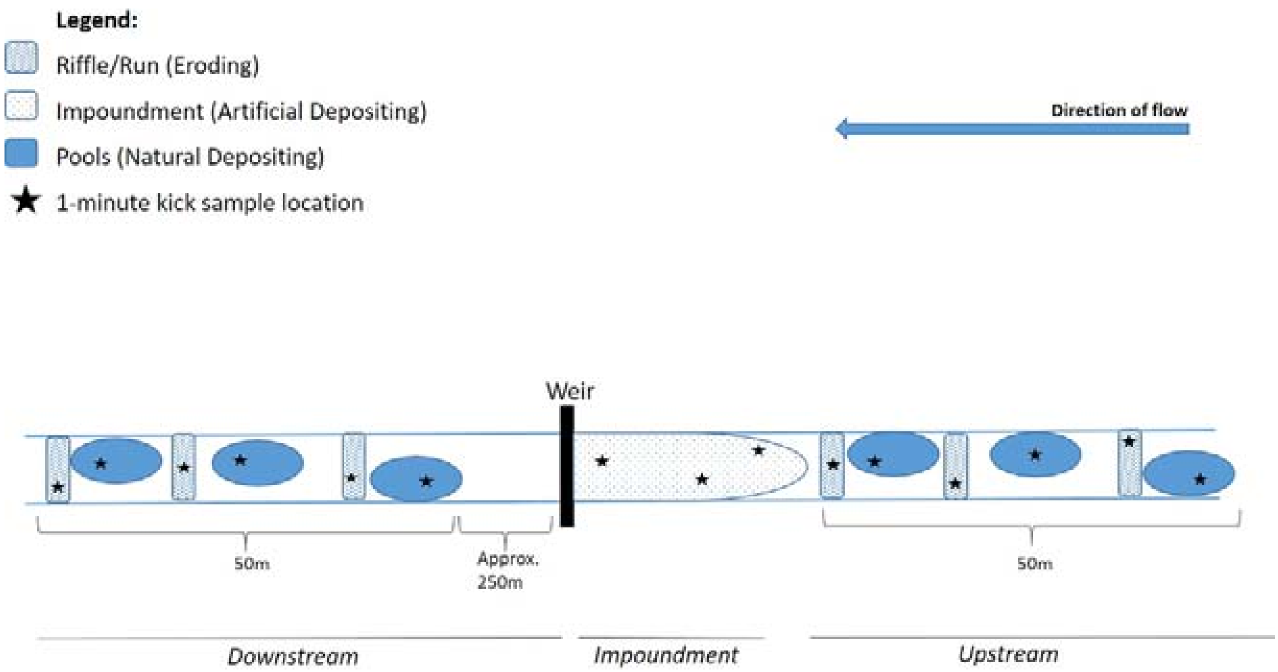

Figure 4.6. Schematic diagram showing the general macroinvertebrate study sampling design (not to scale).

4.2.1 Study 1: macroinvertebrate fauna above and below small impoundments (comparing communities in riffles and natural pools upstream and downstream of the impoundments)

A total of 118,044 individuals belonging to 116 taxa were collected during this study. Chironomidae made up the majority of these individuals (45%), followed by *Elmis aenea* (Müller 1806) (8%), *Caenis rivulorum* Eaton 1884 (7%), *Serratella ignita* (Poda 1761) (5.7%), *Baetis rhodani/atlanticus*(5.4%), *Rhithrogena semicolorata* (Curtis 1834) (5.2%), Simuliidae (3.6%), *Limnius volckmari* (Panzer 1793) (2.4%), *Esolus parallelepipedus* (Müller 1806) (1.9%) and *Hydropsyche siltalai* Döhler 1963 (1.5%). All other taxa accounted for less than 1% of the total abundance.

The location (i.e. upstream vs downstream of the barrier) did not have a significant main effect on any of the univariate metrics. This suggests that the various metrics, while varying between rivers as a result of interactions between geology and habitats, do not differ in the riffle and natural pools sampled upstream and downstream of the impoundments assessed in this study. A similar result was obtained for community composition and structure.

4.2.2 Study 2: macroinvertebrate fauna in natural and impounded river habitats (comparing communities in natural pools and riffles upstream of the impounded reach with those from the impoundment)

Here, the analysis revealed differences in the macroinvertebrate metrics between the natural habitats upstream of the impounded reach and the impoundment. However, the results did not reveal consistent patterns. Total abundance differed significantly between habitats in 4 of the 10 sites, while taxon richness was significant for the habitat pairings in only 3 of the 10 sites. In terms of the Shannon–Wiener index, values were significantly higher in riffles than in impounded reaches in 6 out of 10 sites (Figure 4.7). EPT abundance in the Bann, Breaghmore (lower), Clodiagh and Browns Beck Brook sites was significantly higher in riffles than in impoundments (Figure 4.8). However, the opposite was true in the River Duag (Figure 4.8).

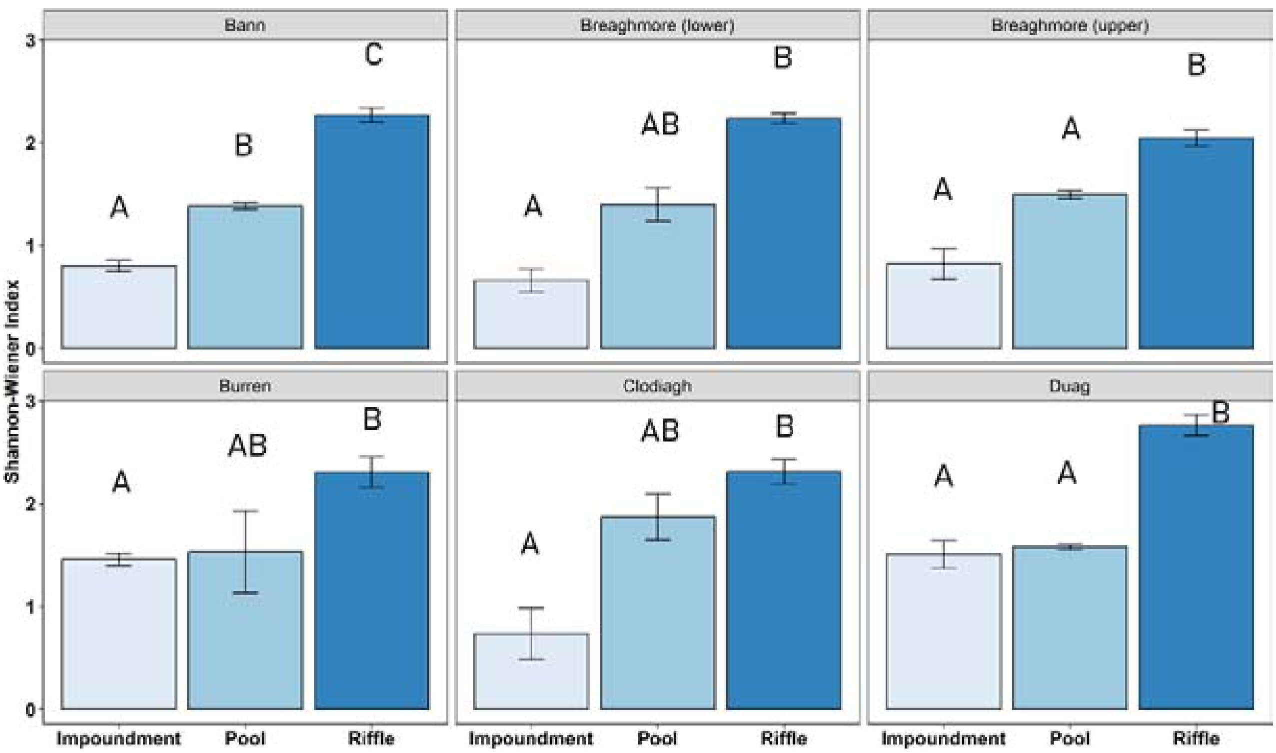

Figure 4.7. Barplots showing mean Shannon–Wiener Index (±SE) in each of the six sites where a significant difference was found between the values in riffles and impoundments. Different letters indicate significant differences at *p*(MC) < 0.01.

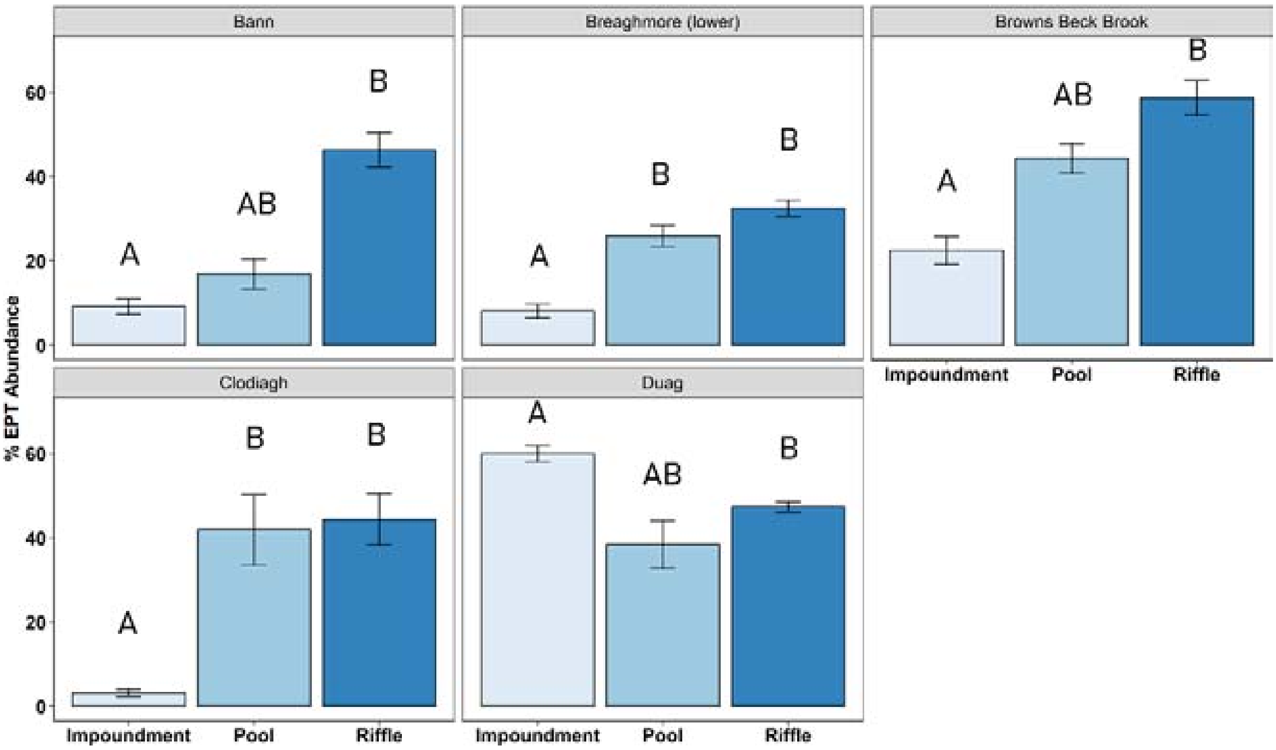

Figure 4.8. Barplots showing mean EPT abundance (%) (±SE) in each of the five sites where a significant difference was found between the values in riffles and impoundments. Different letters indicate significant differences at *p*(MC) < 0.01.

In contrast to the aforementioned metrics, EPT richness was affected only by habitat. The impounded habitats had relatively low EPT richness, while the EPT richness of natural pools was intermediate between that of the riffle and impoundment habitats (Figure 4.9).

In terms of macroinvertebrate trophic structure, passive filter feeders and grazers/scrapers were

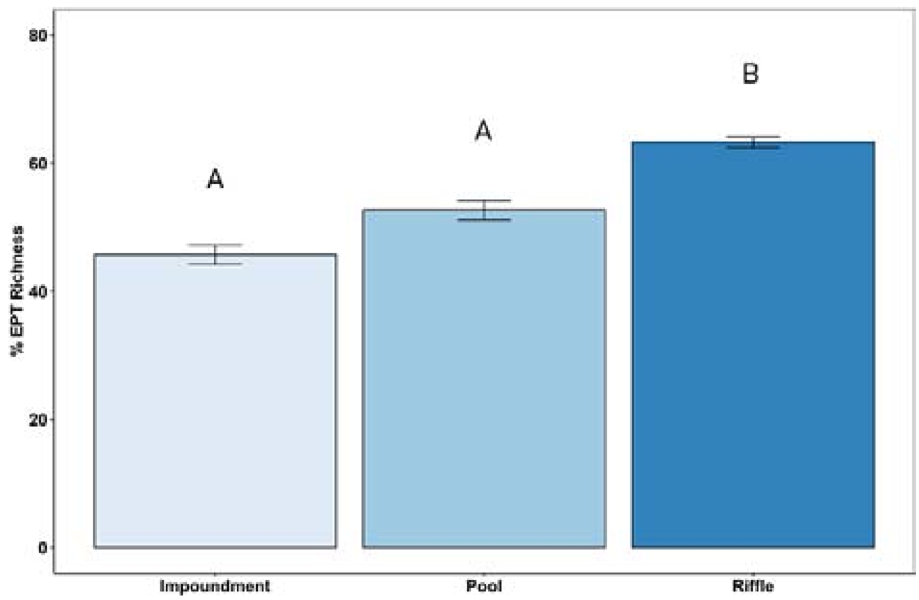

Figure 4.9. Barplot showing mean EPT richness (%) (±SE) in impoundment, pool and riffle habitats in all sites. Different letters indicate significant differences at *p*(MC) < 0.01.

more closely associated with riffle habitats, whereas gatherers/collectors, predators, active filter feeders and miners were more closely associated with the pool and impounded habitats. Furthermore, riffle habitats were characterised by species typical of coarser sediment (fine–medium gravel), and pools and impounded habitat were characterised by species typical of fine sediment (particulate organic matter and unconsolidated silt). The dominant effect detected related to habitat, particularly that of the impoundment.

Community structure, rather than composition, differed significantly between riffle and pool habitats in 3 out of 10 sites, and between riffle and impounded habitats in 7 out of 10 sites. No significant differences were found between pool and impounded habitats, showing that the impounded reaches are essentially elongated pool habitats. Figure 4.10 illustrates that the macroinvertebrate assemblage within the riffle habitat is clearly separated from that of the pool and impounded habitats. Several macroinvertebrate families belonging to EPT (Heptageniidae, Rhyacophilidae, Hydropsychidae, Glossosomatidae, Baetidae, Perlodidae) were closely associated with riffle habitats, as were Simuliidae and Hydraenidae. Members of the Dytiscidae, Limnephilidae and Oligochaeta were more closely associated with pool and impounded habitats in some samples.

Overall, the results indicate that shallow riffle/run habitat is important for maintaining biodiversity in the rivers studied here, particularly for EPT taxa. As a result, inundation of this habitat due to impoundment could be significant for the overall biodiversity of a river. Impacts on EPT could also have implications for salmonid feeding because of reduced EPT diversity and, in some sites, reduced abundances. Impoundments may therefore reduce potential salmonid production, particularly in heavily impounded or lowland rivers. However, the scale of the impact (in terms of loss of free-flowing habitat) may be variable depending on the river and the structure itself. Impoundments are typically larger in low-gradient rivers than in high-gradient rivers and the length of the impoundment is also dependent on the height of the barrier (Poff and Hart, 2002; Mbaka and Mwaniki, 2015), which has been shown to vary considerably in Ireland.

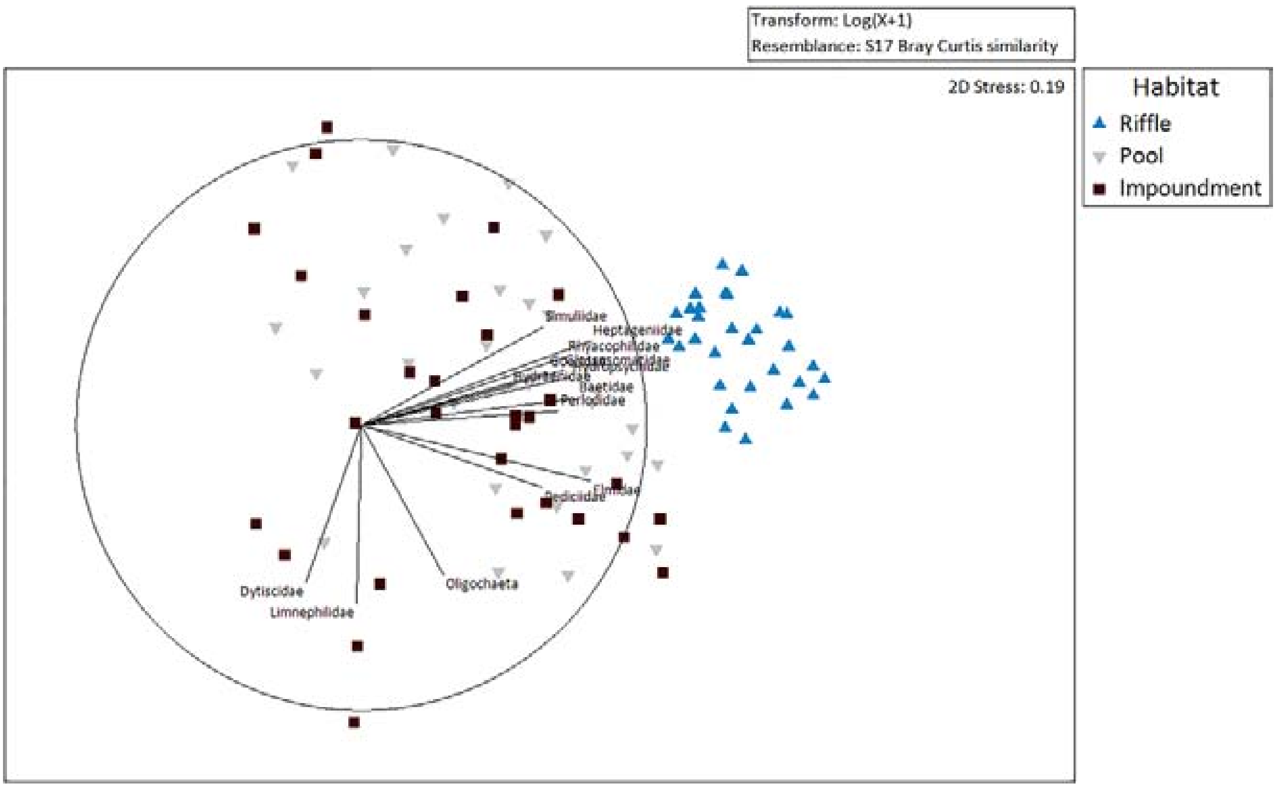

Figure 4.10. Non-metric multidimensional scaling (NMDS) plot showing macroinvertebrate community structure in all sites. The vector graph overlaid shows the macroinvertebrate families that correlate with the macroinvertebrate community associated with the different habitat types (Spearman correlation; results shown for families with vector length > 0.5).

