Inland Fisheries Ireland & Office of Public Works Climate Resilience Research Project

Annual Report 2021

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Iascach Intíre Éireann
Inland Fisheries Ireland

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Iascach Intíre Éireann
Inland Fisheries Ireland

Contents

Executive summary

- Inland Fisheries Ireland (IFI), as the state agency tasked with providing scientific research and management advice to the Minister for the Environment, Climate Action and Communications, has identified the urgent need to address the current knowledge gap regarding how climate change will impact Ireland's different inland fisheries habitats and the resulting ecological consequences for the species they support.
- IFI and OPW commenced a collaborative programme in late 2020 to investigate the climate vulnerability of arterially drained catchments and to assess the capacity to build climate resilience for fishery conservation within these systems.
- At the core of the project was the set-up and installation of catchment-wide water temperature monitoring networks. It is envisaged that these monitoring networks will reveal the response of each index catchment to climate change and inform a national-scale assessment of the climatic vulnerability of freshwater fish habitat, including arterially drained systems.
- Three index catchments were selected for monitoring to encompass east-west geographic variety – Boyne, Inny and Moy.
- A site selection process was completed for each catchment. From all potential stream temperature monitoring locations, 115 monitoring sites were chosen based on landscape and riverscape covariables, in order to capture sufficient spatial variability within each index catchment (Boyne = 46, Inny=16, Moy=53).
- Water temperature loggers were deployed in all index sites by September 2021.
- Seven dissolved oxygen loggers were installed in key stream sites in the River Inny/Lough Sheelin catchment during July 2021.
- A lake monitoring platform recording water temperature at multiple depths in near-real time was installed in Lough Sheelin in July 2021. A dissolved oxygen sensor was also installed near the lake surface.
- A literature review on the impacts of climate change on freshwater fisheries was completed and accepted for publication as a book chapter in the upcoming new edition of the 'Encyclopedia of Inland Waters'.

Glossary

- **Ectotherm**: A species that depends on environmental sources of heat to reach its preferred body temperature.
- **Primary productivity**: Synthesis of organic carbon from atmospheric or aqueous inorganic carbon, principally by photosynthetic organisms. Primary producers in streams and lakes include phytoplankton ('algae') and macrophytes (plants growing in and around water bodies)
- **Salmonids**: Freshwater spawning fish that generally have evolved to survive in cold or cool water conditions. Species may be anadromous (migrate to sea to feed as adults) or freshwater resident. Includes the Atlantic salmon, trout, Arctic charr and pollan species native to Ireland.
- **Coarse fish**: A colloquial term used to refer to most non-salmonid freshwater fish. Irish coarse fish species includes perch, roach, pike, rudd, bream, dace, chub and tench (but usually not eels or lamprey). Coarse fish species typically have a higher tolerance for warm water conditions compared to salmonids.
- **Spawning**: Reproductive activity in fish species, which encompasses movement or migration to a specific spawning ground, creation of spawning nests ('redds') and aggregration of males and females for breeding.
- **Climate change resilience**: The capacity of social-ecological systems to adapt to and absorb negative impacts associated with a modified climate system while maintaining functioning and sustainability.
- **Lentic**: Still or slow-moving freshwater habitat (lakes, reservoirs, ponds, floodplains)
- **Lotic**: Fast-flowing freshwater habitat (rivers and streams)
- **Riparian zone**: A transitional interface between aquatic and terrestrial environments, characterized by a zone of vegetation bordering water bodies.
- **Surface heat fluxes**: Transfer of heat, momentum and material at the air-water interface of streams, rivers and lakes. Critical component in the heat budget of freshwater ecosystems and a primary determinant of how these systems respond to changes in atmospheric forcing.
- **Eutrophication**: Enrichment of the nutrient status of a water body primarily due to human activities. In freshwater systems eutrophication is generally caused by excessive phosphorus loading. Leads to an increase in phytoplankton productivity.
- **Convective mixing**: Predominantly vertical motions driven by buoyancy forces. When the surface of a stratified water body (e.g. lake) cools, the cold more dense surface water overturns and sinks whilst relatively warmer water rises to replace it, resulting in convective motions and a breakdown of stratification.
- **Stream metabolism**: Integration of key rates of organic matter cycling in stream ecosystems. This includes the total fixation of inorganic carbon to organic carbon by primary producers and the total mineralization of organic carbon to inorganic carbon by consumers. Patterns in metabolism assimilate biological and physical properties of stream ecosystems and provide a powerful metric for ecosystem health assessment and response to environmental change.

1. Background

Climate change poses a significant threat to global freshwater biodiversity (Barbarossa et al. 2021). Long-term atmospheric warming and changes in rainfall patterns modify water temperature, river flow regimes and lake mixing and circulation patterns. In addition, changes in the Earth's climate system may lead to an increase in the frequency, intensity and duration of extreme weather events such as heatwaves, droughts, floods and storms (Bellprat *et al*., 2019).

Freshwater fish (defined as fish species that spend all or part of their life-cycle in freshwater bodies such as lakes or rivers) are *ectotherms*, meaning that their physiology, behaviour and ecology are directly influenced by water temperature. Individual fish species and their sub-populations typically can only survive within a specific temperature range bounded by critical upper and lower limits and will preferentially occupy water within an even narrower temperature range that provides optimal conditions for feeding and growth. For example, the critical thermal maximum (water temperature at which mortality will occur even during a brief exposure time) for brown trout (*Salmo trutta*) juveniles is between 26-30 °C (Elliott and Elliott, 2010) and references therein). However, the upper thermal limit for brown trout feeding is much lower, in the range of 18-20 °C. Thus, fish exposed to warmer water temperatures outside of this optimal range may not achieve optimal growth. Warming water temperature can also have significant impacts on fish by decreasing dissolved oxygen concentrations and exacerbating the negative effects of pollutants. Hydrologic flow acts as a master environmental variable for fish in fluvial settings, where it defines stream habitat suitability, structures ecological communities and controls biogeochemical processes (Maddock, 1999). Lake mixing and circulation also exert an important influence over biogeochemical and ecological processes relevant to fish populations, including spatial variability in thermal habitat, dissolved oxygen concentrations and lake food web dynamics. Thus, given the massive potential for climate change to alter such dynamics in freshwater environments, Inland Fisheries Ireland (IFI) have identified a pressing need to understand specific impacts of climate change on stream and lake habitats and the resulting ecological consequences for Ireland's inland fishery resource.

In addition to the direct effects of changing climatic conditions on inland fishery habitat, climate change impacts may interact with and be compounded by pre-existing anthropogenic stressors. These include poor water quality, introduced non-native species and river modification (see section 1.1). Land use alterations, specifically intense urbanization and agriculturalization, can create excessive nutrient loading which could disrupt natural biogeochemical processes and nutrient cycling (Walsh *et al*., 2005). In combination with reduced flows and warmer water temperatures, this can lead to elevated *primary productivity* and heightened biological respiration, creating low oxygen conditions potentially harmful to fish species. The harmful effects of point source pollution may also be intensified by adverse climate conditions such as warm, dry spells. In water bodies where species have been introduced, cold-adapted species such as Irish *salmonids* may be outcompeted by warm-adapted *coarse fish* species (Jeppesen *et al*., 2012). Whilst the impacts of a warmer climate may be most perceptible during summer months, winter warming may also be harmful for freshwater fish. During winter, thermally sensitive salmonid *spawning* and egg life stages are particularly vulnerable to even slight increases in water temperature and changes in wintertime flow (Dahlke *et al*., 2020).

1.1. Climate change, inland fisheries and arterial drainage

Of the many pre-existing anthropogenic stressors that may interact with climate change to produce compounding impacts on stream fish populations, in an Irish context the effects of river modification warrant specific attention. Owing to the naturally inefficient land drainage and propensity for frequent flooding that occurs across much of Ireland, Arterial Drainage Schemes (ADS) have been carried out sporadically since the mid-18th century and systematically by the Office of Public Works (OPW) since the Arterial Drainage Act, 1945. In 1995 the Act was amended to permit the OPW to implement flood relief schemes for cities, towns and villages. Most of the early drainage works have been focused on low gradient river basins generally lying within the flatter interior of Ireland (Fig. 1.1). The primary purpose of ADS was to improve land drainage for the benefit of agriculture and reduce the extent of overland flooding and predominantly involved "channelisation" - the artificial widening and deepening of river channels. Currently, the OPW undertakes channel maintenance on approximately 11,500 km of Irish channels (Fig. 1.1). More generally, growing concern over future flood risks associated with climate change (e.g. Bevacqua *et al*., 2019) is likely to renew and stimulate further interest in flood relief strategies such as channelisation both nationally and internationally. It is therefore pertinent to identify any detrimental impacts of channelisation on stream thermal and ecological regimes in the face of future climate change and human population growth prior to undertaking further flood mitigation strategies and land use alterations that lead to river modification. A mechanistic understanding of how channelisation and related river re-engineering works mediate climate vulnerability of fishery habitat will ultimately allow adoption of measures that increase *climate change resilience* in arterially drained catchments.