4.3 Macrophytes

Macrophyte surveys were carried out at two sites (impounded and natural) in each of the four core study areas. This involved surveying a 50-m stretch at each site from downstream to upstream in a zigzag pattern on a single date in summer 2018. The number of taxa recorded ranged from 11 (the Dalligan site DAL-FUS and the two sites on Browns Beck Brook) to 16 in the impounded reach of the Dalligan (DAL-US). There was no indication that the impounded sites hosted higher species richness than the other sites, and there were no identifiable patterns in assemblage composition between the impounded and natural habitats. Emergent, predominantly marginal, plants have the highest weighting in factor 1, whereas mosses feature strongly in factor 2. The two most dissimilar sites were on the River Dalligan, most likely because of contrasting habitat conditions. The impounded reach had a predominantly sand and silt/mud substrate, providing good rooting conditions for macrophytes, whereas the natural sites were dominated by coarse substrates; thus, there was a predominance of moss species. Most of the species present at the other sites were typical of moderate flow or marginal habitats. Only one species, the alga *Melosira* sp., had a higher cover in the impounded reaches, presumably on account of the lower flow, which reduces the tendency for it to be washed out.

5 Testing of the Feasibility of Using eDNA to Assess the Ecological Impacts of Barriers

As part of the Reconnect project we assessed the feasibility of using eDNA (Box 5.1) to detect the presence of individual species above and below barriers by developing and deploying species-specific eDNA assays (section 5.1) and the broader biodiversity through using metabarcoding (section 5.2).

Water samples were collected from a range of locations, both upstream and downstream of potential barriers (Table 5.1). The downstream samples were collected some distance below the potential barriers to allow for downstream biodiversity to be represented in the downstream sample. Each sample consisted of 2 L of river water sampled in triplicate (total of three water samples per location). Each sample was filtered through 0.45-μm or 2.0-μm glass fibre filters. eDNA was extracted from the filters using chloroform and isoamyl alcohol-based methods (full details are provided in Atkinson *et al*., 2018b). qPCR taxon-specific assays for the detection of sea lamprey, freshwater pearl mussel, shad (allis and twaite), Atlantic salmon and white-clawed crayfish were deployed in this project. In addition, two bulk samples (organisms collected during kick sampling and which were subsequently mixed) were analysed from the same location as water samples to address biases in sampling method (bulk vs water). Furthermore, for metabarcoding, the complete Folmer region mitochondrial DNA (mtDNA) cytochrome c oxidase subunit I (COI) (https://www.boldsystems.org/index.php) was amplified and sequenced using a next-generation sequencer, MiSeq 300PE, capable of generating 25 million sequences or using a mini barcode for the COI region (BF1 and BR1 primers) sequenced on a HiSeq 3000, capable of generating up to 125 million 150PE sequences.

5.1 Taxon-specific eDNA

In the Reconnect project we designed and assessed novel eDNA qPCR assays for Atlantic salmon, white-clawed crayfish and shad (an assay capable of detecting both allis shad and twaite shad). A further two previously developed assays (for lamprey and pearl mussel) were deployed successfully on river water samples. Details of the methods applied are provided in Atkinson *et al*. (2018b, 2019).

In accordance with what was expected, when Atlantic salmon was present above barriers, the eDNA concentration was higher downstream, as the downstream samples will have also contained eDNA from above the barrier, leading to a cumulative effect (Table 5.1). Salmon was not detected above and below the barrier in the River Dalligan. Furthermore, concentrations of salmon eDNA above the ford on Browns Beck Brook were very low before the removal of the ford (while considered a detection, the concentration was too low to quantify), and increased significantly after the ford was removed. The novel

Box 5.1. What is eDNA?

eDNA is a collective term for DNA that is shed by living or dead organisms into the environment (e.g. blood, skin, mucus, gametes and faeces). It is therefore possible to extract the DNA from environmental samples such as air, soil and water, as was done during the Reconnect project. These samples can then be tested for the presence of a species-specific broader biodiversity. eDNA is now used for a range of scenarios including for identifying the presence of specific rare or invasive species and broader biodiversity. The non-invasive properties of eDNA sampling, compared with many other methods (e.g. netting, trapping or electrofishing), make it well suited for deployment in aquatic environments. There are two general methods that are used in eDNA studies: (i) taxon-specific assays using quantitative polymerase chain reaction (qPCR) and (ii) metabarcoding using next-generation sequencing. A single water sample can be interrogated using either of these methods.

Table 5.1. Summary of taxon qPCR eDNA assay results from deployment in the Reconnect project for Atlantic salmon (salmon), white-clawed crayfish (crayfish), allis shad and twaite shad (shad), sea lamprey (lamprey) and freshwater pearl mussel (pearl mussel)

			Target species eDNA concentration (ng/L)				
Year	River	Location	Salmon	Crayfish	Shad	Lamprey	Pearl mussel
2017	Burren	BUR-DS	0.028	0.020	–	No hit	Hit low[a]
		BUR-US	0.017	0.027	–	No hit	Hit low[a]
2017	Delour	DEL-DS	0.110	No hit	–	No hit	No hit
		DEL-US	0.078	No hit	–	No hit	No hit
2017	Dinin Castlecomer	DCC-DS	0.073	0.002	–	No hit	No hit
		DCC-US	0.004	No hit	–	No hit	No hit
2017	Duag	DUG-DS	0.170	0.157	–	No hit	No hit
		DUG-US	0.057	0.027	–	No hit	No hit
2017	Dalligan	DAL-DS	No hit	No hit	–	No hit	No hit
		DAL-US	No hit	No hit	–	No hit	No hit
2017	Multeen	MUL-DS2	0.354	0.060	–	No hit	No hit
		MUL-US	0.435	0.034	–	No hit	Hit low[a]
2017	Dinin Crettyyard	DCY-DS	0.033	0.006	–	No hit	No hit
		DCY-US	0.000	0.011	–	No hit	No hit
2018	Browns Beck Brook	BBB-US	Hit low[a]	No hit	–	No hit	No hit
		BBB-DS	0.371	No hit	–	No hit	No hit
		BBB-FUS2	Hit low[a]	No hit	–	No hit	No hit
2020	Browns Beck Brook	BBB-US	0.357	No hit	–	–	–
		BBB-DS	0.639	No hit	–	–	–
		BBB-FU2	0.393	No hit	–	–	–
2016	Nore Inistioge	NOREI	–	–	Hit low[a]	–	–
2016	Nore Thomastown	NORET	–	–	Hit low[a]	–	–
2016	Suir Kilsheelan	SUIRK	–	–	No hit	–	–
2016	Suir Carrick on Suir	SUIRC	–	–	Hit low[a]	–	–
2018	Barrow St Mullins below weir	BARM-DS	–	–	0.709	3.135	–
2018	Barrow St Mullins	NARM-STM	–	–	2.827	2.421	–
2018	Barrow St Mullins above weir	BARM-US	–	–	No hit	No hit	–

[a]Hit low = outside dynamic range (i.e. while a detection the concentration is too low to be quantified).

qPCR assay for white-clawed crayfish detected the presence of the species in accordance with previous reported distribution based on visual observations. The assay for the detection of shad was used on samples from the River Barrow both above and below the weir at St Mullins, with samples below the weir showing presence of the target species while, as projected, there had been no positive detection above the weir. Similarly, sea lamprey was detected below the weir at St Mullins but not above the weir. A number of samples were also checked for the presence of freshwater pearl mussel, with the only positive detections in the River Burren (above and below the barrier) and upstream of the barrier on the River Multeen. In summary, species-specific eDNA qPCR assays were proven to be highly effective in assessing the distribution of target species and demonstrated fish passage after the barrier had been removed.

5.2 Field Deployment of Metabarcoding

Metabarcoding involves taking advantage of conserved regions in the mitochondrial genome and generating universal primers that are capable of PCR amplification of a wide range of taxa. These amplifications are then sequenced using next-generation sequencing platforms (MiSeq, HiSeq, etc.) that are capable of generating millions of sequences per amplified sample. The sequenced amplicons are then compared with existing sequences available in public repositories (Barcode of Life and GenBank) through bioinformatic pipelines to assess what taxa are present in a sample. In the Reconnect project, eDNA from water samples was used to amplify a small section of the mtDNA COI region. It should be noted that, similar to qPCR eDNA assays, metabarcoding is not likely to detect all taxa present, as taxa occurring at very low densities are likely to be outcompeted in the PCR reaction and sequencing procedure. However, by increasing the number of sequences generated, the detection level will also improve. Furthermore, while the term “universal” primers is often used, there are no primers that will detect all biodiversity because of differences in the priming region of the mtDNA among different taxa. Hence, metabarcoding can detect only what is amplified, and not all taxa will be amplified with a single primer pair. To further improve on the detection range (biodiversity) of metabarcoding, a battery of primers needs to be used. Therefore, studies using a particular gene region (primers) will be comparable only with other studies that use the same gene region for specific taxa. The Reconnect project deployed two metabarcoding approaches focusing on the COI gene region, using next-generation sequencing approaches.

The results from the analysis of the water and bulk samples indicated lower biodiversity (operational taxonomic units, OTUs) in the bulk samples than in water samples, demonstrating that water samples will give a broader diversity (Figure 5.1). This is probably because the bulk samples comprise few, but large, individual organisms and because the water samples reflect not only biodiversity in the local area but also eDNA transported from upstream sources to the local area.

The MiSeq approach was able to detect a total of 1024 unique OTUs across samples, demonstrating that measurement of eDNA is a very powerful method of assessing biodiversity. The HiSeq approach suffered

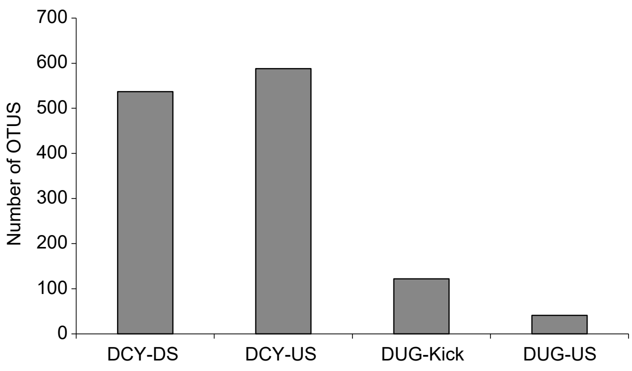

Figure 5.1. Number of OTUs detected in samples subjected to MiSeq sequencing from Dinin (Crettyyard) downstream of the bridge apron (DCY-DS) and upstream of the bridge apron (DCY-US) and Duag kick samples (DUG-Kick) from upstream of the weir (DUG-US).

from bad sequence quality, due to non-optimal PCR conditions, poor DNA extractions or lower than expected sequence performance. While the sequence yield was high (100 million sequences), the quality of the initial sequence was poor and the conclusions that could be drawn from the HiSeq approach were severely limited. However, we were unable to find a taxonomic match for *c.*80–90% of the sequences obtained with both approaches, indicating that our sequence databases for Irish freshwater fauna are poor and need to be populated with sequence data from Irish aquatic fauna.

The specific question about the impact of barriers on invertebrate freshwater fauna is, however, not likely to be resolved using metabarcoding, as the vast majority of macroinvertebrates in running water have a winged life stage that enables dispersal across barriers; hence, differences in the composition of macroinvertebrate fauna are more likely to represent different habitat types than the presence or absence of barriers.

6 Hydromorphology and Sediment Connectivity

The research described here assessed the hydromorphological impact of barrier emplacement and removal. Detailed investigations of baseline hydromorphological condition, including bed and suspended sediment connectivity, were carried out at three of the core sites, with the impacts of the ford removal limited to the Browns Beck Brook. An additional bedload transport study, to capture real-time movement of clasts over a barrier structure, was carried out on the River Boro, Co. Wexford.

6.1 Research Design

Study reaches were defined directly upstream and downstream of the barrier structure to assess the impact of barrier emplacement/removal, and a reference reach that captured the representative channel form and flow types was also defined (Figure 6.1). The monitoring reach lengths varied on account of accessibility considerations and the influence of confounding factors, but they were sufficient to capture hydromorphic heterogeneity. Flow gauging was carried out at all sites using continuous water level monitoring and integrated velocity measurements employing a Valeport electromagnetic flow meter (Model 801) for lower flows, combined with theoretical weir equations and acoustic Doppler current profile (ADCP) measurements as appropriate. For all sites, stage–discharge relationships were refined and extended using a synthetic rating curve developed in a one-dimensional hydraulic modelling package, the Hydrologic Engineering Center's River Analysis System (HEC-RAS) (US Army Corps of Engineers Hydrologic Engineering Center River Analysis System, version 5.0.5; Brunner, 2016).

6.2 Hydromorphological and Physical Habitat Assessment

River hydromorphology assessment technique (RHAT) surveys (Murphy and Toland, 2014) were carried out in 2017 on 500-m reaches immediately upstream and downstream of the barrier structures at each core site. The results indicated "good" hydromorphological status at the Dalligan site and downstream at the Duag, "moderate" status upstream at the Duag and "poor" status at the Browns Beck Brook site. Although RHAT surveys are widely employed in Ireland to assess hydromorphological condition, they are not specifically designed to isolate the impact of barrier emplacement. RHAT results were largely influenced by factors other than the presence of the barriers.

To complement the RHAT assessment, the project team undertook higher-resolution hydromorphological surveys using the Modular River Physical (MoRPh) survey tool. This tool captures a broader range of attributes and is scaled for channel width, making it more sensitive to spatial scales corresponding to channel and riparian habitats. A total of 14 indices are determined using the MoRPh survey approach (Gurnell *et al.*, 2020a). The results of the baseline surveys conducted in the summer of 2017 on the Dalligan and Duag rivers are shown for indices 1 (number of flow types), 8 (channel physical habitat complexity) and 9 (number of aquatic vegetation

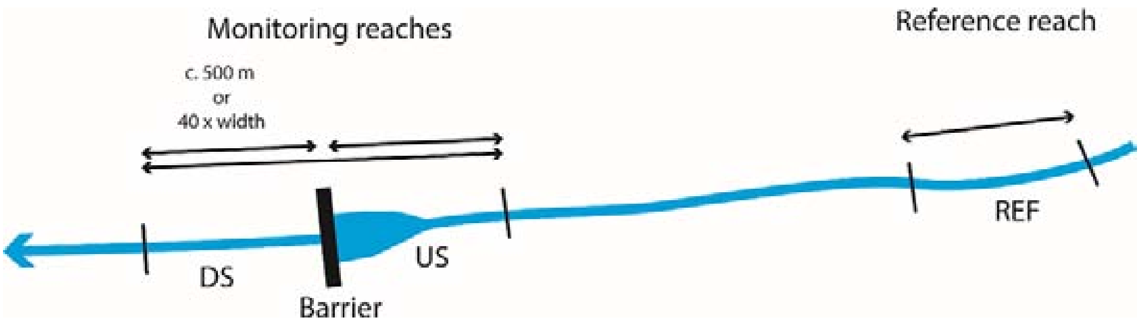

Figure 6.1. The experimental research design employed in work package 6 to assess hydromorphological impacts. DS, downstream; US, upstream.

morphotypes) in Figure 6.2. Index 1 shows that the barrier had a greater effect on flows on the lower gradient River Duag than on the River Dalligan. The highest flow diversity on the Duag was recorded immediately downstream of the barrier, where the channel bifurcates around a vegetated island. The marginal increase in flow complexity resulting from the tributary input (opposite a church cemetery) in the impounded zone is also recorded by the survey. In terms of physical habitat complexity (index 8), both rivers show marginally lower complexity upstream of the structures, but there is no systematic pattern in relation to the barriers. At the Dalligan site, the higher complexity observed downstream was largely due to a high proportion of large woody debris in the channel, while at the Duag the effects of gravel shoaling and the aforementioned channel bifurcation were important. At both sites, the number of vegetation morphotypes (index 9) was generally higher immediately upstream of the barrier impoundment and lower in the downstream reach. These results may reflect the sediment disconnectivity that are reported in section 6.3. However, at the Dalligan site the absence of aquatic macrophytes may also be due to the low levels of light penetration through the overhanging riparian canopy. Thus, while the MoRPh tool provided a more precise assessment of the hydromorphological impacts of the barrier emplacement (using an audit survey approach) the results also revealed the complex pressure–response hydromorphic dynamics at each site.

6.3 Sediment Dynamics and Connectivity

6.3.1 Bed sediment

At the Duag and Dalligan sites, bed sediment transport dynamics were investigated with radio-frequency identification (RFID) technology in a sediment tracer

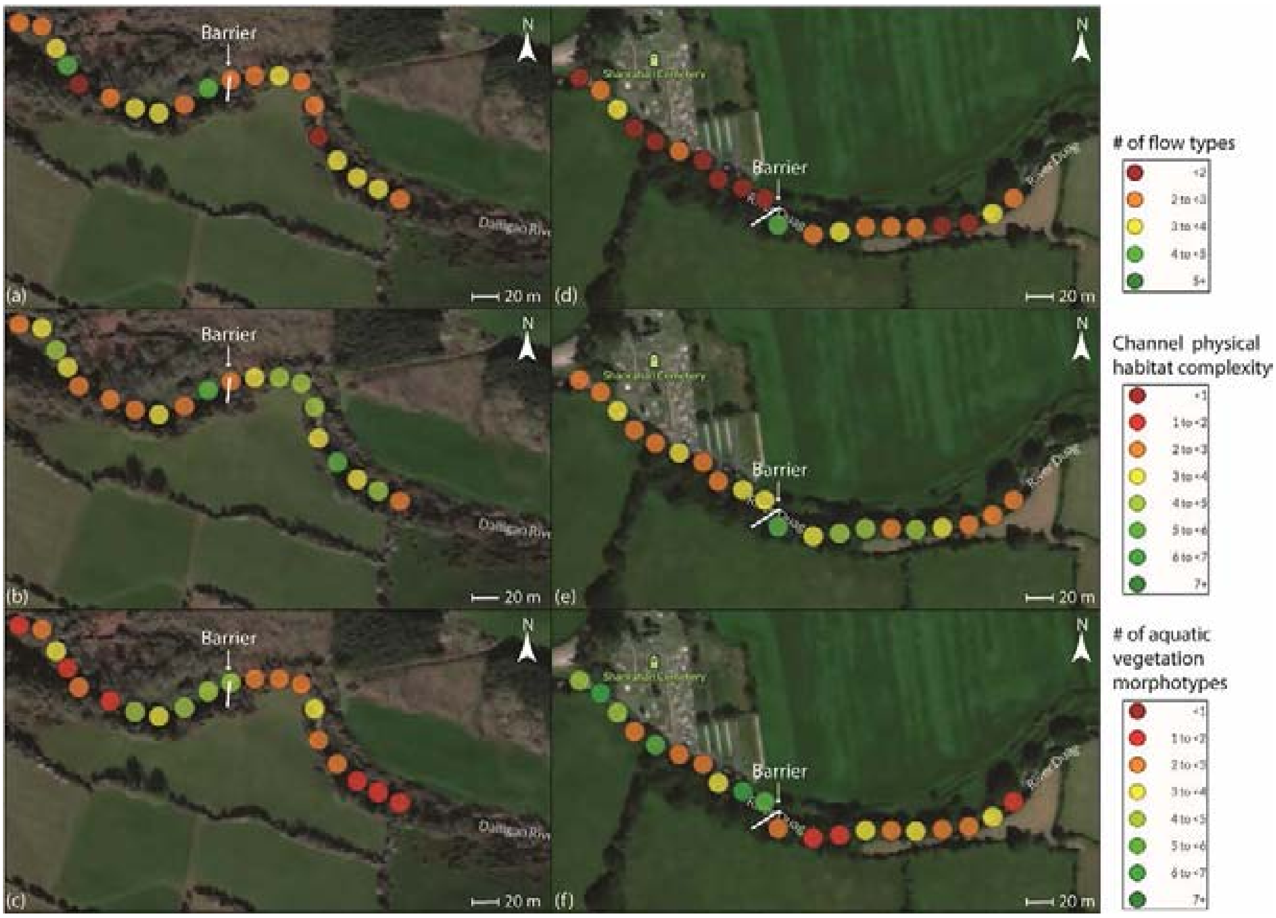

Figure 6.2. MoRPh survey results for the 2017 surveys on the Dalligan (a–c) and Duag (d–f) for index 1 (number of flow types; a and d), index 8 (channel physical habitat complexity; b and e) and index 9 (number of aquatic vegetation morphotypes; c and f). The length of river surveyed using MoRPh was 20 m at each site (based on stream width).

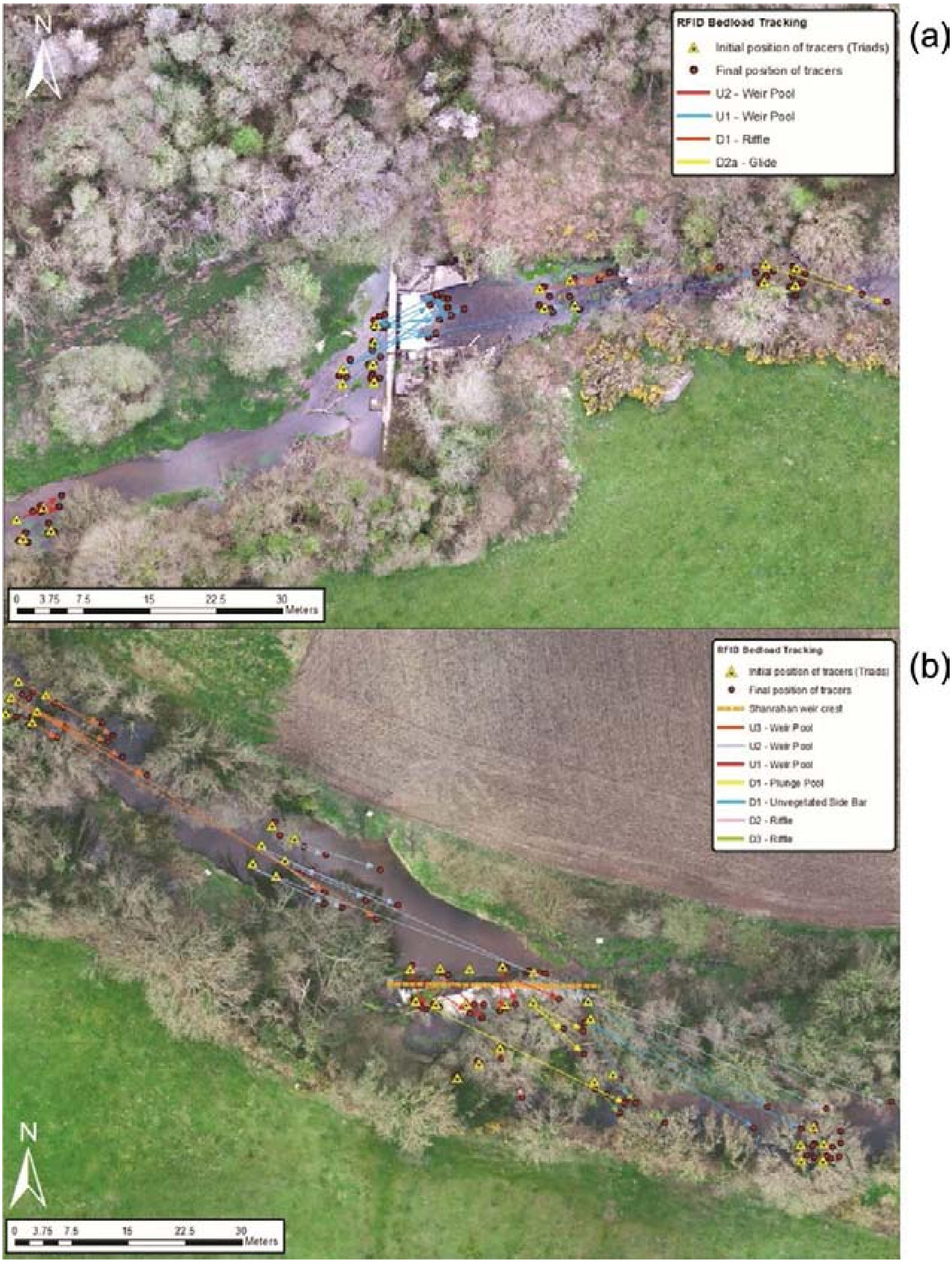

Figure 6.3. Spatial distribution of tracer movement over the structures on the (a) Dalligan and (b) Duag catchments. Initial triad (set of three clasts) seeding positions (yellow triangles) and final recovery positions (red circles) are indicated. Travel distances were calculated along the channel centre line for tracers that moved >1 m, while arrows, for illustration purposes only, indicate straight-line travel of tracers that moved >2 m. Reproduced from Casserly *et al*. (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

study, using particles (gravels and cobbles) retrieved from the reference, upstream and downstream reaches (see Casserly *et al*., 2020). Eleven tracer particles (39–110 mm) passed over the Dalligan Weir and eight clasts (42–142 mm) passed over the weir on the River Duag (Figure 6.3). These particles constituted 29% and 24%, respectively, of all the tracers seeded within the first 50 m upstream of the two structures. Particles that were larger than 90% of the measured bed material (i.e. $>D_{90}$) were carried over the weirs at both sites.

Sediment connectivity was assessed by comparing fractional transport rates in each reach, using the mean travel distance of RFID-tagged particles and the time duration of competent flows (Haschenburger and Church, 1998; Vázquez-Tarrío and Menéndez-Duarte, 2014). Details of the analytical workflow are given in Casserly *et al*. (2020). Transport rates were estimated for size fractions ranging from the D_{16} to the maximum tracer mobilised; these are presented in Figure 6.4. At both sites there was a marked difference in the bed sediment transport rates between reaches for all but the coarsest size fractions, with patterns indicative of supply limited conditions downstream. These findings were consistent with the coarser reach-scale particle size distributions observed downstream of the weir structures.

A follow-up RFID study to capture real-time movement of RFID-tagged particles over a weir was undertaken using the novel design and installation of a stationary RFID antenna at the crest of a 1.3 m high × 5.4 m wide weir on the River Boro, Co. Wexford (Figure 6.5) (Casserly *et al*., 2021a). Two antenna set-ups were employed. The first adopted a “pass-under”

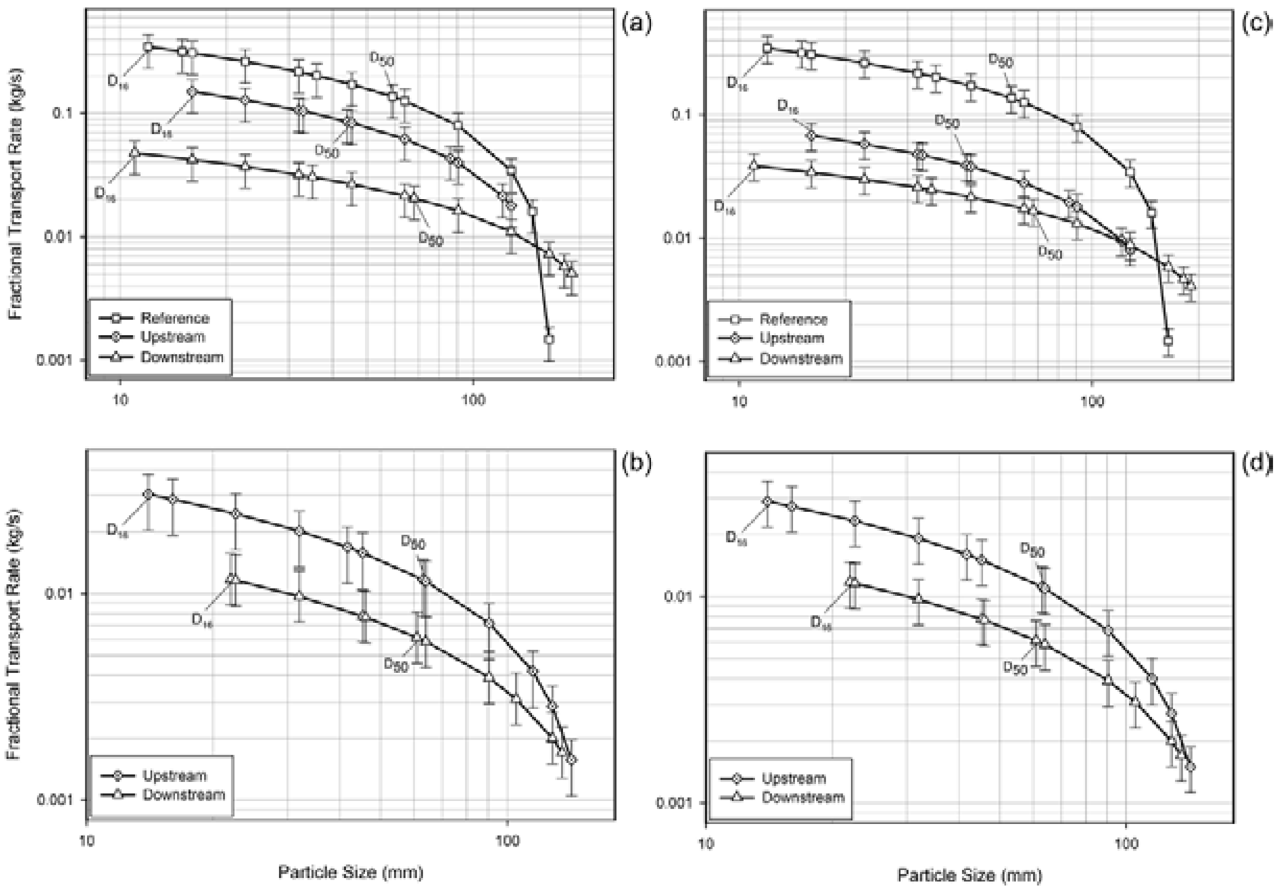

Figure 6.4. Fractional bedload transport rates for each monitoring reach at (a) the River Dalligan and (b) the River Duag taking account of the inter-reach variability in critical discharge Q_c, and at (c) the River Dalligan and (d) the River Duag when a common Q_c is assumed for each river. Error bars represent the maximum increase and decrease in transport rates resulting from a sensitivity analysis (±25%) of computational variables. Reproduced from Casserly *et al*., 2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

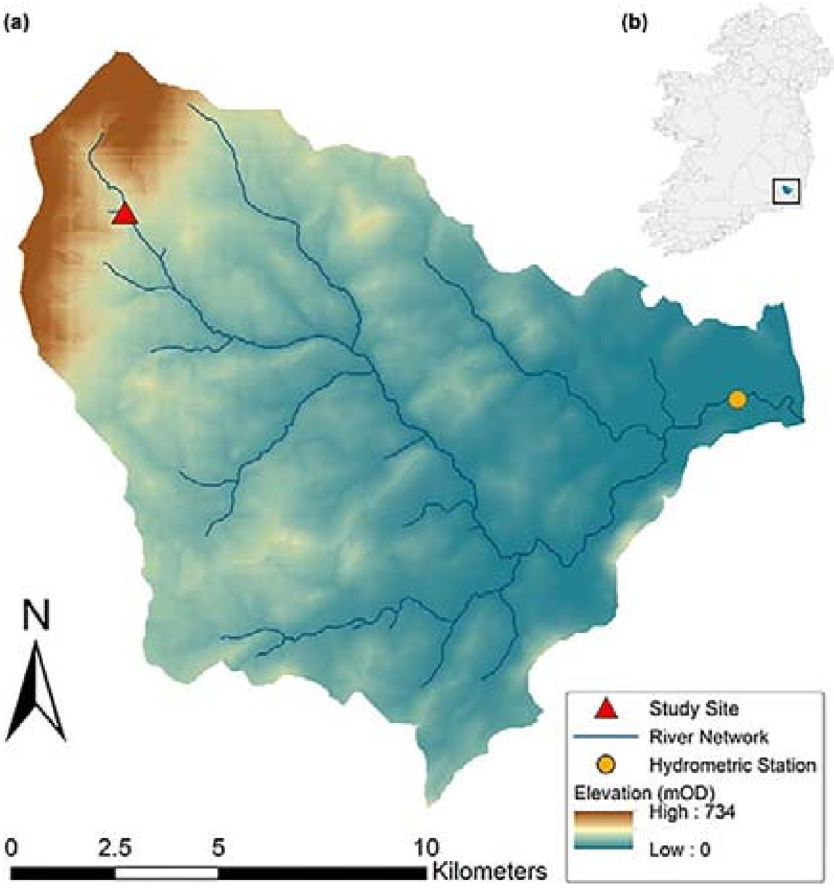

Figure 6.5. Location of (a) the sub-basin containing the study site and (b) the Boro sub-catchment within the island of Ireland. The red triangle indicates the location of the weir.

configuration, where the antenna was secured to a wooden mount suspended 0.5 m above the weir crest (Figure 6.6). Following storm damage to this set-up in December 2019, the antenna was reinstalled using a "pass-over" configuration, with the antenna being secured to the concrete ramp on the downstream side of the weir (not shown). The impounded area was seeded with 105 RFID-tagged tracers (22–115 mm intermediate axis diameter), approximately corresponding to the upstream reach D_{30}–D_{80} size fractions. Sediment baskets (22 × 22 mm) were installed flush to the channel bed downstream of the structure to quantify event-scale bed sediment load.

Of the 105 tracers, 10 were detected passing over the structure and a further 16 that were not detected were recovered downstream. In this study, bedload material as large as the upstream D_{70} passed downstream. Sixty tracers were also confirmed to have remained in the impoundment, 30 of which had become buried (29% of total seeded tracers), while 19 tracers were absent from the impoundment but not recovered downstream. Thorough searches of the impoundment indicated that as many as 43% of the tracers moved over the weir, indicating that tracers crossed after the antenna was damaged or were missed as a result of particle velocity or signal collision.

The "First Transport" model predicted a Q_{ci} (critical discharge of particle of size *i*) of 5.3 m^3/s for the largest (diameter 90 mm) particle that was missed by the antenna (Figure 6.7), which corroborated the presupposition that this clast crossed the antenna after it was damaged, but before the recorded event peak discharge of 5.7 m^3/s. Total bedload from the sediment baskets, which ranged from 16.2 kg to 76.7 kg, showed a very strong positive relationship to peak discharge Q_p ($r = 1$, $p < 0.01$), but only a moderate and not statistically significant relationship to the time duration of flows above critical discharge (T_{Qc}) ($r = 0.8$, $p > 0.05$).

6.3.2 *Suspended sediment*

Suspended sediment transport data were obtained using the turbidity surrogate approach (Lawler, 2016).

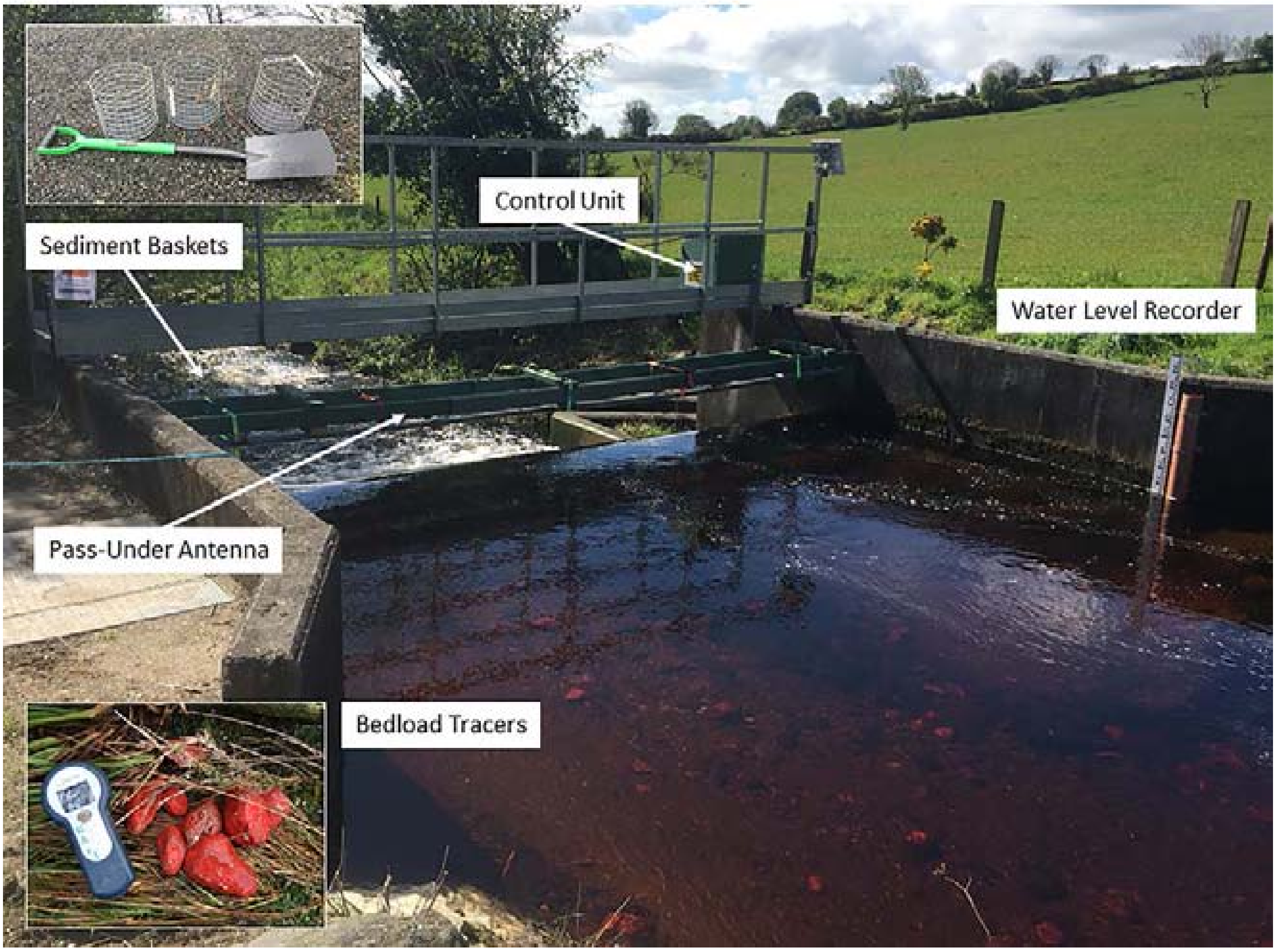

Figure 6.6. Study site showing the locations of the pass-under stationary antenna, water level recorder, control unit and bedload tracers. Reproduced from Casserly *et al*. (2021a); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Suspended sediment connectivity effects were investigated through the comparison of suspended sediment concentration (SSC) patterns and total suspended sediment load for inputs (upstream station) and outputs (downstream station) for 31 high-flow events (Duag, $n=15$; Dalligan, $n=16$). A selection of storm hydrographs showing the patterns of suspended sediment inputs and outputs at the Dalligan and Duag sites is shown in Figure 6.8. Results revealed a predominant net export of sediment from both sites, implying a local source of sediment between the two monitoring stations during the storm events.