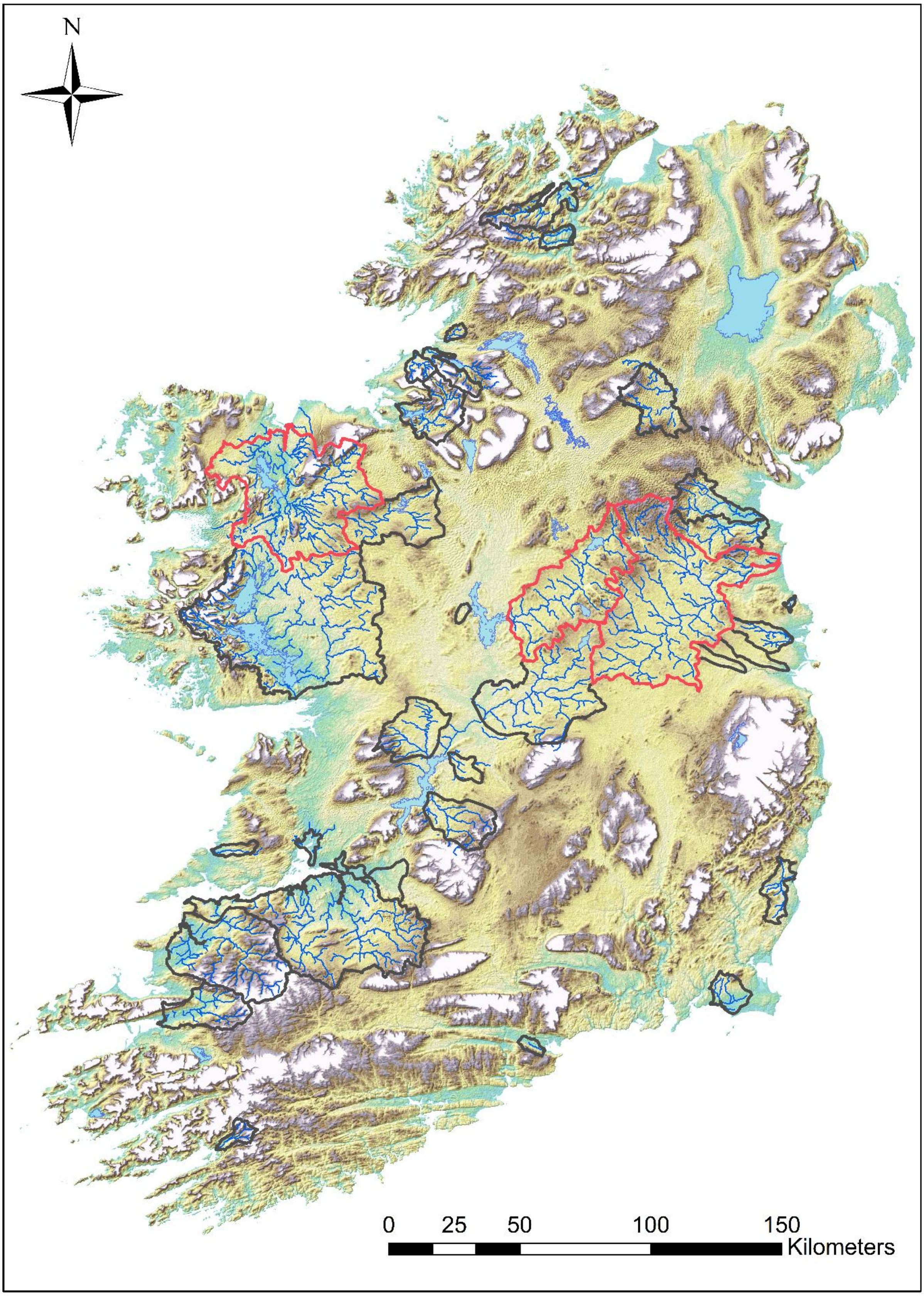

Fig. 1.1 Catchments in Ireland subject to OPW Arterial Drainage Schemes (red outlines denote selected index catchments for OPWCRP)

ADS and river channelisation have significant potential to influence the vulnerability of Irish stream fish to climate change effects. Following channelisation, the natural hydrological response of a catchment to rainfall events is altered. Artificially increasing the cross-sectional area of flow through widening and/or deepening and removing natural channel features improves the conveyance (discharge-carrying) capacity of the channel. Compared to a pre-drainage natural state where overland flooding can serve to smooth discharge peaks by decreasing their height and prolonging the duration of flood hydrographs, the post-drainage channel will typically exhibit much 'peakier' discharge events (i.e. higher, more responsive flood peaks with rapid recessions). A rainfall-runoff hydrograph from the Robe River, Co. Mayo comparing flow response during comparable periods of rainfall pre- and post-drainage of the Corrib-Mask Catchment in western Ireland illustrates this concept (Fig. 1.2). The main notable long-term hydrological outcome of extensive ADS throughout a catchment is to increase mean discharge over time, perhaps best illustrated by the 80-year timeseries recorded at Slane Castle, Co. Meath on the Boyne River (Fig. 1.3). Furthermore, climatic modifications to the rainfall climatology of Ireland could also interact with the effects of ADS, further altering flow regimes. Wetter winters in conjunction with ADS may act together as concurrent drivers to increase median annual discharge within a catchment (e.g. Harrigan *et al*., 2013).

Given that the rationale behind ADS is overland flood mitigation, much of the assessments of hydrological change following channelisation has focused on high discharge events. However, a primary climate-related concern for fish populations is that in the event of a prolonged period of low rainfall, the high conveyance capacity of many drained channels could lead to decreased hydraulic variability and long water residence times during periods with low downstream current velocities. In addition to homogenous flow regimes, heavily channelised river reaches may lose mesohabitat variability entirely, especially at lower flow velocities. Mesohabitats refer to ecologically-relevant stream habitat units, such as glides, riffles and pools. A patchy mosaic of distinct habitat units are generally considered critical for a flourishing and diverse stream fish assemblage, with different species and life-stages showing preference and biological requirement for different mesohabitat types (e.g. Wegscheider et al. 2020). Whilst long-term flow records for the Boyne River at Slane Castle illustrate that flows at the lower end of the streamflow probability distribution (i.e. lowest 5% of daily streamflow values per year) have increased with marginal significance (alpha = 0.1) following extensive arterial drainage works in the 1970s (Fig. 1.4a), discharge records alone do not provide a complete overview of impacts on fish habitat. If discharge (Q) is held relatively constant yet cross-sectional channel area increases (A_s), mean downstream flow velocities ($\bar{u}_x$) will decrease ($Q = \bar{u}_x \; x \; A_s$). Focusing a trend analysis on the 35-year period following completion of extensive arterial drainage works (1986-2021), discharge at Slane Castle reveals no statistically significant trend in the lowest annual streamflow values (and emerging evidence of a (non-significant) negative trend in minimum annual discharge values). This implies that in channels with an artificially increased cross-sectional area and relatively stable (or slightly decreasing) trends in total discharge during low flows, downstream velocities will be slower compared to a natural river course that has shallower and narrower dimensions.

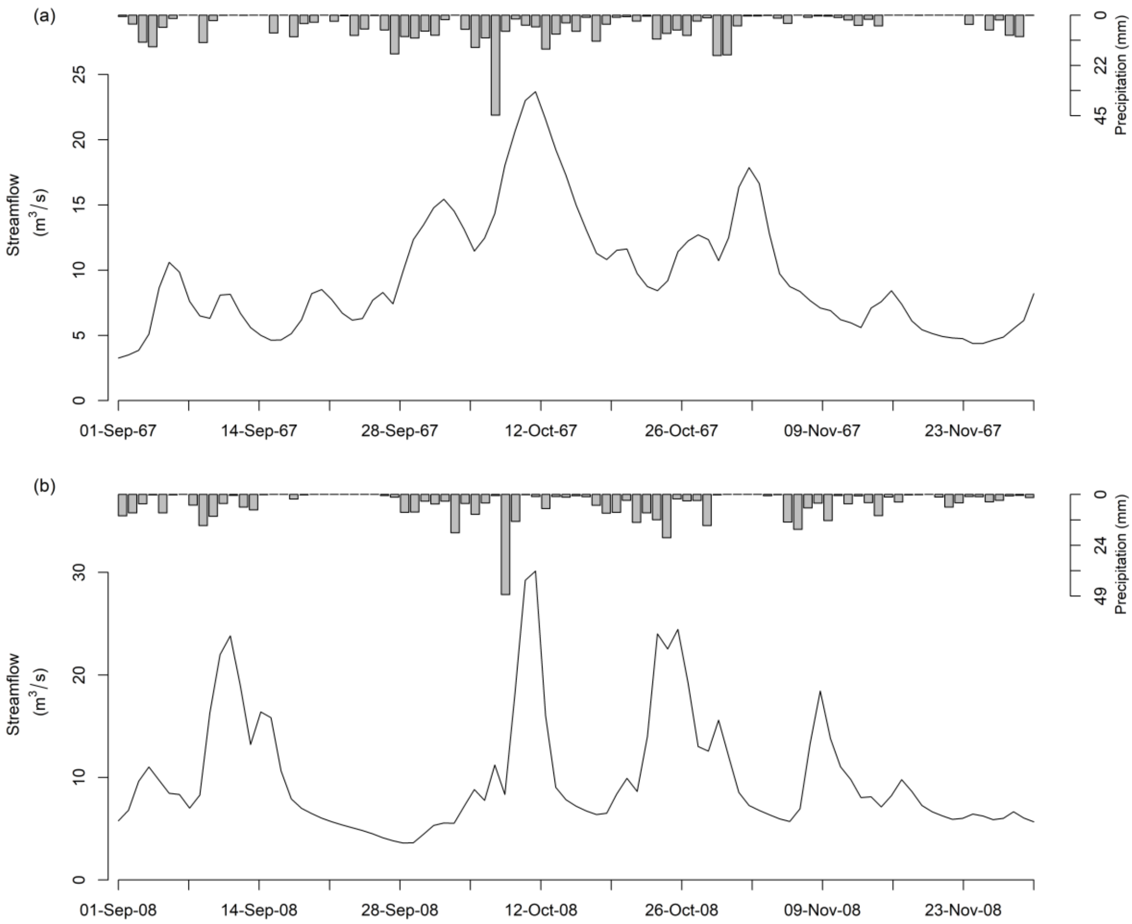

Fig. 1.2 Rainfall-runoff hydrographs for the Robe River, Corrib-Mask catchment. (a) Sept-Nov 1967 pre-ADS and (b) Sept-Nov 2008 post-ADS. ADS in this sub catchment was carried out between 1979-1986. Flow was obtained from the Foxhill OPW gauging station and rainfall from the Milltown rain gauge (approx. 18 km away). Despite very similar rainfall statistics over each 3-month period (total rainfall 443 vs 430 mm; greatest daily fall 72 vs 80 mm; total number of wet days (1.0 mm or more) 60 vs 58 days for 1967 and 2008 respectively) hydrograph response exhibits different behaviour, with higher peaks and more rapid recessions observed in the post-drainage flood response.