With no tributary inputs or significant evidence of bank erosion between the monitoring stations at either site, it is likely that the weir impoundment (which is typically viewed as a depositional zone) becomes an additional source of fine sediment during the passage of a storm event, as illustrated schematically in Figure 6.9.

6.3.3 Summary

RFID tracers showed that the full particle size range can pass over barrier structures. However, a comparison of particle size distributions, mean travel distances and fractional bedload transport rates revealed that, downstream, some transport may remain supply limited. These results imply a new state of dynamic disconnectivity, characterised by changes to the frequency and magnitude of bed sediment-transporting events, while maintaining the long-term sediment conveyor system (Casserly *et al*., 2020). Although effects are likely to be relatively localised, given that a channel’s prevailing flow and sediment regime is a determinant of physical habitat and benthic community structure, a reduction in the temporal frequency of sediment transport may prove to be ecologically significant, at least until the sediment delivery system recovers downstream.

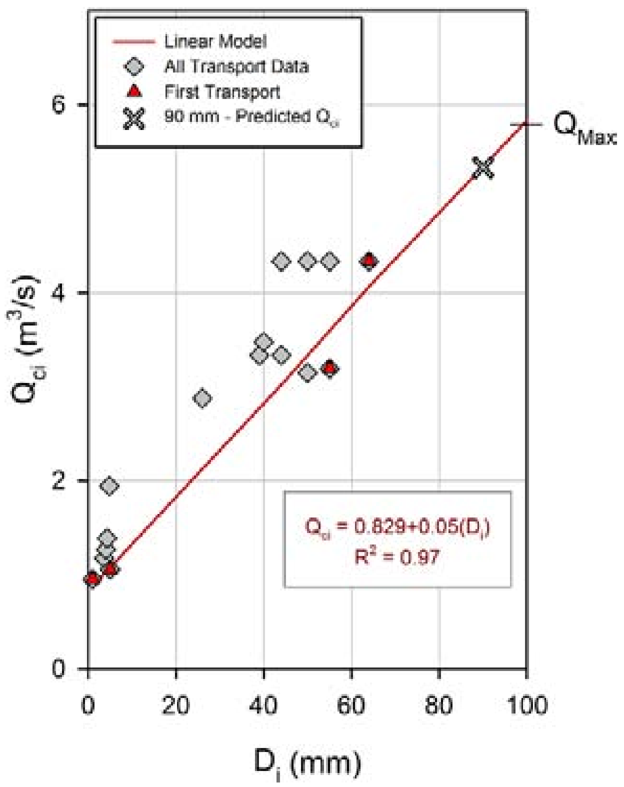

Figure 6.7. Fitted relationship between particle size (D_i) and critical discharge (Q_{ci}) for the observed movement of bedload over the weir with increasing particle size. The predicted Q_{ci} for the largest tracer found downstream (D_i = 90 mm) that was not detected by the antenna or used in the fitted relationships is included. Reproduced from Casserly *et al.* (2021a); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

6.4 Pre- and Post-barrier Removal Morphological Adjustment

Lateral and vertical morphological adjustment at Browns Beck Brook were assessed through repeat cross-sectional and longitudinal surveys using a real-time kinematic global positioning system (RTK GPS). Additional planform information was acquired through unmanned aerial vehicle (UAV) surveys using a DJI Phantom IV drone. Georeferencing using ground control points (GCPs) was undertaken using PIX4D software, with root-mean-squared errors for GCPs ranging from 0.03 m to 0.11 m.

6.4.1 Planform adjustments at Browns Beck Brook site

Figure 6.10 shows the pattern of bank erosion at the Browns Beck Brook site. Total and time-averaged annual rates of erosion (m^2/year) are given in Table 6.1. No measurable lateral erosion was detected in BBB-REF during the monitoring period. Prior to removal, small-scale erosion (*c.*1 m^2) was mainly confined to a fence line between the upstream monitoring station and cross-section U5 (Figure 6.10Ai). Following the removal of the ford structure, maximum erosion was observed in BBB-US, especially between cross-sections U4 and U2 (Figure 6.10A), including evidence of slab bank failure (Figure 6.10Aii). Active channel widening along both banks was also recorded downstream of U2 (Figure 6.10iii), although much of this change will have resulted from artificial re-sectioning of the channel during the installation of the culvert. Downstream of the structure (BBB-DS), natural lateral channel change was not observed, aside from localised erosion around large boulders that were partly exposed on the left bank below cross-sections D4 and D5 (Figure 6.10B and C). For both reaches, the highest total area of erosion was recorded between 2018 and 2020, but lateral erosion rates (per annum) were higher during the final monitoring period (August 2020 to February 2021) in BBB-US and BBB-DS, which corresponded to the autumn/winter storm season only.

6.4.2 Cross-sectional and longitudinal adjustments at Browns Beck Brook site

In BBB-REF (CR3 to CR1), minor incision was recorded in CR3 and CR1 before and after removal of the ford structure, while there was negligible net adjustment in CR2. Cross-section profiles at CR1 and CR3 revealed minor deposition across the channel of a similar magnitude, suggesting that observed adjustments reflect natural bed reorganisation. In both BBB-US (U5 to U1) and BBB-DS (D1 to D7), relatively little change was detected before removal, and no clear pattern beyond small-scale bed reorganisation was observed. Following the installation of the culvert, cross-sectional geometry adjustments were detected in both monitoring reaches, especially in BBB-US, where systematic vertical (and lateral) changes were evident. Bed lowering was highest in U1 and U2 in 2019 and was recorded as far upstream as U4. In 2021, incision had continued at a lower magnitude in U2 to U3, but was detected for the first time in U5, where there was a *c.*30% lowering of the channel bed. Lateral erosion that occurred in BBB-US (and which was reported in section 6.4.1) coincided only with the

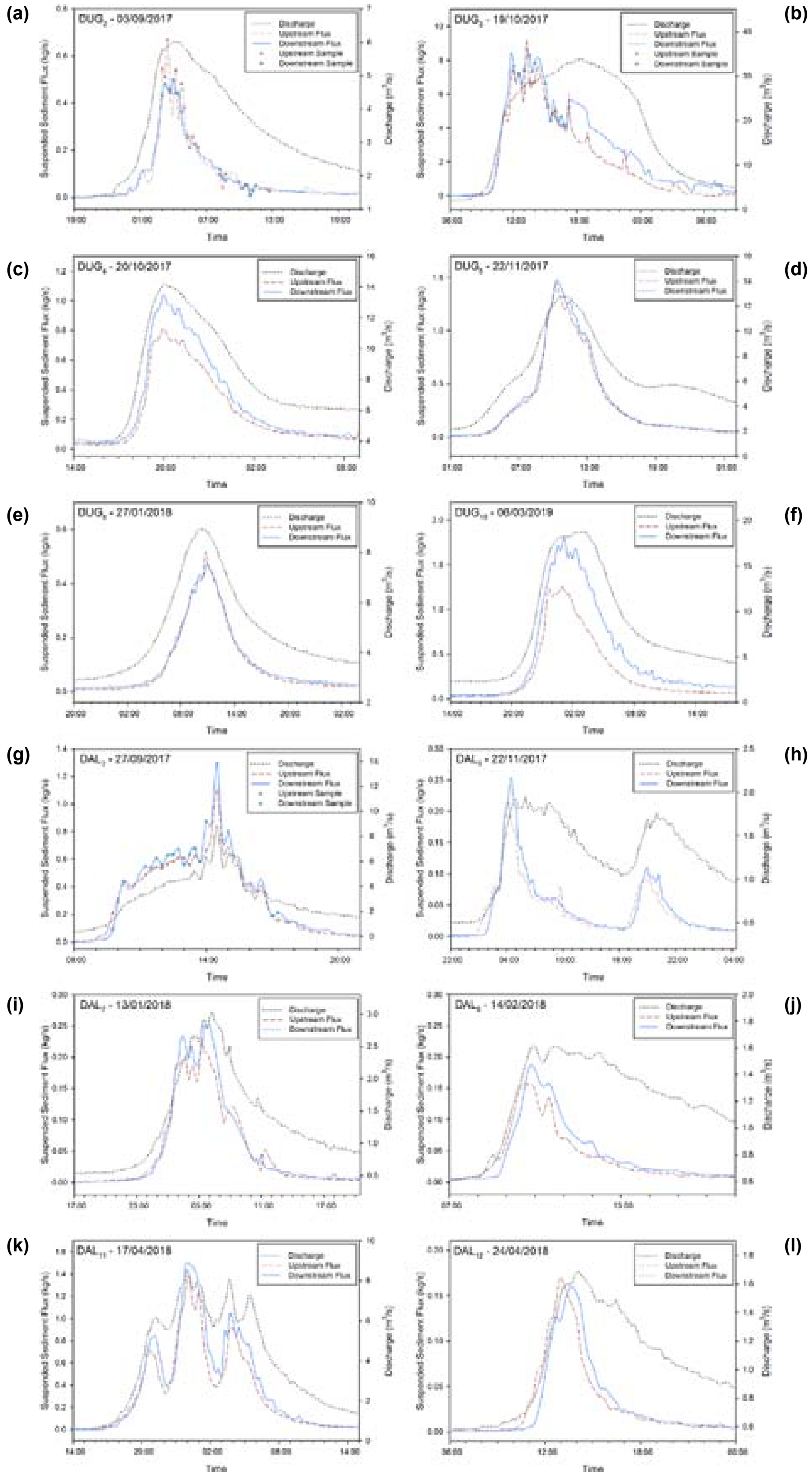

Figure 6.8. Plots showing examples of event-scale suspended sediment flux (SSF) upstream and downstream at the (a–f) River Duag and (g–l) River Dalligan.

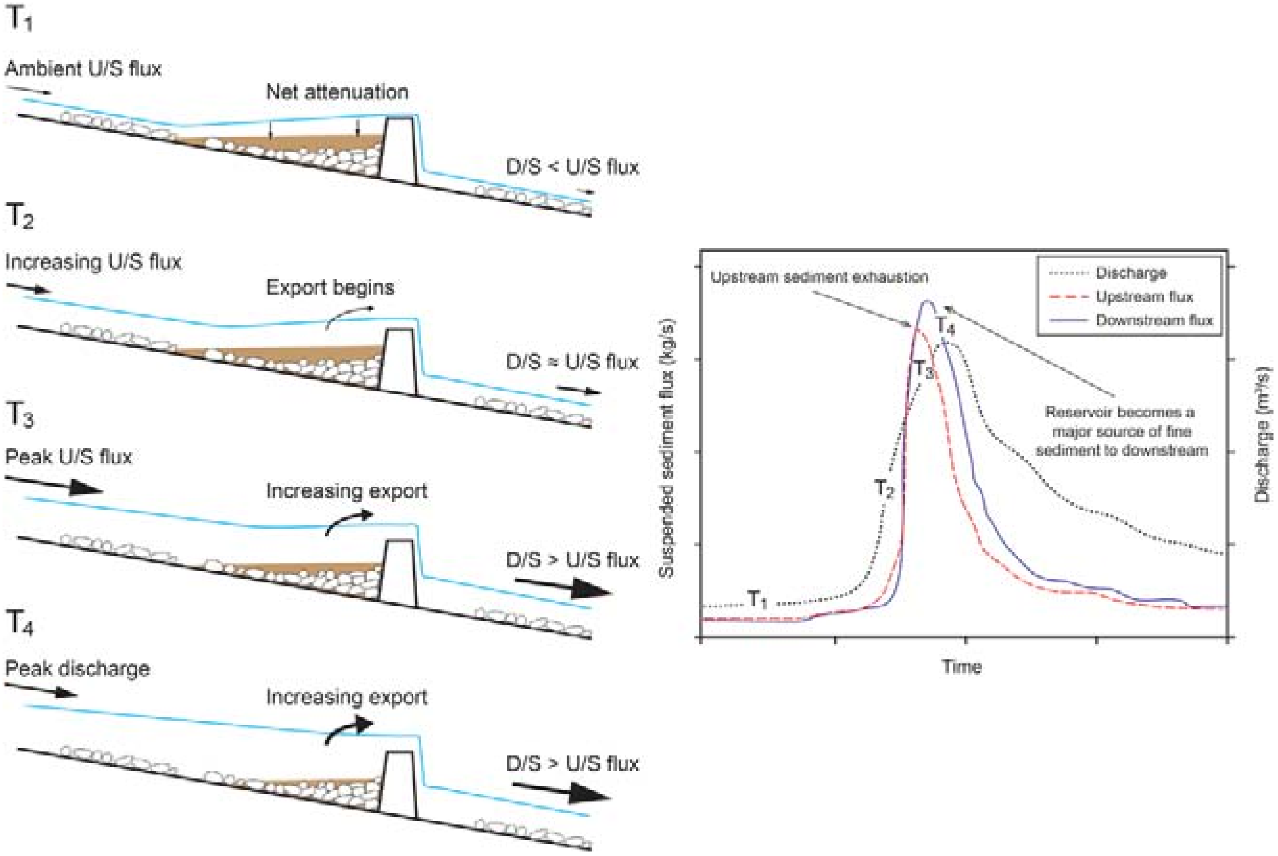

Figure 6.9. Schematic diagram showing the proposed hydrosedimentary dynamics for fine sediment transport during the passage of a storm. Inset figure and corresponding timestamps illustrate the increase in suspended sediment output (blue) below the weir after sediment exhaustion has occurred upstream (red). Reproduced from Casserly *et al.* (2021b); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

locations of U1 to U3. In BBB-DS the magnitude of adjustments was lower and the patterns were more variable. Bed level rise and lateral changes at D1 were largely attributed to artificial channel re-sectioning, but aggradation was recorded as far downstream as D5 in 2019, which reflects the channel response to the barrier removal. Adjustments in 2021 showed no clear spatial pattern between cross-sections.

Longitudinal profiles in Figure 6.11 show that post-removal downcutting terminated upstream of U5 at a large riffle, which remained at a stable bed elevation throughout the study period. Downstream of the former ford structure, the initial post-removal aggradation is evident in the long profile for much of the channel above D5, together with localised bed scour below D4 and above D5, which corresponds to the erosion around boulders reported in section 6.4.1. By February 2021, the average channel bed gradient in BBB-US corresponded closely to that of BBB-REF, which showed very little change throughout the project. While some complexity had returned to the profile, there continued to be less variability in bed elevation than in the non-channelised reach BBB-REF.

Morphological adjustments following barrier removal were accompanied by some changes in bed sediment characteristics, most notably in BBB-US, where the reach-averaged D_{50} increased from 22 mm to 42 mm. Repeat pebble count surveys for selected reaches in BBB-US and BBB-DS beyond the direct impacts of the barrier also showed active bed sediment reorganisation before barrier removal.

6.4.3 Pre- and post-removal hydromorphological assessment

The results of the pre- (September 2017) and post-removal (October 2020) hydromorphic assessment using the MoRPh survey tool are shown in Figure 6.12

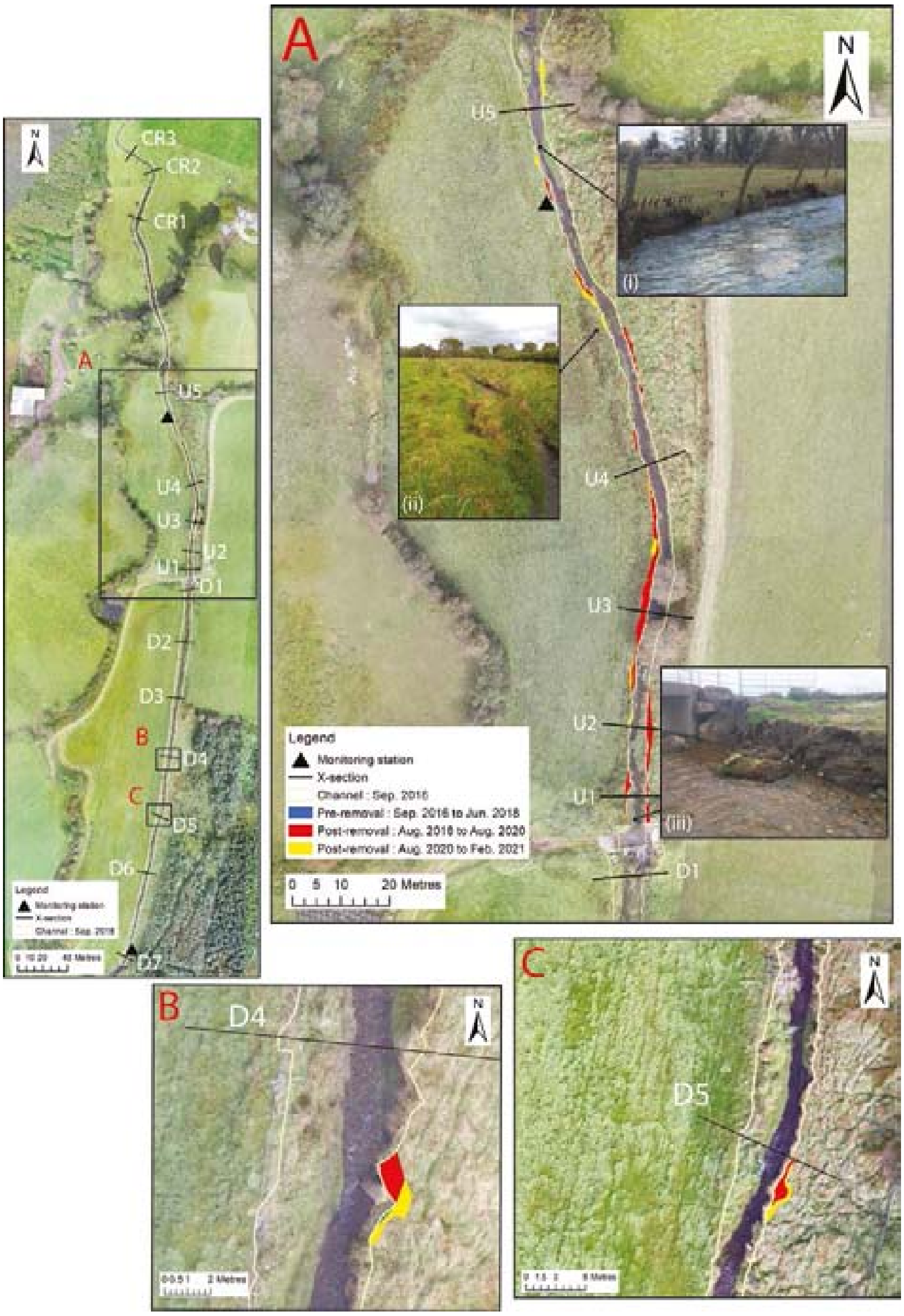

Figure 6.10. Planform adjustments at Browns Beck Brook between September 2016 and February 2021. The locations of panels A, B and C are shown in panel the site map (top left). Inset photos in panel A correspond to (i) linear erosion along a fence line above the upstream monitoring station in February 2018; (ii) slab failure in BBB-US in September 2020; and (iii) failure of cohesive banks immediately upstream of the new structure in September 2019.

Table 6.1. Measured planform erosion at Browns Beck Brook between 2016 and 2021

Period	BBB-REF total (m²)	BBB-US total (m²)	BBB-US rate (m²/year)	BBB-DS total (m²)	BBB-DS rate (m²/year)
2016–2018	–	1	–	< 1	–
2018–2020	–	90	43.2	7	3.4
2020–2021	–	21	50.4	4	9.6

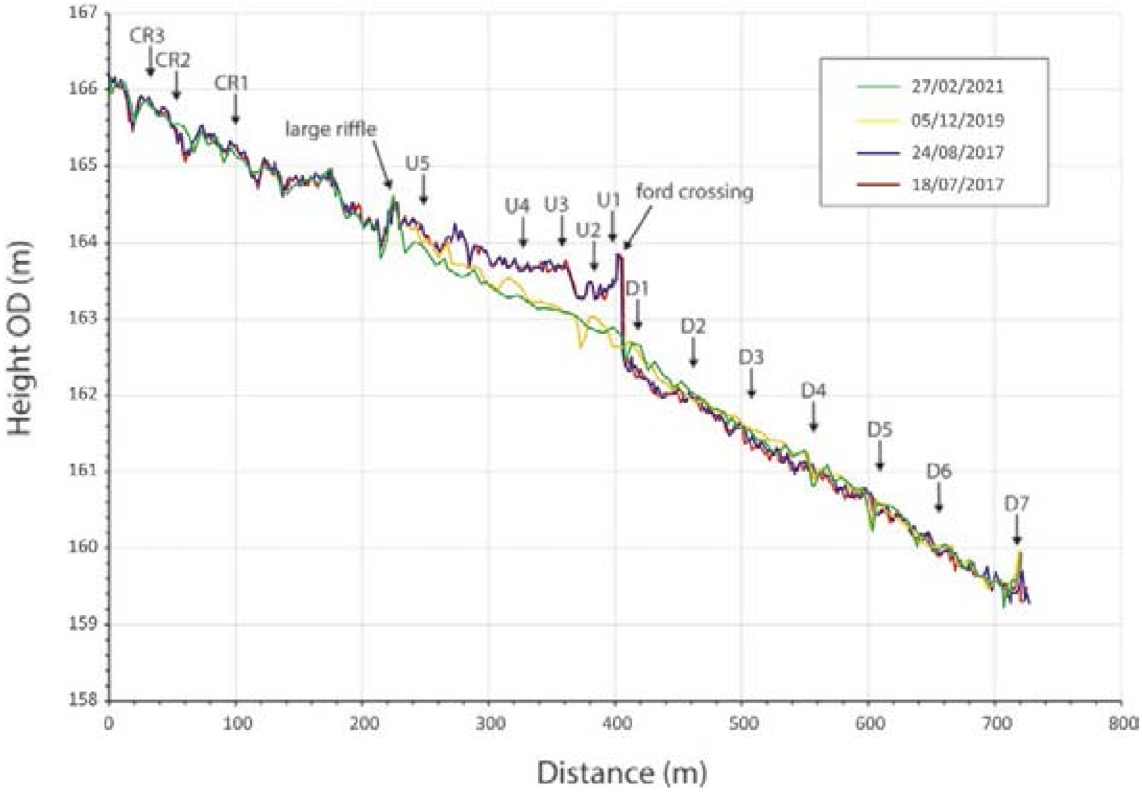

Figure 6.11. Longitudinal profiles at the Browns Beck Brook site showing bed level changes before (July 2017 and June 2018) and after (December 2019 and February 2021) barrier removal. Cross-section locations and position of ford crossing are shown, together with the large riffle mentioned in the text.

for index 1 (number of flow types), index 8 (channel physical habitat complexity) and index 9 (number of aquatic vegetation morphotypes). Flow complexity (index 1) increased between 2017 and 2020 in the former impounded zone and downstream of the structure. Similarly, there was a general increase in physical habitat complexity (index 8). The most significant change was for index 9, for which the 2020 channel showed a systematic reduction in macrophyte abundance and complexity across all MoRPh modules. While this may be partly attributed to the marginally later time of the post-removal survey (October as opposed to September), these results strongly reflect the lateral and especially vertical instability that characterised channel adjustment following barrier removal, which emphasises the need for longer-term post-removal assessment to capture ongoing spatial patterns and temporal rates of recovery.

6.4.4 Summary

Removal of the structure followed current best practice, but it nevertheless resulted in vertical and lateral instability, particularly upstream of the former barrier structure. Over a 2-year period, changes to the channel gradient resulted in the establishment of a slope that was very similar to that of the unimpacted reference reach upstream, but downcutting of the channel had moved further upstream than originally expected (i.e. significantly further upstream than the original impoundment). Lateral adjustments were less dramatic but still significant and ongoing. These changes would require continued monitoring and possibly intervention in the context of the loss of adjacent grazing farmland. Channel change, however, needs to be placed in the context of historical channelisation at this site and the resultant pre-existing disequilibrium conditions. This final point emphasises the importance of establishing hydromorphic trends and trajectories before undertaking barrier modification or removal.

Figure 6.12. Pre- and post-removal MoRPh survey results for indices 1, 8 and 9 at the Browns Beck Brook site. Module lengths were 10 m based on active channel width (i.e. < 5 m wide).

7 Numerical Modelling of Flows and Sediment Movement

Numerical models of water and sediment movement were reviewed to identify one model suitable for representing the effects of barrier removal at the project study sites. We are specifically interested in models addressing sediment movement in rivers and particularly the changes that occur following the removal of a barrier from the channel. A literature review seeking models of river morphology and sediment was undertaken; from this, a model was chosen for use in this project and was then applied to the study sites.

7.1 Models Investigated

The main models considered are listed below (more details of each can be found in Kelly-Quinn *et al*., 2021).

- **openLISEM.** This would have been an interesting option if catchment sources of sediment and management measures were a significant element of the analysis. However, as this is not the case in the Reconnect project, this model was not considered further.
- **HEC-RAS (1D or 2D).** This model offers good potential as a compromise between complexity, input data requirements and computational speed. It includes an example of sediment wedge movement in its supporting documentation (see Figure 7.2). Source: https://www.hec.usace.army.mil/software/hec-ras/
- **MIKE.** This is an impressive hydrodynamics and sediment transport model. It is not clear if it can be applied to the mobilisation of sediment wedge on barrier removal. This is a commercial package, so a licence is required.
- **Cellular Automata (e.g. Caesar).** This model mainly focuses on land surface erosion and sediment delivery to rivers. However, it does include modelling of rivers. This requires further investigation, as it potentially allows both river and catchment to be simulated together. As it is computationally fast, it may be a feasible solution for simulating very long periods of time. Source: https://sourceforge.net/p/caesar-lisflood/wiki/Instructions/
- **UBCRC model.** Because the effects of barriers on sediment transport are modelled only using the trapping efficiency, this model was not considered further.
- **STOCHASIM stochastic model.** While it is acknowledged in the literature that a stochastic approach has potential, the uptake of the approach (judging only from publications) has been slow. The STOCHASIM package is written in R language and is available from the original author.
- **MAST-1D.** The more recent version (with flow time series inputs) could be suitable for estimating the long-term effect of regime change.
- **SRH-1D.** This model is potentially a good candidate and has capabilities similar to the 1-D version of HEC-RAS. It is worthy of further investigation. However, HEC-RAS is preferred here because of the authors' prior experience with using HEC-RAS for sediment modelling. Source: https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh1d/index.html

Of the above models, HEC-RAS met the modelling requirements with manageable implementation requirements and, importantly, had already been validated for sediment modelling by the authors in a prior EPA-funded project (HYDROFOR; Kelly-Quinn *et al*., 2016).

7.2 HEC-RAS Models Applied to the Core Study Sites

7.2.1 Dalligan

The River Dalligan flows through a relatively narrow valley that has at least one steep side; sometimes both sides are steep. The HEC-RAS model of the study reach consists of 22 primary cross-sections over a reach length of 1589 m from the sections DAL-US to DAL-DS. The average longitudinal slope is steep, at 0.013.

Cross-sections were surveyed where there were significant changes in either the slope or the cross-section shape. Intermediate cross-sections were interpolated between the measured sections to give a maximum distance between sections of 5 m. In the longitudinal profile (Figure 7.1), the black dots on the channel bed indicate the position of measured cross-sections, the grey dots show the position of interpolated sections and the blue area shows a typical high-flow profile (4 m^3/s). The upstream boundary condition was a specified inflow to the reach. Manning's "*n*" resistance values were estimated visually from an inspection of the channel and floodplain (with trees and fences) at 0.04 for the main channel and 0.16 for the boulder strewn or treelined floodplain slopes.

The project required a rating relationship between discharge and water levels to convert the recorded water level time series into a discharge time series. A small number of discharge measurements were taken on site, and the theoretical equation for the ogee spillway crest could be used when flows were confined to the width of the spillway (up to about 4 m^3/s). The HEC-RAS model was used to obtain such a rating curve that allowed the discharge for flood peaks to be estimated and associated with the movement of cobbles, as described in Chapter 6.

7.2.2 Browns Beck Brook (Donard)

The HEC-RAS model for the Browns Beck Brook reach consists of 19 primary cross-sections over a reach length of 691.6 m from sections BBB-US to BBB-DS. The average longitudinal slope is 0.009, which is quite steep. The density of cross-sections was greater both upstream and downstream of the original ford/weir, as this is where the greatest immediate change was expected. This is shown in Figure 7.2, with the blue area showing a typical high-flow profile (5 m^3/s). There is a solid rock lip at the downstream end of the reach, and this provides a hydraulic control with critical depth assumed to occur there for most reasonable flows. The upstream boundary condition was a specified flow. The ford/weir is a critical depth boundary condition for the upstream section and for all flows simulated (1–10 m^3/s) it remained critical. The ford/weir was not drowned out.

7.2.3 Duag (Shanrahan Weir)

The HEC-RAS model for the Duag (Shanrahan) reach consists of 22 primary cross-sections over a reach

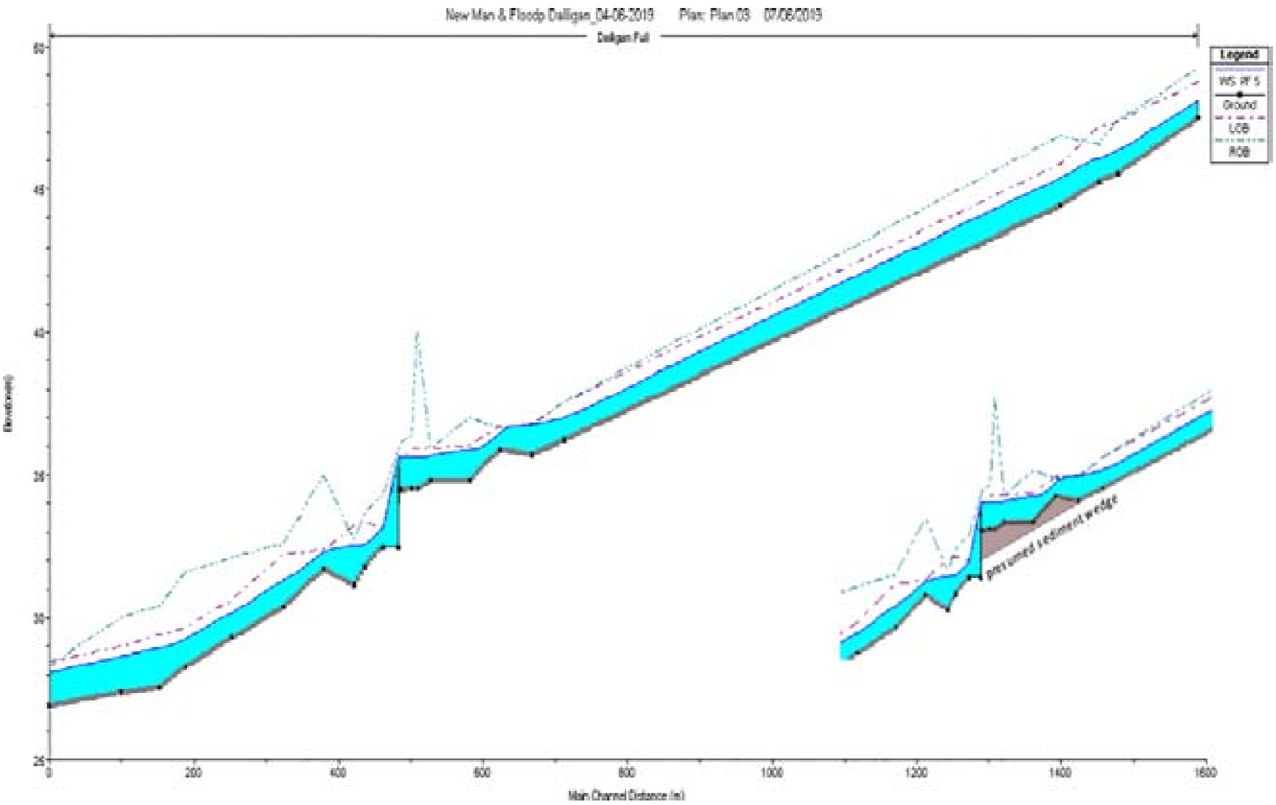

Figure 7.1. Longitudinal profile of the Dalligan reach. Black dots, the position of measured cross-sections; grey dots, the position of interpolated sections; blue area, a typical high-flow profile (4 m^3/s).

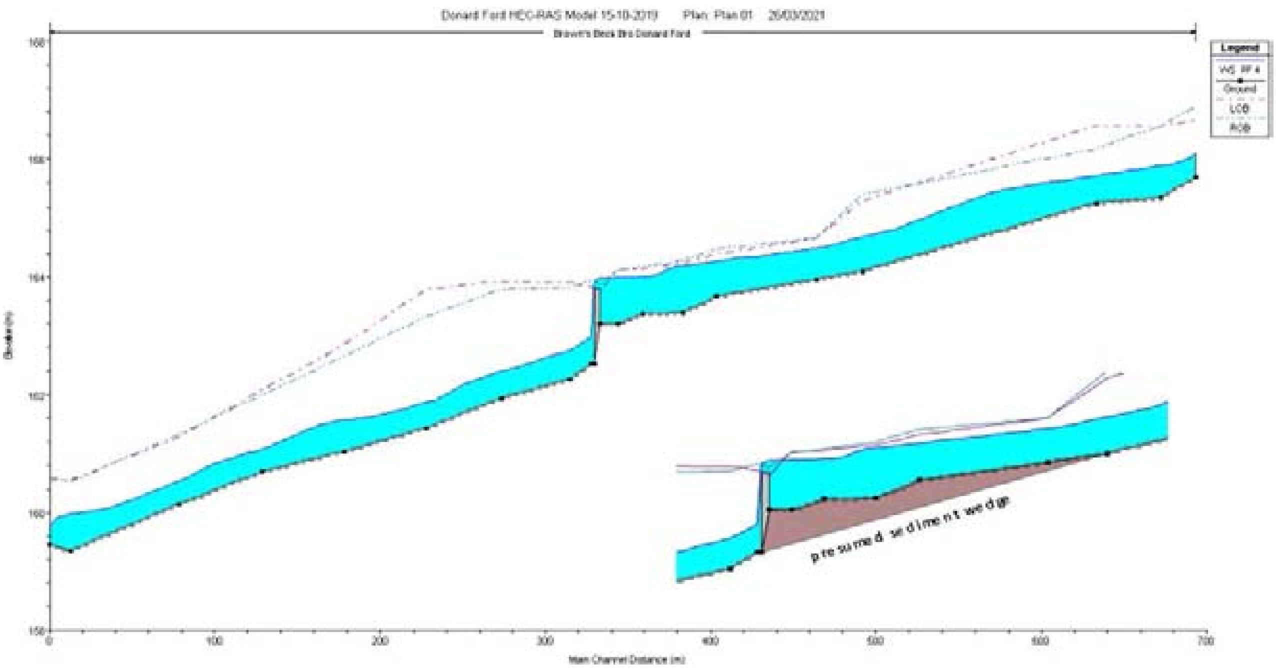

Figure 7.2. Longitudinal profile of the Browns Beck Brook (Donard) reach.

length of 918 m from sections BBB-US to BBB-DS (Figure 7.3). Over this distance, the channel falls by 2.83 m, so the average longitudinal slope is a moderate 0.0031. The upstream boundary condition was a specified inflow to the reach. Manning's *n* resistance values were estimated visually from an inspection of the channel and floodplain (with trees and fences) at 0.035 for the main channel and from 0.08 to 0.1 for the floodplain. At high flows, the weir can be drowned out and does not necessarily divide the study reach into two parts, and therefore may be passable at such flow rates. Its presumed sediment