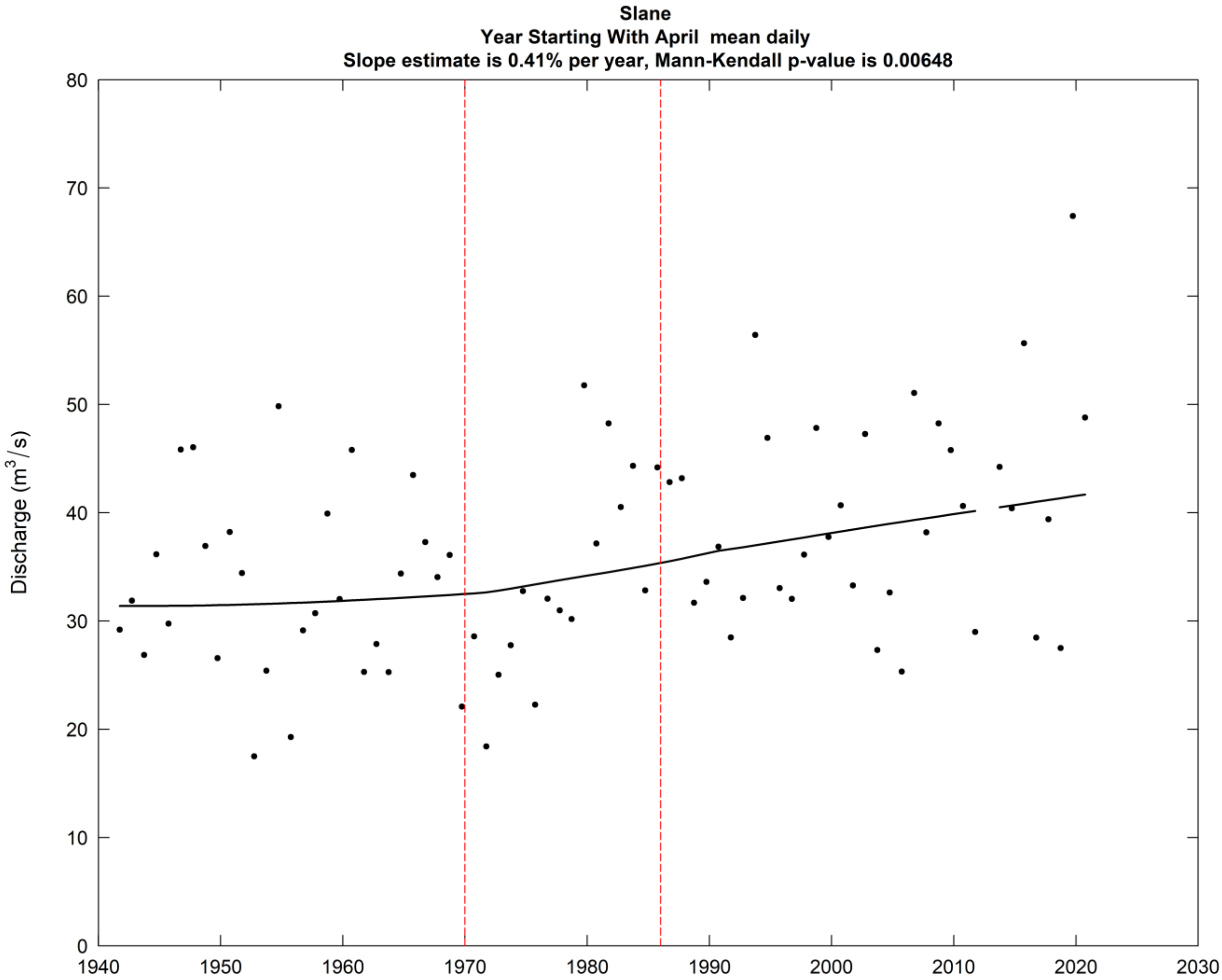

Fig. 1.3. Mean daily annual discharge ($m^3 s^{-1}$) for the River Boyne 1940-2021, recorded at Slane Castle OPW gauging station (53.707 N, -6.562 W). Each dot represents the mean streamflow for all days within each climatic year defined as April 01 – March 31 of the following year. Discharge trend has increased significantly (Mann-Kendall p-value of < 0.05) at a rate of 0.41% per year. Dashed vertical red lines denote the beginning and end of ADS in the Boyne catchment, with the visible increase in mean annual discharge since the completion of the work largely accounting for the positive trend illustrated here.