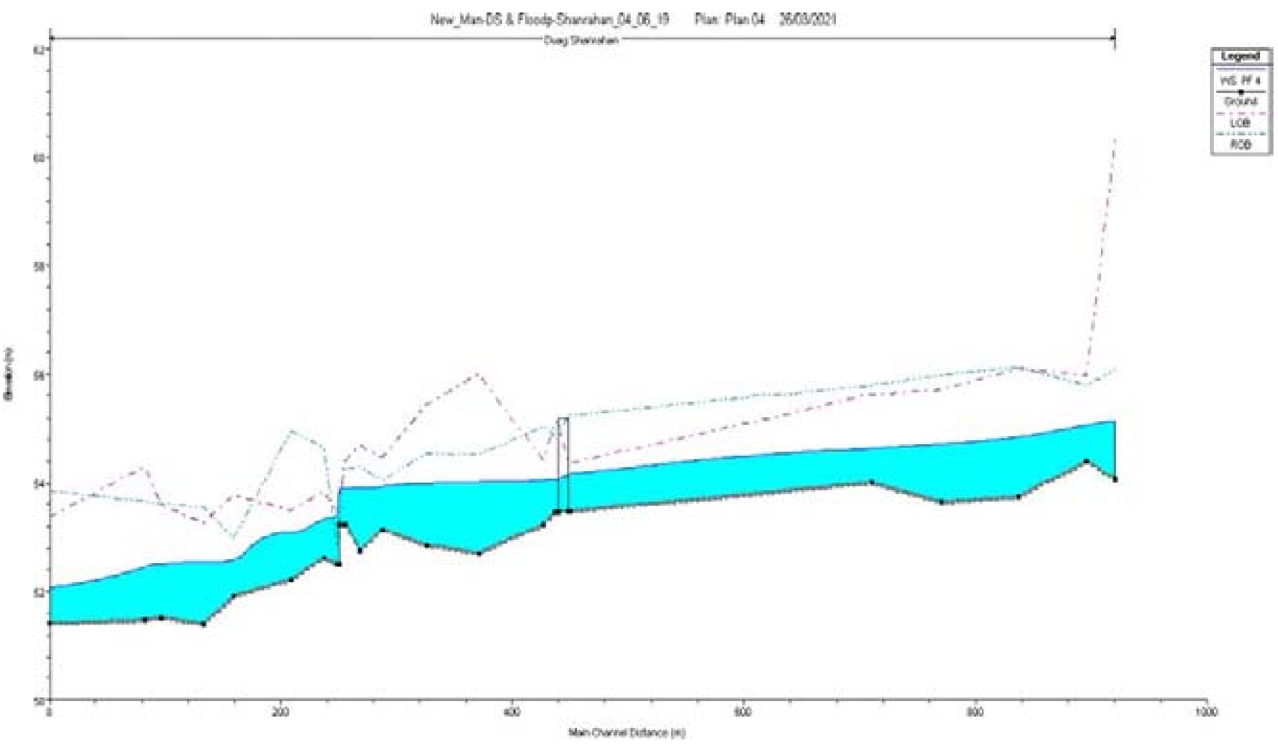

Figure 7.3. Longitudinal section of the Duag (Shanrahan) reach.

wedge is shown. At low flows, the weir is a critical depth boundary condition for the upstream reach, but the model suggests that at high flows, above 12 m^3/s, the weir is drowned out and the hydraulic control shifts to downstream conditions. The HEC-RAS model was used to develop a rating equation to convert water level measurements into discharges. As HEC-RAS has surveyed cross-sections for the weir, it can simulate the relationship between discharge and water levels immediately upstream, and uncertainties in Manning's *n* have little influence at flows up to about 12 m^3/s.

7.2.4 Boro

For brevity in this report, details of the Boro HEC-RAS model can be found in Kelly-Quinn *et al*. (2021).

7.3 Summary

The HEC-RAS models built for all of the study reaches were used, together with some gauging at low flows and equations for the elevation–discharge relationship at structures. These were used to develop or validate rating relationships for medium and high flows so that recorded time series of water levels could be converted to time series of discharges, thus providing a continuous flow series. This was essential for the analyses in Chapter 6, as peak discharges could then be estimated to relate flows to the movement of cobbles in the reach; flows on the rising and falling limbs of the hydrograph could also be quantified.

The project intended to simulate the concentrations and movement of sediment after removal of the barriers for the study sites. However, this was not possible, as two of the barriers were not removed during the expected timescale. In a number of years, it should be possible to model and check the readjustment of the downstream longitudinal bed profile, but this would require a new follow-up project, which could also incorporate the other structures when they are removed, as the baseline study of all the project locations is complete and valuable.

8 Economic Analyses of the Costs and Benefits of Barrier Removal/Modification

The objective of this research element was to investigate the economic costs and benefits associated with barrier removal or modification. To this end, data on the costs and logistics of barrier removal were obtained from IFI and the Office of Public Works (OPW), while information of the benefits was investigated by means of reviewing examples across the country, including the River Boyne, drawing on interviews with anglers and other stakeholders.

8.1 Economic Context: Cost and Benefits

From an economic perspective, barriers, such as weirs, can have benefits but also impose a negative externality on various interests. The negative externality can be a sizable social cost, for example when individual anglers or angling club members lose part of their fishing resource. While the removal of a barrier could result in lower capital values for estates downstream of a weir, higher values would be realised by fishing rights owners above the weir once more fish, e.g. salmon, can access these stretches. Overall, if the spawning length of the river or conditions are improved sufficiently, then there should be higher catches for most rights owners. However, while an increase in salmon numbers may be the objective and expectation, this is not guaranteed, given the many pressures on salmon populations, including exogenous factors, such as climate change.

In addition, there can be a variety of stakeholder interests associated with a weir, and proposals for removal would require negotiation. The weir owners would need to be involved, although their interests may now be different from those of the owner at the time of construction. Furthermore, the owner can sometimes be difficult to identify. The owner could also be different from the landowner, whose interests will often (but not always) include agriculture, and for whom removal could affect the levels of the water table or present concerns in relation to flood risk or erosion. The owner may, or may not, also have an interest in using the weir for hydropower or the pool above for abstraction. Also to be considered are the owners of fishing rights (not necessarily the landowner), kayakers and boaters, walkers, and those with other environmental or amenity interests or an interest in cultural or historical values, for whom a weir can provide a local sense of place. Even within these stakeholder groups there will be different interests; for example, some anglers will favour slow-moving stretches for coarse fishing and others faster-flowing waters for game angling of trout or migratory fish (e.g. salmon), while others still will simply prefer to fish at the base of the weir. Removal of a weir will result in external costs or benefits for each of these stakeholder groups, and this needs to be recognised.

8.2 Potential Costs of Barrier Removal

Table 8.1 provides examples of removal costs gathered by the Reconnect project with the assistance of IFI. Demolition costs depend mainly on weir height, but also on width. Recent examples have varied between €11,000 (1.3 m high × 40 m wide) and €80,000 (2.5 m × 106 m). The cost of alternative rock ramps has varied from €60,000 to €124,000. In these cases, other factors that influence cost come into play. For example, the construction of access roads for machinery could cost €5000, while the movement of abrasion pipes could add up to €20,000. Impact assessment and consultation costs vary considerably (€30,000–70,000), with engineering assessment, topographical surveys and hydrological surveys generally being the more expensive elements. More detailed surveys will be necessary when a barrier is located in a Natura 2000 site. In principle, survey work of this nature requires a minimum lead time of 12 months and it therefore requires a budget that is separate from the cost of demolition. If a public consultation is required, then the lead time could increase to 18–24 months, which could add as much as a further €70,000 to costs.

At the other extreme, the replacement of the degraded Fermoy Weir has been estimated at €3 million and has

Table 8.1. Examples of barrier removal costs and costs of rock ramp construction

Example	Width at weir (m)	Channel width (m)	Height (m)	Impact assessment/ surveys (€)	Demolition or modification costs (€)	Construction costs for ramps or fish pass
Brett's Weir, River Nore, Co. Kilkenny (€42,000–50,400 to planning permission stage only)	137	31	1	38,000	n/a yet	Rock ramp/fish pass (weir also provides water for hydropower)
Hanover Weir, River Burren, Co. Carlow (€25,200 estimated to planning permission)	100	10–13	1.6	30,000–40,000	Weir lowered 300 mm to get preferential flow through fish pass	€106,000 for a 13 × 50 m ramp and 600 mm lowering of weir crest
River Blackwater, Co. Cork (Clondulane)	106	43	2.5	70,000	n/a yet	€100,000 spent to date, before any physical works
Ahascragh Weir, River Bunowen, Co. Galway	10	10	1.5	23,900	Weir lowered 300 mm to get preferential flow through fish pass	€124,000 for rock ramp/fish pass
Castletown, River Nore, Co. Laois	30	20–32	1.5	30,000–35,000	Weir lowered < 300 mm to get preferential flow through fish pass	€66,000 for rock ramp
Shanrahan Weir, Co. Tipperary	32	13–14	1.5	54,000	n/a yet	–
Urrin Weir, River Slaney, Co. Wexford	40	12	1.3	€30,000	n/a yet	Figure is funds allocated
Martry Weir, Blackwater River, Co. Meath (€33,000 to date to planning permission)	15	10	> 1	50,000	n/a yet	€140,000–200,000 for a rock ramp and a weir (50/50). Provides hydroelectricity
Balmoral Weir, Blackwater/Boyne, Co. Meath	20	15	2	n/a yet	n/a yet	Fish pass possible at €100,000

attracted controversy, given the opposition of some interest groups, including the local rowing club. A cost–benefit assessment is therefore needed for each individual weir that takes into account the particular conditions and circumstances. It is useful to remember that, in this analysis, the tangible cost of removal is a one-off, while the benefits are continuous and long term and would need to be discounted to the present. The benefits are also subject to uncertainty, given the prospects of the recovery in salmon numbers, but are potentially higher when a series of barrier removals in a single river catchment can deliver cumulative benefits.

In practice, given the logistics of barrier removal, IFI has taken the approach of removing barriers when the opportunity has arisen, albeit guided by the angling potential of a river or tributary. In some cases, it might be more effective to install or improve a fish pass. Various options exist, but not only is it more expensive to install fish passes than to remove barriers, but fish passes can fail to assist the movement of lamprey or eels or provide the other hydrological benefits of removal (Vowles *et al*., 2017). Where there is a risk of significant environmental impacts, a rock ramp is often preferred (e.g. on the River Burren in Co. Carlow; see Chapter 2), as this can accommodate fish or other species and can potentially be designed as an amenity for kayakers. In principle, a strategic approach to barrier removal is advisable following the methodology discussed in Chapter 9.

8.3 Potential Benefits of Barrier Removal

In principle, the benefit of barrier removal is the creation of conditions that are more suitable for salmon or sea trout. This approach is compounded by many anglers being more familiar with existing catches of coarse fish than with salmon, given that numbers of the latter have declined in recent years. However, brown trout is a popular quarry and their populations would benefit from weir removal, as they would then have access to additional tributaries and could avoid genetic isolation.

Based on a choice experiment survey of anglers, the research team's ESManage project estimated the value to Irish anglers of an additional salmon caught per day on the River Moy (above the average catch) at €66. If additional fish were to attract more visiting anglers, the average local expenditure has been estimated by Grilli *et al*. (2018) to be €300 per day.

While the removal of a barrier could result in lower capital values for estates downstream of a weir, which represents the established interest, higher values would be realised by owners of fishing rights above the weir once more salmon can access these stretches. Overall, if the spawning length of river or conditions are improved sufficiently, then there should be higher catches for most owners of fishing rights. However, while an increase in salmon numbers is the objective, this is not guaranteed, given the many pressures faced by salmon populations, including exogenous factors such as climate change. As of 2017, only 45% of "salmon rivers" that were judged to have sustainable numbers (as assessed by IFI) had catches that were achieving their conservation limit.

Another interest group, namely kayakers, enjoys the experience of "shooting" weirs. The activity requires skill but also knowledge of the conditions below different weirs in different flows. Potentially, kayakers would be attracted to rivers with more turbulent conditions downstream of weirs that have been removed and with fewer slow-flow sections or impoundments upstream.

9 Multi-criteria Decision-making Methodology to Facilitate Practical Management Decisions

The large number of barriers in many of the river catchments in Ireland and Europe complicates the problem of choosing which structures to remove or modify to achieve a desired outcome, be it in relation to fish movement, habitat creation or river rewilding. Numerical decision support methods are essential to achieving the best return for money spent. Here, we first review methods that have been applied to this problem and then frame it as a classical multi-criteria decision problem and develop a methodology that can be applied in practical cases.

9.1 Considerations from Previous Decision Methods

The ecological importance of unregulated tributaries to regulated rivers was stressed by Milner *et al*. (2019) and that of headwater streams by Colvin *et al*. (2019), but often downstream structures disconnect them from lower reaches. However, increasing connectivity may not be the only change resulting from removing barriers, as flow regime and patterns of water level variations will be altered, and changes in biotic integrity (Karr, 1991) and habitat suitability can be expected.

The literature about the ecological impact of dams on invertebrates is reviewed by Ellis and Jones (2013), who tested the serial discontinuity concept of Ward and Stanford (1983). They found substantial differences in macroinvertebrate communities and fish habitat in the vicinity of barriers, both upstream and downstream.

A comparison of the passage of trout through culverts with their passage through reference natural stream reaches showed that culverts (even with unperched outfalls) reduced the passage of fish, as predicted by passability software (FishXing) (Mahlum *et al*., 2014). However, the software was too conservative at predicting the hydraulic limits on passability, so quantitatively the estimates from the software did not match the "empirical" observations well.

Nevertheless, the sensitivity of passability estimates to the methodology used was demonstrated for Ireland by Barry *et al*. (2018), who compared the SNIFFER method used in the UK with the ICE method used in France. While the methods agreed on the passability of structures at the extremes of the scales (i.e. impassable or not a barrier), there were substantial disagreements on intermediate values, mainly as a result of the treatment of factors such as pool depths and length, height of drop, slope and flow velocity. A study of cyprinids attempting to pass up through weirs on which low-cost baffle fishways had been installed showed a similar success rate for both stocked and wild fish of the same species that attempted to pass. However, the stocked fish were more likely to attempt to pass the weir, perhaps because they more actively explore their new habitat (Lothian *et al*., 2019).

The extent of the movement of aquatic organisms is controlled by the connectivity of the river network and particularly by any obstacles or barriers in the channel. These may deny or reduce access of organisms to one part of a river network from another. Stream network fragmentation also alters fish community structure (Perkin and Gido, 2012). The subject is complex but does require a metric that describes the range of access of individual species to parts of a channel network. Here we concentrate on the effects of connectivity on migratory fish.

The DCI was defined by Cote *et al*. (2009), using the concept of coincidence probability, as used in indices for habitat connectivity on land (Pascual-Hortal and Saura, 2006) and which is explained in Chapter 3 and by Atkinson *et al*. (2020). The relationship between connectivity indices and fish and other communities may be scale dependent. For instance, a stronger relationship was found between the two quantities at smaller spatial scales than at larger scales (Mahlum *et al*., 2014). It is possible that the larger scales allow a larger range of confounding influences on the relationship.

9.2 Choice of Decision Criteria

A list of possible criteria to be used in selecting potential barriers for modification or removal was produced, and included factors summarised in Chapter 8. Following discussions at a steering committee meeting, the following seven criteria emerged.

9.2.1 C_1: cost of modifications/removal (monetary amount)

In some cases, it may be appropriate to treat cost (or perhaps initial cost) as a constraint, e.g. when there is a fixed budget for the removal or alteration of barriers. The problem thus becomes an optimisation one, with an objective function to be maximised (or minimised) subject to the budget and possibly other constraints, e.g. relating to habitat or connectivity. If budget is not a fixed constraint, then cost can become a criterion so that it can be "traded off" against other criteria depending on the multi-criteria decision analysis (MCDA) method used.

In both of these cases, costs must be assessed. The assessment should include the initial cost of the modifications or removal and the net recurring costs to be either incurred or saved. It should also include any net changes in the capital valuation of (i) fishing rights (including redistribution effects) and (ii) recurring costs or benefits associated with changes in angling opportunities and variations in catch. While there is an argument for the inclusion of changes in abstractions and hydropower (potential and/or use), in this study these are incorporated in the flow regime change factor. They can be calculated initially as a monetary amount (e.g. net present value or equivalent annual cost) using discounted methods, which requires that the appropriate discount rate(s) and duration for the analysis be specified.

9.2.2 C_2: river regulation – change in flooding and low-flow regime (upstream and downstream) (monetary amount or expert judgement)

The removal or modification of a potential barrier may result in significant changes in flooding regime, both upstream and downstream of its location. Typically, in the downstream reaches, an increase in the magnitude of flood discharge peaks and corresponding water levels may be expected. The magnitude of the effect will depend on the nature of the structure, the planned modifications and hydraulic factors in the downstream reach. For small structures with small impoundments, the downstream effects may not be significant. The relative impact will diminish with increasing distance downstream, as lateral inflows and tributaries contribute additional water unaffected by changes to the barrier. Removal of a structure will typically lower upstream water levels for most flows, particularly the lower flows. For higher flows, some structures may be "drowned out" by hydraulic controls downstream, so their removal/modification may or may not influence upstream flooding.

The following steps can be used to assess this criterion:

1. Determine if the river reach is in a Catchment Flood Risk Assessment and Management (CFRAMS) area for further assessment. Tables are available from documents available from the CFRAMS website.
2. Determine if historical flooding has occurred from the river reach (http://www.floodinfo.ie/).
3. If sufficient information is not available from these sources, then, particularly with large structures on large rivers, a combination of hydrological and hydraulic modelling is required to predict the changes in flow and water level regime.

The flooding issues can be costed using the techniques in the cost–benefit analysis of flood protection measures and must include consideration of "intangible" issues, relating to the perception of risk and impact of flooding on the psychological and physical health of the population affected. The impact of changes in a low-flow regime will depend on the nature and vulnerability of the ecosystems affected and on the use of and dependency on the river's water by humans (e.g. abstractions for water supply or hydropower). Overall, this factor may be expressed as a monetary amount or as an impact index, and the choice will depend on the resources available.

9.2.3 C_3: heritage issues (expert opinion)

The heritage value of an existing structure should be considered in two steps. The first step is to determine if the structure is a “protected” one. This is a structure that a planning authority considers to be of special interest from an architectural, historical, archaeological, artistic, cultural, scientific, social or technical point of view. The initial source of information on this for a specific site can be the Heritage Maps website (www.heritagemaps.ie) or the national inventory of architectural heritage (www.buildingsofireland.ie). In addition, each local authority keeps a register of protected structures for its area. An inspection of the registers for each county undertaken in 2020 determined that there were 43 protected weirs in Ireland at that time. If a barrier is protected then this is a constraint, as there will be limitations on what changes (if any) can be made. Protected structures would normally be removed from the analysis. If the structure is not protected, then an index of its heritage value can be assigned by a combination of experts with architectural, industrial heritage and/or local historical knowledge.

9.2.4 C_4: recreation (stakeholder opinion)

This criterion considers navigation, swimming, rowing (requiring sufficient water depth) and kayaking that may be affected by changes in water surface levels or flow regime. It also takes into account other activities, such as walking or jogging, that do not involve the river directly but which are often associated with the river. Weirs tend to enhance these activities (except perhaps kayaking, but not always, as overflow spillways can create attractive standing waves) so removal would typically reduce these existing benefits. The extent of the potential impact can be assessed by a survey of people involved in these activities, i.e. the opinion of stakeholders.

9.2.5 C_5: changes in sediment transport, deposition and removal (expert opinion)

The barrier structures and their upstream impounded areas can change the sediment transport regime both directly and indirectly through changes in the flow regime, particularly in relation to floods. The initial effect of the removal of a weir is the potential mobilisation of sediment impounded upstream of the structure. This may be modified by the removal of some of the sediment from the site as part of the works. A longer-term effect is the morphological adjustment, particularly of the downstream channel to the change in flow regime and sediment movement and this may continue for years. This can be assessed by an expert in river morphology and the main factors relate to the nature of the impounded sediment wedge and the condition of downstream riverbanks and riverbeds.

9.2.6 C_6: angling/connectivity (dendritic connectivity index)

The implications for angling of the removal or modification of barriers is connected to the degree of river connectivity and the availability of habitat to the key species involved. In Ireland, these are mainly salmon and trout. The removal or modification of barriers generally increases the range of migration and habitat possibilities of these species and is thus normally beneficial. Note that other species can benefit as well. If downstream reaches of the river are not visited by migratory species, then the removal of the barrier, although it can increase habitat availability even for resident fish, may not have a significant effect on angling possibilities. This can be assessed using a morphology-based index, e.g. the DCI (Atkinson *et al*., 2020; see also Chapter 3), or a contingent valuation approach, which surveys the population that fishes the river (Loomis, 1996).

9.2.7 C_7: rewilding of the river (river condition assessment)

The term rewilding is generally taken to mean reversing human changes to rivers in the hope of recreating its natural condition and benefiting from the various services that it can provide. It has both aesthetic and ecological implications for the river. There are many practical difficulties with the concept, particularly (i) determining what the natural condition was (e.g. see Brown *et al*., 2018) and (ii) achieving that condition in circumstances in which land use and climate are now very different. While attitudes to how this can or should be done are evolving, the potential must be assessed from both bioenvironmental and hydromorphological points of view, perhaps starting with metrics such as a river condition assessment (Gurnell *et al*., 2020b). Subsequently, the results of EPA projects such as ESManage (Kelly-Quinn *et al*., 2020) and ESDecide (www.ucd.ie/esdecide) can contribute to the assessment of the benefits of improving ecosystem health in a river.

9.3 Choice of Multi-criteria Method

A large number of potential multi-criteria methods are available. We chose to use the analytic hierarchy process (AHP) (Saaty, 1980) because it is one of a number of multi-criteria methods that can deal with combinations of quantitative and qualitative attributes (Rogers and Bruen, 1995). (More details of other methods are given in Kelly-Quinn *et al.*, 2021.) A hierarchy enables the decision problem to be broken down into individual elements whose relationships with each other can then be analysed. In most cases, a hierarchy has at least three levels: the required decision at the top, possible options in the middle and assessment criteria at the bottom (see Figure 9.1).

9.3.1 Priority in hierarchies

The elements in the lowest level (criteria) are evaluated for each option and are combined using weights to produce a score for each option. One of Saaty's innovations (Saaty, 1980) was a method for determining these weights from surveys of decision-makers/stakeholders. Saaty suggested asking several simple questions, each comparing only two of the criteria at a time. Taking each of the possible combinations of any two of the criteria, the stakeholders are asked first which of the two criteria they think is more important than the other; they are then asked to grade the strength of that opinion using a simple numerical scale (1, 3, 5, 7, 9) to represent the results of each pair-wise comparison. Saaty (1977) believed that, within the framework of a simultaneous pair-wise comparison, no more than 9 scale points (he allowed the use of intermediate, even, numbers if stakeholders so wished) to distinguish between the strength of the opinions. Saaty noted that the ability to make qualitative decisions was well represented by five attributes (equality, weak preference, strong preference, very strong preference and absolute preference). He also determined a mathematical method for determining the priority weights for each criterion from the pair-wise comparison survey data.

9.3.2 Scoring options (alternatives)

In AHP, the procedure for scoring options (alternatives) on a particular criterion is analogous to that for estimating weights. However, although stakeholders are usually the appropriate group to use in estimating criteria weights, a panel of technical experts is often used to score options.

9.4 Determining the Analytical Hierarchy Process Weights for the Reconnect Criteria

9.4.1 Stakeholder survey

A pair-wise questionnaire was emailed to 122 stakeholders. Twenty of these were marked undelivered as a result of email addresses no longer being valid and/or the person named no longer being with the organisation. In addition, 10 of the emails were sent to canoeing clubs and they sent a single joint response through their national umbrella organisation. There were thus effectively 93 potential responders. Twenty-one responses were received (23%). Following a reminder email to the active addresses that had not responded, a further eight responses were received, giving a total of 29 (31%). These were distributed among different categories of stakeholders, i.e. OPW employees (6), IFI employees (8), local authorities (7), consultants (4) and non-governmental organisations (4).

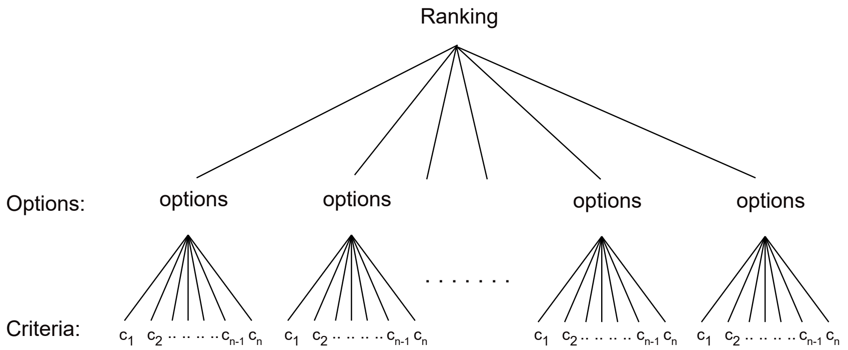

Figure 9.1. Example of hierarchy tree. See section 9.2 for descriptions of the criteria.

9.4.2 Survey results

The first series of analyses estimated the criteria weights separately for each respondent and grouped them by stakeholder category. For example, the weights for the six respondents from the OPW are shown in Table 9.1, together with their means, geometric means, standard deviations and coefficients of variation. The results cluster strongly into two groups, illustrated by their geometric means: (i) relatively high weights for river regulation (0.376), sediment (0.173) and then rewilding (0.150); and (ii) a group of low weights, namely costs (0.062), recreation (0.035) and angling/connectivity (0.050). One criterion, heritage (0.093), lies between these. Note that the highest weight was more than twice that of the second highest, indicating a very strong preference. As these respondents were mainly engineers, some of whom have responsibility for managing river flow, including flood protection, the highest weight for regulation is to be expected. As the OPW also has responsibility for maintaining the channels for over half the rivers in Ireland (those that have been affected by arterial drainage schemes), the concern for sediment is also understandable. The low weight for costs (0.062) is perhaps a little surprising, but the higher weight for heritage (0.093) is not, considering that other sections of the OPW have a heritage remit. The standard deviation and coefficient of variation of the results were calculated for each criterion to indicate the degree of agreement between the members of the group about each weight. The coefficient of variation is lowest for sediment (0.22), recreation (0.23) and regulation (0.26). For all the other criteria it is above 0.38, indicating some variation between the members of this group, with most variation for the rewilding (0.62) and heritage (0.49) criteria. Note that for this group there is very little difference between the arithmetic and geometric means for each criterion.

This procedure was repeated separately for each group of respondents and the means of the responses from each group are shown in Table 9.2. Higher weights (above an average) are highlighted with a green background and lower weights with an orange background. Despite the variations in detail within each group, there was remarkable agreement on the most important and least important criteria. Note particularly:

- the strength of support for rewilding;
- consistently low weights for costs;
- that heritage lies between high and low groups, perhaps indicating some ambiguity;
- the placement of heritage in the high weight group by consultants only;
- the more even distribution of weights for consultants than for other groups.

In this application, the first five criteria describe negative outcomes if a structure is removed and the last two describe positive outcomes. Concern has been raised about the effect this may have on stakeholders' assessments (Saaty and Ozdemir, 2003). The project investigated a number of possible ways of addressing this. One way is to estimate the weights for positive criteria separately from those of negative criteria, essentially dividing the survey data into three parts, with the first part relating to negative criteria only, the second part relating to positive criteria only and the third part relating to comparisons

Table 9.1. Individual weights from OPW respondents

Characteristic	Costs	Regulation	Heritage	Recreation	Sediment	Angling/connectivity	Rewilding	CR (%)
1	0.055	0.397	0.113	0.048	0.220	0.051	0.115	5.9
2	0.058	0.378	0.129	0.045	0.144	0.074	0.172	7.9
3	0.087	0.275	0.030	0.027	0.180	0.027	0.373	4.4
4	0.026	0.560	0.060	0.034	0.120	0.080	0.120	12.2
5	0.088	0.300	0.167	0.031	0.182	0.057	0.175	14.1
6	0.091	0.408	0.149	0.032	0.214	0.032	0.074	6.4
Mean	0.068	0.387	0.108	0.036	0.177	0.054	0.171	
GM	0.062	0.376	0.093	0.035	0.173	0.050	0.150	
STD	0.026	0.101	0.053	0.008	0.039	0.021	0.106	
CoV	0.38	0.26	0.49	0.23	0.22	0.40	0.62	

CoV, coefficient of variation; CR, consistency ratio; GM, geometric mean; STD, standard deviation.

Table 9.2. Means of responses from each group

Group	Costs	Regulation	Heritage	Recreation	Sediment	Angling/ connectivity	Rewilding
OPW	0.068	0.387	0.108	0.036	0.177	0.054	0.171
IFI	0.087	0.147	0.041	0.032	0.154	0.228	0.311
LA[a]	0.052	0.187	0.129	0.053	0.249	0.085	0.245
Consultants	0.074	0.193	0.141	0.110	0.129	0.137	0.216
Others	0.043	0.137	0.070	0.117	0.150	0.149	0.333
Overall[a]	0.071	0.216	0.098	0.072	0.168	0.135	0.241

Green, above-average weight; orange, below-average weight.
[a]Excluding one outlier response.
LA, local authority.

of negative with positive criteria. The third group is ignored in this procedure, which is conceptually unsatisfactory, as it ignores some survey information. A new alternative method was suggested by Professor Jesse O’Hanley. In Professor O’Hanley’s method the elements of the pair-wise comparison matrix are given negative signs when the corresponding comparison is of a negative criterion (e.g. a cost) with a positive one (e.g. a benefit). For comparison of two negative criteria or of two positive criteria the corresponding element of the pair-wise matrix is positive. The AHP analysis is done as before, using the eigenvalue method, and produces weights with signs that indicate whether they are benefits or costs. This is conceptually better, as it allows all the survey data to contribute to the result and enforces a consistent scale (–1 to +1) on the estimated weights. In this study, all the approaches, while giving different weights, gave the same ranking of alternatives as the basic method, summarised in Table 9.2.

In conclusion, the multi-criteria method AHP is proposed here, because of its global use. However, any of the many compensatory methods could be used instead. Seven criteria are proposed for assessing barriers to be removed or modified and methodologies for applying them are suggested. The weights determined here placed greatest importance on river rewilding, followed by flow regulation and sediment. Costs and recreation had the lowest weight, and connectivity/angling and heritage considerations were in between. Note that weights can be expected to change with time and with diversity of stakeholders, so separate new surveys are recommended to determine weights from time to time, if possible. A new method for dealing with mixtures of negative and positive criteria was demonstrated.

10 General Conclusions and Recommendations

10.1 General Conclusions

The focus of the Reconnect project was on artificial structures or barriers that may interrupt or modify the flow of water, the transport of sediments and the movement of organisms and which can cause longitudinal discontinuity (AMBER, 2020). This approach acknowledges that barriers can affect fluvial systems, including aquatic ecology, in ways other than through restricted movement of aquatic biota. Thus, in addition to considering the impacts of barriers on fish, for which there is a considerable body of research (e.g. Perkin and Gido, 2012), this research adopted an integrated, multidisciplinary approach that investigated the potential impacts of barriers from hydromorphological, ecological, economic and management perspectives. This approach recognises that information of these elements is required to support decision-making relating to barrier removal or modification, alongside assessment of the traditional interruption of freshwater fish movement and migratory routes.

In this project, 2361 km of river channel was assessed in a desk study covering the mainstem and tributaries in 10 Irish catchments. The presence of barriers was assessed in *c*.250-m segments from source to the sea using extant maps and aerial photography. Potential barriers (1401) were then visited in a field survey to validate whether or not they could pose a barrier to fish. This compares with the estimated 2715 km surveyed by the AMBER project to ground-truth barrier densities (AMBER, 2020). The artificial barriers identified fell within five broad groups, namely weirs, sluices, road crossings, dams and others, with most being low-head structures (i.e. <5 m in height) that allowed the free movement of water through or over the barrier. These barrier groups broadly align with the six functional types described by the AMBER project. The Reconnect project did not include ramps, which were included in the data submitted by IFI to the AMBER project. Detailed measurements of the physical dimensions of 372 structures, deemed barriers to fish movement under the conditions at the time of surveying, enabled further differentiation of 13 river barrier types comprising four types of bridges/culverts and five types of weirs. This breakdown of barrier type should be of use when evaluating their potential impact on, for example, fish passage. Height is an essential measurement and its absence from many of the European databases (including Ireland) has been highlighted (AMBER, 2018).

Barrier density is a key issue when it comes to the evaluation of impact and planning for their removal or modification. Values were quite variable across the catchments surveyed, ranging from 0.02 to 1.2 structures/km, with a mean density of 0.21 barriers per kilometre of river. Data reported to the AMBER project from Ireland covering 19,503 km of river channel, including Reconnect project data at that time, give a barrier density of 0.43 barriers/km. If this density is extrapolated to second-order and higher-order river channel length in the entire country, it would result in an estimated 19,528 barriers. Culverts and weirs are the two most prevalent barrier types identified in this study. Restoration efforts are perhaps best focused on weirs, given their greater potential for impact on river habitat. Replacing poorly designed existing culverts is more challenging and should focus on those structures that present the highest risks to the movement of fish (e.g. Figure 10.1). Construction of new culverts generally follows best practice guidelines (e.g. NRA, 2008), but there should be follow-up evaluations to ensure that they are constructed as designed.

Apart from restricting the movement of fish, fragmentation by barriers may have equally significant effects in terms of habitat availability and may also promote increased residency, a problem not addressed in this project (e.g. Branco *et al*., 2017). The fish studies highlighted clear issues with upstream fish migration in the River Dalligan, where there is a vertical barrier (2.3 m high) *c*.2 km from the sea. Salmon are not present in this river and sea trout can migrate only as far as the barrier, which also poses problems for eel and lamprey attempting to move upstream. The precise effect of the other barriers investigated depends on their dimensions and the characteristics of the impounded reaches. However, in general, trout and salmon fry and salmon parr

Figure 10.1. Culverting that would impact fish movement.

were absent or in low abundance in the impounded reaches. This was not always related to the impacts on upstream movement but sometimes was related to change in habitat, i.e. to impounded reaches that are more lacustrine than riverine, as higher salmon numbers could be found further upstream in some rivers (e.g. BUR-FUS2). It is also important to note that the impounded reaches did not always hold the highest density of 1+ fish (fish in their second year) and older fish as might have been expected. The homogeneity of the habitat in some of the impounded reaches probably limits the fish-carrying capacity (e.g. River Burren upstream of Hanover Weir before restoration works). Thus, the effect on habitat is an important consideration when assessing barrier impacts, and this was also evident from the macroinvertebrate studies.

The macroinvertebrate communities were dominated by species that have aerial stages, so barriers do not pose an issue for dispersion. In the case of other taxa with non-aerial life stages we did not detect any effect of the barrier on their occurrence in riffle and pool habitats upstream and downstream of the barriers. The macroinvertebrate communities of the impounded reaches were shown to be similar to natural pools, and most were significantly different to those of riffle habitats, especially in terms of community structure, and particularly in EPT richness. The impounded habitats had lower EPT richness, while natural pools were intermediate between riffles and the impounded habitats. In effect, the impounded reaches are, as expected, creating elongated pool habitats.

The specific ecological impacts are likely to be dependent on the characteristics and location of the barrier and will require local study. However, ecological assessment of some elements can be time-consuming and expensive to complete. Thus, the Reconnect project investigated the potential value of eDNA techniques. Since the start of the project, eDNA approaches and analyses have developed rapidly across the world (see www.dnaqua.net). In the Reconnect project, the focus was on developing and using species-specific eDNA qPCR assays for species that might be affected by river barriers and a broader approach using metabarcoding methods focusing on invertebrate diversity. Assays for species that might be affected by obstructions (Atlantic salmon, allis and twaite shad and white-clawed crayfish) were successfully deployed; this demonstrated the potential of the assays to detect the presence of target species.

Metabarcoding, in contrast to the qPCR approach, is not species specific. The method takes advantage of universal primers and is capable of detecting a wide range of taxa. Two approaches were evaluated for metabarcoding in the Reconnect project: the Illumina MiSeq and Illumina HighSeq platforms. The Miseq approach used the entire COI region while the HiSeq used mini barcodes designed to result in shorter amplicons. While the MiSeq does not render the same number of sequences as the HiSeq (*c.*22–25 million and 250–400 million reads, respectively), the read length (sequence length) is longer (MiSeq: 300 bp × 2, HiSeq: 150 bp × 2). MiSeq metabarcoding's ability to detect biodiversity was superior to that of standard kick samples. Furthermore, the bioinformatic approaches used were capable of higher taxonomic resolution than traditional visual identification. On the other hand, the HiSeq performance was suboptimal. This can probably be attributed to technical issues in the laboratory. However, the poor performance of the HiSeq is unlikely to indicate that the approach is not useful. Further tuning of the laboratory protocols should confirm the usability of the approach.

Alongside the ecological investigations, hydromorphological conditions associated with barrier structures were assessed using a range of tools, including novel and high-resolution field monitoring of riverbed and suspended sediment transport. These investigations mainly focused on the core study sites of the Duag, Dalligan and Browns Beck Brook catchments. Results have provided valuable empirical data on the ongoing impact of low-head structures on sediment connectivity that hitherto have largely been limited to numerical modelling studies in the USA (e.g. Pearson and Pizzuto, 2015). Differences in the relative magnitude of fractional transport rates upstream and downstream of the barriers at the Duag and Dalligan sites suggest that hydrosedimentary disruption is likely to depend on site-specific variables, including site setting and structure age, height and storage capacity. As reported recently by Magilligan *et al*. (2021), these disruptions may be no more significant than the natural trapping effects that occur in deep pools or behind large woody debris. However, the widespread distribution of barriers in Ireland reported by the Reconnect project (Atkinson *et al*., 2020) and across many European river catchments (reported by AMBER in Belletti *et al*., 2020) means that the potential impacts on sediment connectivity and hydromorphological conditions remain highly relevant. While it is impracticable to undertake the detailed investigations on sediment connectivity used by the Reconnect project, it is possible to undertake baseline riverbed sediment characterisation using traditional Wolman (1954) counts, as a preliminary assessment of potential transport-limited conditions downstream of barrier structures targeted for removal. Pre-removal hydromorphic assessment should also determine the risk to aquatic life of fine-sediment release downstream.