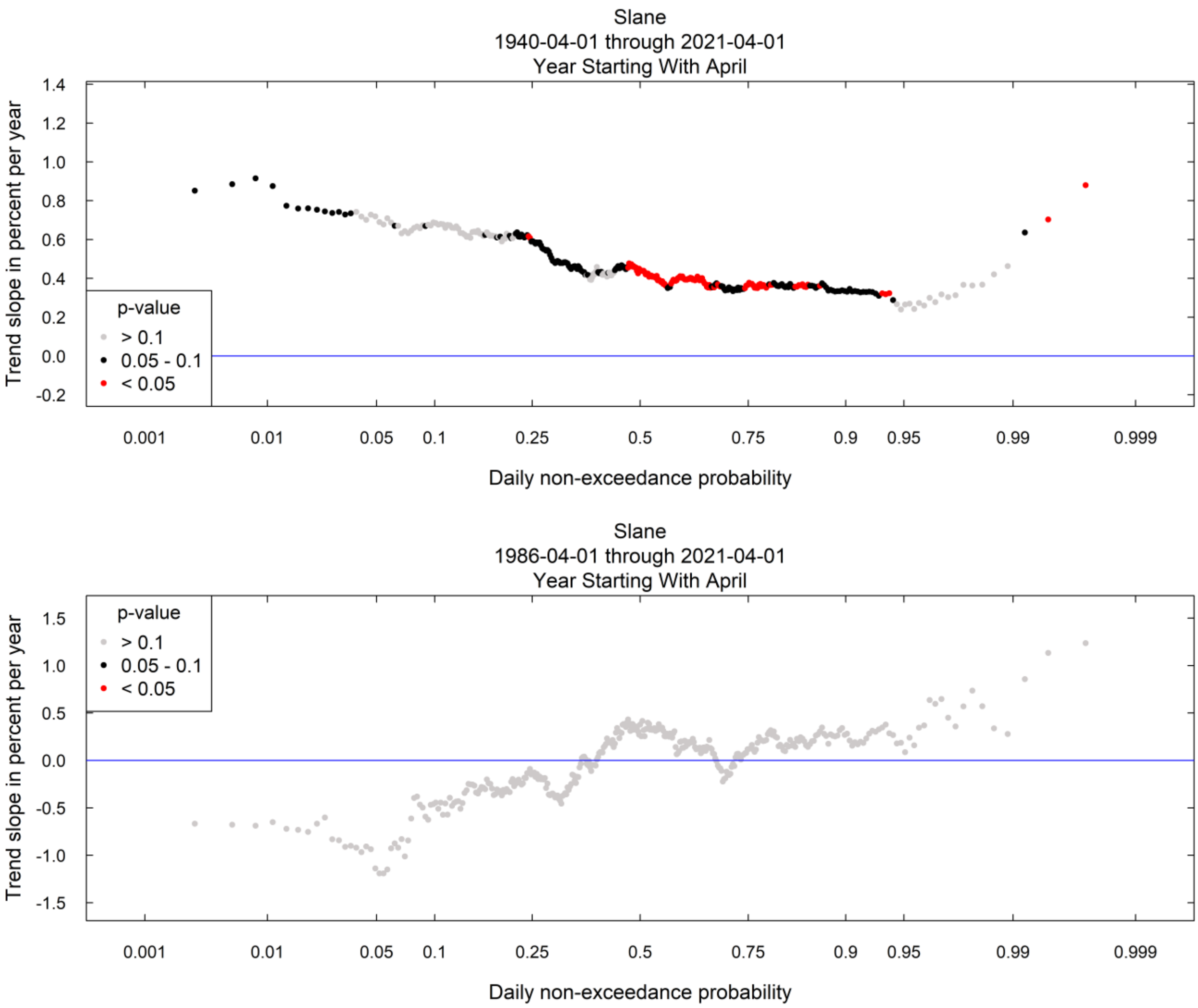

Fig. 1.4. Quantile-Kendall plots (see Hirsch and De Cicco, 2015 for further information) of streamflow trends for the Boyne River using records from the Slane Castle OPW gauging station 1940-2021. Each point represents the trend slope for a given order statistic computed for each year in the timeseries shown in each panel, from minimum daily annual discharge on the far left through all 365 order statistics of the year ending with maximum daily annual discharge on the far right. The upper panel shows the full record, including pre- and post-ADS time periods, and illustrates significant positive trends throughout much of the streamflow probability distribution, particularly for mean and maximum flows (red indicates significance at the 95% confidence level). Marginally positive trends (p-value < 0.1) are seen in flows in the lower 10% probability distribution for the full record. Overall positive flow trends are likely to be mainly a result of ADS. However, by focusing the trend analysis on the time period following ADS only (lower panel) no significant trends are noted for any flow statistic and the trend slopes for lower flows are negative compared to the full 80-year record.

A primary concern of such lower cross-sectional averaged downstream velocities is that the in-stream water residence times may increase at low flows in channelised reaches. Long residence times may create excessively warm conditions especially if periods of low velocities occur during summer months when incoming atmospheric heat terms are largest. Slower moving river water remains exposed longer to incoming *surface heat fluxes* from the atmosphere, particularly shortwave radiation. Slow flowing surface water in deep, wide channels may warm at a rate more comparable to *lentic* water bodies rather than faster flowing *lotic* waters. Further compounding this situation is that most drained channels have undergone significant *riparian zone* modification (e.g. tree removal), which greatly decreases shading effects from solar radiation. Riparian zones and submerged vegetation, which increase flow resistance, are typically trimmed and pruned to improve channel conveyance capacity and trees and shrubs are often removed entirely on one bank to allow machinery access to the channel for drainage maintenance works. Much of the ADS carried out in Ireland are also concentrated within intense agricultural or urban areas, where the economic damage associated with flooding is highest. Therefore the riverscape of many channelised rivers is subject to additional anthropogenic disturbances and modifications, including riparian zone removal for livestock access, embankment construction, bridges, dams and weirs and the diversion and straightening of the natural river course. These modifications in combination with ADS and warming atmospheric conditions have the potential to greatly influence the river energy balance and magnify heat accumulation.

In addition to modulating air-water heat fluxes, modification of flow and slower velocities during low flow events can also exert considerable influence over the suitability of stream fish habitat. Spatially heterogenous flow velocities and turbulence levels (e.g. eddies) increase suitability of stream habitat for different fish populations and can increase species diversity (Guégan *et al*., 1998). Sluggish flow in deep, wide channels combined with the removal of instream structures such as boulders and woody material reduce overall fluvial complexity and may also lead to reductions in fish species diversity and abundance (Fleming et al. 2020).

In Ireland, notable hydrological and limnological changes driven by climatic variability appear to be occurring during winter months (e.g. a positive winter rainfall trend over 1941-2010 (Domonkos *et al.*, 2020) and a warming freshwater temperature trend over 1979-2020 (Kelly *et al.*, 2020). Long-term increases in the intensity of heavy precipitation events (Ryan *et al*., 2021) may lead to an increase in flood intensity and frequency. Given the increased peak flows associated with channelisation and surrounding land drainage practices in some drained channels excessive downstream velocities may occur following heavy rainfall events. Such strong velocities may adversely affect stream dwelling fish by increasing energy expenditure associated with holding position in a current. In such strong turbulent flows, high horizontal shear stress may create inhospitable conditions for some species and specific size and age classes. In channels with simplified fluvial geomorphology and minimal instream features and natural structures, flow refugia are scarce. Turbulent shear stress and velocity magnitude are also negatively correlated with the abundance and species richness of invertebrate communities (Brooks *et al*., 2005), implying that potential prey items for fish may be reduced during large flow events in channelised rivers.

1.2. Objectives

The project objective is to bridge a significant knowledge gap related to the climate vulnerability of Ireland's fish species, specifically in catchments subject to ADS and in channelised river reaches. A large-scale *in-situ* sensor monitoring network focused on key determinants of fish habitat suitability including water temperature, dissolved oxygen and flow was to be initiated in three selected drainage catchments. This monitoring network will capture the spatial and temporal response of fish habitat to climatic variability and thus provide an evidence-base for understanding how future projected climate change pressures will impact Ireland's inland fishery resource. Spatial modelling techniques and additional targeted experimental work will attempt to develop a process-based understanding of how climate may interact with physical stream habitat characteristics typically associated with channelisation, which may have a deleterious impact on the resilience of fish populations and their habitats to climate change. A primary goal is to deliver high quality scientific advice to inform OPW environmental guidance regarding the development of modified drainage maintenance practices that may increase inland fishery resiliency to climate change impacts (e.g. IFI (2020)). The project represents the latest joint research effort between IFI and OPW, who have already collaborated toward understanding the impacts of arterial drainage maintenance on the river habitat and biota, most recently through the Environmental River Enhancement Programme in place since 2008 (e.g. Fleming et al. 2020). The current project will also complement and run in parallel with an internal IFI programme (Climate Change Mitigation Research Programme (CCMRP)) tasked with achieving similar objectives in non-drained, near natural catchments. It is envisaged that both programmes in combination will enable a national-level assessment of the vulnerability of Ireland's inland fisheries to climate change and allow effective targeting of resources to increase the resilience of the most sensitive fish populations.

This report summarises the progress of the OPW Climate Resilience Research Project (OPWCRP) in its inaugural year 2021, provides an overview of the design and setup of the monitoring network and presents preliminary results from targeted experimental work in the Lough Sheelin and the Inny catchment.

2. Methods

2.1. Index catchment selection

The initial catchment selection process was limited to river basins historically subject to OPW ADS and ongoing annual drainage maintenance programmes (Fig. 1). From this subset, catchments were selected to represent a broad spatial and environmental scale across Ireland and therefore included an east coast, midlands and west coast catchment. Final catchment selection also attempted to consolidate additional data sources. This included targeting catchments with considerable historic IFI data (e.g. archival electrofishing sites) and that are currently the focus of ongoing IFI monitoring programmes (e.g. Water Framework Directive Surveillance Monitoring Programme, Environmental River Enhancement Programme). In addition, the density of other valuable environmental data sources from state agencies (e.g. EPA/OPW hydrometric gauges, Met Éireann weather gauges/synoptic stations) were included.

2.2. Stream temperature monitoring site selection

The approach utilised to design the catchment-scale stream temperature monitoring network drew heavily from the methodology of Chang and Psaris (2013), Jackson *et al*. (2016) and Isaak *et al*. (2017). Following initial catchment selection, a GIS-based analysis was performed to determine an efficient stream temperature network coverage within each catchment. This first involved creating a candidate water temperature monitoring point every 500m along the river network. For each point, a suite of landscape and environmental characteristics, deemed to potentially influence spatial and temporal variability in stream thermal response to climate conditions, were computed (Table 1.). An approximate number of water temperature logger sites per chosen catchment was predetermined based on feasible cost and time resources. A Balanced Acceptance Sample (BAS) was then drawn from all potential 500m-spaced monitoring points using the R software provided by McDonald and McDonald (2020). Briefly, the method involves a selection of samples from a discrete population in multi-dimensional space, ensuring even distribution of points over the spatial domain and a spatially balanced sample design (see Robertson *et al*. (2013) for further details on this approach). For each catchment, the total number of potential monitoring points was defined as the discrete population to select from and the number of sample locations to choose was based on the approximate number of temperature monitoring points that were deemed feasible to install.

Once a spatially balanced sample design had been created, the coverage of the monitoring points in terms of their ability to capture the range of landscape and environmental variables was assessed.

This was achieved by creating pairs of XY scatterplots for all values calculated for each monitoring point for each variable in Table 1 plotted against both latitude and longitude. The values of points drawn from the BAS were then highlighted in each of these scatterplots. Adequate coverage of proposed monitoring points was assessed based on visual inspection of each pair of scatterplots and ensuring adequate spread across the range of computed values with reference to spatial location. In instances where the value range of a particular landscape variable did not have sufficient coverage, a redundant sampling point was relocated or a new point was added.

Following this procedure, the proposed monitoring site locations were further refined following practical considerations and consultation with regional IFI staff with local knowledge of proposed sites. Notably, some proposed sites were relocated based on issues relating to access or in accordance with local IFI staff feedback. In other instances, monitoring points were relocated to consolidate pre-existing data sources, particularly hydrometric gauging stations and routine electrofishing survey sites. In all such instances, manual relocation of a temperature monitoring point was validated by updating XY scatterplots to ensure that adequate coverage across landscape values was maintained by the modified monitoring network.

2.3. Stream temperature monitoring methodology

Following site selection, water temperature monitoring was implemented through installation of HOBO Water Temperature Pro v2 Data Loggers (U26-001) (Onset Computer Corporation, MA, USA). Data loggers were initially calibrated over a water temperature range of 0-30 °C in a water bath against a factory calibrated reference temperature logger prior to deployment. Data loggers were set to record stream temperatures at 30-minute intervals prior to deployment.

In-stream monitoring points were chosen to ensure that data loggers were set within the main flow of the channel (avoiding stagnant or recirculating “dead-zones”). To avoid detecting heating by direct solar radiation, loggers were fixed inside white 61 mm diameter square PVC downpipe to act as a solar shield. Two methods were utilised to secure housings to the stream temperature monitoring site (Fig. 2.1). In shallower streams with amenable river substrate, two 45-65 mm lengths of 12-16 mm thick rebar were hammered into the river bed, with the logger housing secured to each rebar length at either end (Fig. 2.1a). In deeper, channelised sites access to the river and securing rebar to the bed was often not possible and typically the soft, silt bottom of dredged ADS channels were not amenable to securing buried rebar. In such sites an alternative method was devised. The logger was again housed inside PVC housing but attached to a custom length of heavy mooring chain weighing approximately 15 kilograms (Fig. 2.1b). The logger housing was attached to a line running from the chain and suspended underwater using a small cork float to ensure the housing was kept from being buried in soft substrate. In addition, small notice signs were erected at active OPW drainage maintenance sites in agreement with OPW personnel as a means of notifying operational crews of a water temperature logger installation point and to avoid damage or removal of loggers.