Morphological adjustments following the barrier removal at the Browns Beck Brook site included riverbed grade changes and substrate reorganisation, which were not unexpected given the date of barrier construction in the 1960s and the historical channelisation. However, rates of adjustment were relatively rapid and resulted in changes in flow conditions, physical habitat and a marked reduction in the macrophyte population two years following the commencement of work on the ford (based on the MoRPh survey results). Lateral adjustment resulting from ensuing channel instability has also placed pressure on adjacent farmland and is ongoing. These observations emphasise the importance of assessing the risk of dynamic adjustment at a site before barrier removal (including historical antecedent pressures) and the importance of post-removal monitoring beyond the two-year period available to the Reconnect project team. UAV surveys, undertaken in late winter, when vegetation coverage is minimal (possibly supported by ground-level field photographs), represent a low-cost alternative to the detailed topographic surveys undertaken as part of the Reconnect project. Pre- and post-barrier removal monitoring should also be supported through on-site assessment. We recommend using the multi-MoRPh survey tool (or similar), which offers a higher resolution, quantitative alternative to RHAT. Following restoration works, we propose that monitoring is continued for a number of years to capture morphological adjustments that may have an impact on land and/or infrastructure, and in some cases will require intervention such as bank/bed stabilisation or tree planting. It is also worth noting that any assessment of ecological recovery at former barrier sites, using traditional biotic indices, will need to be cautiously interpreted until more stable geomorphic conditions have been achieved.

As expected, the economic costs of barrier removal vary considerably depending on the height and width of the structure and the local environmental conditions. Demolition costs varied between €11,000 (1 m × 15 m weir) and €80,000 (2.5 m × 106 m weir), while the cost of environmental impact surveys ranged between €24,000 and €70,000. For smaller barriers, removal and mitigation works may be all that is needed, but typically the construction of alternative structures to address the change in channel gradient is a significant cost. In recent years, rock ramps have been the preferred option here, with construction costs ranging from €66,000 to as much as €200,000. Given the number of barriers and the significant costs involved, barriers would ideally be selected for removal based on a prior cost–benefit analysis to determine the scale and benefit-to-costs ratio of the project. Benefits would include a proportion of non-market values, the estimation of which would require the application of relevant methodologies.

Seven criteria were used in developing a decision support methodology for selecting barriers for removal. These were cost, flow regulation, heritage, recreation, sediment, angling/connectivity, and rewilding the river. They were selected from factors mentioned in the review (Chapter 8) and have a broader range than those used in many studies reported in the literature. These criteria can be used as part of a multi-criteria process; the AHP was used here and was chosen because of its widespread use. A methodology was presented for assessing each criterion for barriers under consideration for modification or removal. Weights were determined for the criteria using Saaty's eigenvalue method applied to survey data from a pair-wise comparison questionnaire from a number of stakeholder groups (but not the general public). In total, 29 responses were received and analysed. Overall, the greatest importance was placed on river rewilding, closely followed by flow regulation and sediment effects. Costs and recreation had the lowest weight, and connectivity/angling and heritage considerations were in between. The results were broadly consistent across the various stakeholder groups, except for consultants. They show a broad appreciation of river benefits, as shown by the greater importance placed on rewilding and flow regulation than on angling/connectivity and heritage value. It was somewhat surprising that even those groups working with organisations that would be involved in any removal/modification works did not consider cost to be an important criterion.

It is clear from the research undertaken that decision-making in relation to barrier removal/modification should be cognisant of the broadest range of potential impacts, not just on fish but also on hydromorphology/hydrology and its implications for other biological elements. After structures are removed or modified, follow-up studies are required to improve knowledge of how rivers may adjust to the works and the responses of the aquatic biota.

10.2 Recommendations

1. In order to plan for barrier removal or modification, a comprehensive, open-access national barrier database is needed. The desk mapping methodology applied by the Reconnect project provides a rapid initial assessment and enables more focused field investigations, eliminating the need to walk entire river catchments to locate barriers.
2. Barrier height is recognised as a key measurement in terms of fish passability and should, at a minimum, be recorded in the national database.
3. Barrier density could be coupled with the DCI to identify severely impacted catchments, where removal or modification of many barriers may be required to significantly improve connectivity, as well as identifying catchments whose connectivity can be substantially improved by making only a few modifications. This approach could be used by IFI staff engaged in the selection of barriers for removal or modification.
4. Guidelines on characterisation of barriers in terms of their widest potential impacts are needed.
5. Species-specific eDNA assays are suitable for non-invasive detection of the presence of focal species above and below barriers and offer a complementary or stand-alone tool for detecting target species upstream of barriers after barrier removal. They should be carried out as part of the assessment of barriers to be removed or modified, and as part of post-removal/modification monitoring. This is technically feasible, as demonstrated in the Reconnect project, and should reduce the costs associated with fish surveys.
6. Metabarcoding has the capacity to efficiently assess biodiversity with often a higher taxonomic resolution than traditional visual studies and should be employed in Biosphere Atmosphere Change Index (BACI) biodiversity studies.
7. Practical tools are needed to assess the hydromorphological impacts of barriers to support decision-making for barrier removal. The multi-MoRPh tool shows promise in this regard for

both pre- and post-removal hydromorphological assessment.

8. The effects of barriers on sediment connectivity should not be overlooked in decisions on barrier removal. These effects, however, are not easy to quantify without some level of sediment transport monitoring.
9. Barrier removal best practice should include consideration of channel morphological response following restoration. Further research is needed to determine controls on channel adjustment, but these are likely to be linked to inherent riverbank and riverbed stability, combined with metrics related to geomorphic work, such as unit stream power (i.e. width, slope and discharge). High-resolution LiDAR (light detection and ranging) data for Irish catchments would facilitate quantification of these metrics and significantly improve the accuracy and precision of morphometric studies. Coordinated efforts should also be made by the relevant authorities to document past and future barrier removal initiatives to support this work.
10. Barriers that are in poor condition and at risk of failure should be identified and be either repaired or removed under controlled conditions. This is an important public safety issue.
11. Follow-up studies should be undertaken post barrier removal or modification to improve knowledge of how rivers may adjust to the works and the responses of the aquatic biota. This would further enhance our ability to model and predict the consequences of removal.
12. A methodology was proposed for prioritising options in relation to barriers, using an MCDA approach. While most of the commonly used MCDA methods could have been used, the project used the AHP. Importance weights were determined for seven criteria by surveying river experts from a variety of organisations. Rewilding the river, flow regulation and sediment consequences were the factors identified as most important in the decision process. Costs and recreation were identified as the least important of the criteria.
13. The full MCDA assessment methodology described here is mainly applicable for barriers that provide significant flow regulation or have sizable sediment wedges and where significant costs would be incurred in removal or modification. Where a barrier has a small impoundment and small sediment wedge, decisions on changes could be made by an appropriate group of experts without a full MCDA assessment. In particular, improvements in barriers (e.g. culverts) associated with road crossings could be incorporated opportunistically, without any prioritisation, into planned road improvement schemes, which would have corresponding cost savings.
14. Barrier removal/modification should be combined strategically with integrated catchment management and associated objectives to gradually re-naturalise rivers (a high priority of the surveyed experts), with multiple benefits for all types of users and the river ecology.

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Abbreviations

AHP	Analytical hierarchy process
AMBER	Adaptive Management of Barriers in European Rivers
COI	Cytochrome c oxidase subunit I
DCI	Dendritic connectivity index
DCI_D	Dendritic Connectivity Index of diadromous species
DCI_P	Dendritic Connectivity Index of potadromous species
eDNA	Environmental DNA
EPT	Ephemeroptera, Plecoptera and Trichoptera
GIS	Geographical information system
HEC-RAS	Hydrologic Engineering Center's River Analysis System
IFI	Inland Fisheries Ireland
MCDA	Multi-criteria decision analysis
MoRPh	Modular River Physical (survey)
mtDNA	Mitochondrial DNA
OPW	Office of Public Works
OTU	Operational taxonomic unit
POD	Probability of detection
qPCR	Quantitative polymerase chain reaction
REF	Reference reach
RFID	Radio frequency identification
RHAT	River Hydromorphology Assessment Technique
UAV	Unmanned aerial vehicle
WFD	Water Framework Directive

Appendix 1 Site Locations in the Four Core Study Areas (with Codes) and the Range of Research Activities Undertaken at these Sites

River	Location	Code	Latitude	Longitude	eDNA	Fish	Macroinvertebrates	Macrophytes	Hydromorphology
Duag	Furthermost upstream	DUG-FUS2	52.272792	–8.017168	–	✓	–	✓	–
	Further upstream	DUG-FUS1	52.27279	–8.01581	–	✓	✓	–	–
	Upstream of weir	DUG-US	52.272239	–8.013812	✓	✓	✓	✓	✓
	Downstream of weir	DUG-DS	52.271795	–8.011374	✓	✓	✓	–	✓
Dalligan	Furthermost upstream	DAL-FUS2	52.13415	–7.55844	–	✓	–	–	–
	Reference site	DAL-REF	52.123474	–7.52888	–	–	–	–	✓
	Further upstream	DAL-FUS1	52.1193	–7.52193	–	–	✓	✓	–
	Upstream of weir	DAL-US	52.117983	–7.516682	✓	✓	✓	✓	✓
	Downstream of weir	DAL-DS	52.11798	–7.51668	✓	✓	✓	–	✓
	Further downstream	DAL-FDS1	52.11803	–7.51415	–	–	–	–	–
	Furthermost downstream	DAL-FDS2	52.11732	–7.51161	–	✓	–	–	–
Browns Beck Brook	Furthermost upstream	BBB-FUS2	53.02891	–6.60928	✓	✓	–	–	–
	Further upstream	BBB-FUS1	53.01723	–6.62326	–	–	✓	✓	–
	Reference site	BBB-REF	53.019221	–6.623474	–	–	–	–	✓
	Upstream of ford	BBB-US	53.017432	–6.623359	✓	✓	✓	✓	✓
	Downstream of ford	BBB-DS	53.013556	–6.623913	✓	✓	–	–	✓
	Further downstream	BBB-FDS	53.01261	–6.62523	–	–	✓	–	–
Burren	Furthermost upstream	BUR-FUS2	52.81494	–6.88045	–	✓	–	✓	–
	Further upstream	BUR-FUS1	52.825569	–6.916888	✓	✓	✓[a]	–	–
	Upstream of weir	BUR-US	52.832622	–6.924414	✓	✓	✓	✓	–
	Downstream of weir	BUR-DS	52.83317	–6.92551	✓	✓	✓[b]	–	–

Detailed descriptions of the catchment features, geology and land use are given in Kelly-Quinn *et al.* (2021).

[a]Precise location: 52.65684, –6.7903.

[b]Precise location: 52.659, –6.79104.

DS, downstream; FDS, further downstream; FUS, further upstream; US, upstream.

Appendix 2 Locations of Non-core Study Sites (with Codes) and the Range of Research Activities Undertaken at these Sites

River	Location	Code	Latitude	Longitude	eDNA	Fish	Macroinvertebrates	Macrophytes	Hydromorphology
Delour	Upstream of weir	DEL-US	52.977661	–7.54453	✓	✓	–	–	–
	Downstream of weir	DEL-DS	52.978288	–7.544176	✓	✓	–	–	–
	Further downstream	DEL-FDS	52.979083	–7.542492	✓	✓	–	–	–
Dinin (Crettyyard)	Upstream of bridge apron	DCY-US	52.845066	–7.126535	✓	✓	–	–	–
	Downstream of bridge apron	DCY-DS	52.845474	–7.128047	✓	✓	–	–	–
Dinin (Castlecomer)	Upstream of weir and bridge apron	DCC-US	52.806449	–7.204745	✓	✓	–	–	–
	Downstream of weir and bridge apron	DCC-DS	52.805511	–7.205399	✓	✓	–	–	–
Multeen	Upstream of weir and bridge apron	MUL-US	52.613078	–8.008708	✓	✓	–	–	–
	Downstream of weir and bridge apron and upstream of small rock weir	MUL-DS1	52.61213	–8.0094	✓	✓	–	–	–
	Downstream of previous stretch	MUL-DS2	52.611976	–8.009598	✓	✓	–	–	–
Bann	Further upstream	BAN-FUS	52.7548	–6.34723	–	–	✓	–	–
	Upstream of weir	BAN-US	52.75397	–6.34778	–	–	✓	–	–
	Downstream of weir	BAN-DS	52.75227	–6.3475	–	–	✓	–	–
Clodiagh	Further upstream	CLO-FUS	53.15907	–7151827	–	–	✓	–	–
	Upstream of weir	CLO-US	53.16077	–7.51781	–	–	✓	–	–
	Downstream of weir	CLO-DS	53.16692	–7.51483	–	–	✓	–	–

River	Location	Code	Latitude	Longitude	eDNA	Fish	Macroinvertebrates	Macrophytes	Hydromorphology
Glashaboy	Further upstream	GLS-FUS	51.96233	–8.42047	–	–	✓	–	–
	Upstream of weir	GLS-US	51.96099	–8.41738	✓	–	✓	–	–
	Downstream of weir	GLS-DS	51.95877	–8.41754	–	–	✓	–	–
Breaghmore (lower)	Further upstream	BRL-FUS	53.09168	–7.78691	–	–	✓	–	–
	Upstream of weir	BRL-US	53.09279	–7.78859	–	–	✓	–	✓
	Downstream of weir	BRL-DS	53.09692	–7.78599	–	–	✓	–	–
Breaghmore (upper)	Further upstream	BRU-FUS	53.08229	–7.78323	–	–	✓	–	–
	Upstream of weir	BRU-US	53.08379	–7.78527	–	–	✓	–	✓
	Downstream of weir	BRU-DS	53.08559	–7.78812	–	–	✓	–	–
Parkbeg	Further upstream	PRK-FUS	52.34855	–7.52146	–	–	✓	–	–
	Upstream of weir	PRK-US	52.34971	–7.51956	–	–	✓	–	–
	Downstream of weir	PRK-DS	52.35221	–7.51805	–	–	✓	–	–
Nore	Inistioge	NOREI	52.48731	–7.06374	✓[a]	–	–	–	–
	Thomastown	NORET	52.52453	–7.13789	✓[a]	–	–	–	–
Suir	Kilsheelan	SUIRK	52.36038	–7.58000	✓	–	–	–	–
	Carrick on Suir	SUIRC	52.34503	–7.41585	✓	–	–	–	–
Barrow	St Mullins below weir	BARM-DS	52.50150	–6.94021	✓	–	–	–	–
Barrow St Mullin	At St Mullins below weir	BARM-STM	52.49470	–6.93699	✓	–	–	–	–
Barrow	St Mullins above weir	BARM-US	52.50203	–6.93931	✓	–	–	–	–
Boro	At a weir	BOR-WEIR	52.514083	–6.803722	–	–	–	–	✓

[a]**eDNA investigated only for shad and sea lamprey.**

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;

> Sceitheadh fuíolluisce uirbigh;

> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;

> Foinsí radaíochta ianúcháin;

> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;

> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;

> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;

> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú

> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;

> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;

> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;

> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;

> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;

> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;

> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;

> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;

> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;

> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;

> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;

> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;

> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;

> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;

> Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;

> Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;

> Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;

> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;

> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;

> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Assessment of the Extent and Impact of Barriers on Freshwater Hydromorphology and Connectivity in Ireland (Reconnect)

Authors: Mary Kelly-Quinn, Michael Bruen, Jonathan N. Turner, John O'Sullivan, Jens Carlsson, Craig Bullock, Siobhan Atkinson and Colm M. Casserly

Identifying Pressures

Barriers to freshwater connectivity can impact aquatic fauna and ecological water quality as well as Water Framework Directive (WFD) status, either directly or through their effects on hydrological and morphological elements. It is estimated that there are at least 1.2 million instream barriers in Europe, 68% of which are low-head structures such as weirs, fords and culverts. The Reconnect project contributed to efforts to identify the extent of low-head barriers in Ireland by refining a desk study methodology. The desk study largely eliminated the need to walk entire river catchments to locate barriers, allowing more focused site visits, especially in remote locations, where walkover surveys may be especially difficult and time-consuming. This work was followed by surveys of the nature, extent and characteristics of barriers in 10 catchments. The mapped barriers have been added to the national barriers database held by Inland Fisheries Ireland and to the European Atlas of Barriers. Investigations on fish, macroinvertebrates and sediment dynamics in relation to barriers and their removal have highlighted how their presence may impact these elements through restricted movement or declining habitat quality.

Informing Policy

The WFD requires Member States to achieve at least good ecological and chemical status in all surface water bodies. It recognises that physical habitat is critical in terms of aquatic community structure and functioning, and ecological status rating. The key elements of hydromorphological quality supporting the biological elements include hydrological regime, condition of geomorphic elements (e.g. channel morphology, substrate composition, bank condition and sediment transport) and river connectivity. Barriers to freshwater connectivity impact ecological quality through restricted movement of aquatic organisms, best described for fish. They also impact habitat quality due to the creation of ponded areas behind these structures and altered sediment storage and conveyance. The Reconnect project provided an evidence base on the extent and potential impacts of low-head barriers in Irish rivers that will inform policy relating to their potential removal or modification. The results and recommendations will be particularly important in the 2021–2027 river basin planning cycle and policy development to address alterations to hydromorphological conditions.

Developing Solutions

The Reconnect project produced an evidence base on the extent and potential impact of low-head barriers in Irish rivers that can support identification and justification of appropriate, context-dependent solutions to mitigate their impact. Information on the extent and characteristics of low-head barriers have been provided for 10 river catchments. The project also tested and refined a number of tools that can help prioritisation of barriers for removal or modification to improve connectivity and habitat quality. The species-specific environmental DNA (eDNA) quantitative polymerase chain reaction (qPCR) assays that were developed during the project for Atlantic salmon, white-clawed crayfish and shad (allis and twaite) and previously for sea lamprey and pearl mussel proved to be highly effective in assessing the distribution of these target species. They provide a valuable, non-invasive solution for determining the effect of barriers on the species. Finally, a multi-criteria framework that included seven key criteria (cost, flow regulation, heritage value, recreation benefits, sediment, angling/connectivity and river rewilding) for ranking barriers for removal or modification was developed with stakeholder involvement.

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