Table 1: Physical catchment variables used in the stream temperature site selection

Variable	Description	Rationale
Latitude/longitude (coordinates)	Spatial location	Account for regional climatic influences that may vary spatially within a catchment
Strahler stream order (integer scale)	Simplistic stream classification based on number of tributaries upstream	Account for influence of stream size on thermal capacity
Upstream distance (m)	Distance upstream along the stream network from the sea outlet	Account for influence of proximity to a source/sea outlet on heat fluxes along the stream network
Elevation (m)	Mean elevation of the stream reach on which a potential temperature monitoring point lies	Account for decreasing total heat content with elevation
Hill shading (%)	Amount of solar shading provided by the landscape (calculated for both summer and winter, to encompass solar position variation)	Account for variation in direct solar heating caused by topographical shading
Upstream catchment area (m^2)	Total watershed area draining to a point location on a stream	Account for variation in advective heat fluxes and thermal capacity related to discharge magnitude and stream size
Gradient (slope) (%)	Bed gradient along the entire stream reach	Account for instream residence time (time available for heat exchange)
Channel orientation (°)	Stream vector azimuth (angular distance of stream direction from true north-south)	Account for receipt and duration of solar radiation
Forestry percentage (%)	Percentage of forestry land use occurring along the stream reach	Account for direct shading by forestry land cover
Drained channel (y/n)	Arterially drained channel or non-drained channel	Account for influence of channelisation on heat fluxes
Area of upstream lakes (m^2)	Total upstream catchment area comprised of lake surface area	Account for influence of lentic water on downstream temperatures
Majority watershed land use (categorical)	Majority land use category comprising upstream catchment area draining to a point along the stream	Account for influence of land use practices on mediating stream heat fluxes
Bedrock/aquifer (categorical)	Underlying bedrock/aquifer category on which proposed stream site lies	Account for influence of groundwater on stream temperature

2.4. Stream dissolved oxygen monitoring methodology

In addition to the primary focus of monitoring water temperatures, a pilot study was initiated in the Inny catchment, focused on the tributaries draining into and out of Lough Sheelin. The aim was to monitor the response of dissolved oxygen dynamics to hydroclimatic variability and land use practices.

Seven monitoring sites were selected to overlap with stream temperature monitoring sites and to encompass geographic variation across the catchment. Experimental pilot work in this region of the Inny catchment was rationalised based on the focused monitoring of Lough Sheelin and the legacy of environmental issues in this area (section 2.3.). HOBO Dissolved Oxygen Data Loggers (U26-001) (Onset Computer Corporation, MA, USA) with anti-fouling guards were calibrated to 100% saturation using water saturated air and to 0% saturation using sodium sulphite solution. Data loggers were set to record dissolved oxygen and temperature at 10-minute intervals and deployed in a similar manner to water temperature loggers secured to heavy mooring chain (Fig. 2.1c). A larger diameter plastic housing was used for oxygen loggers and caps were secured on either end to minimise fouling. Dissolved oxygen sensors were maintained and downloaded every 6-8 weeks and a concurrent measurement was taken using a multiparameter water quality meter prior to removal in order to assess drift in oxygen readings.

(a) (b) (c)

Fig. 2.1. Methodology for data logger installation. (a) PVC housing with temperature logger inside secured to rebar, which is suitable for most small and natural channels (note steel chain in bottom left running to bank which adds extra security in stream sites susceptible to bed movement, burial by gravel etc); (b) for deeper, soft bottomed channelised sites, temperature logger and housing were secured to a heavy anchor chain and tethered to the bank for retrieval; (c) larger, sensitive dissolved oxygen loggers were housed inside large diameter pipe with caps on each end. Sufficient ventilation holes were drilled and the housing tightly secured to the river bed (lying flat in shallow streams or suspended upright in deeper channelised reaches).

2.5. Lough Sheelin data buoy

To complement the stream monitoring network and to account for the complex role of lakes in the thermal response of freshwater catchments to climate variability, a state-of-the-art data buoy was installed on Lough Sheelin in the Inny catchment in July 2021 (Fig. 6.). Lough Sheelin is a large (18 km^2), shallow (mean depth 3.4 m; max depth 14m) midlands lake (63 m a.s.l.) and is internationally renowned as a wild brown trout fishery. The lake has a history of *eutrophication* issues with high phosphorus loading from the surrounding watershed (Kerins *et al*., 2007). In addition to water quality concerns, non-native zebra mussels and introduced cyprinid fish species inhabit the lake (Millane *et al*., 2012; Connor *et al*., 2017). The lake therefore represents an ideal natural laboratory to study the interactions between climate change and pre-existing environmental stressors on Ireland's inland fish populations. The data buoy consists of a monitoring platform housing an internal datalogger and telemetry system that records and uploads measured data in near real-time. Currently, the system comprises a thermistor array with seven temperature loggers recording water temperature every 10 minutes at depths of 0.5, 2.5, 4.5, 6.5, 8.5, 10.5 and 12.5 metres from the surface. A multiparameter water quality meter and wind anemometer are scheduled for installation in early 2022.

In order to perform a preliminary characterisation of the limnology of Lough Sheelin during 2022, the high-frequency temperature profiles were used to derive key indices related to lake stratification. Stratification can occur during warmer seasons when heat exchange with the atmosphere warms surface water more rapidly relative to deeper parts of the lake water column. Warmer, buoyant surface water overlays cooler, denser water and the lake stratifies into distinct water masses. Vertical stratification can thus exert considerable influence over lake ecology and the habitat and depth preferences of specific fish species. Whether Lough Sheelin was stratified was defined based on a water density difference threshold between the surface and bottom water. Assuming negligible influence of salinity, density was calculated from water temperature and the lake was assumed to be vertically stratified when the surface density differed from bottom density by 0.025 kg m^{-3}.

2.6. Literature review

In addition to the design and implementation of the OPWCRP monitoring network, a literature review was conducted on the potential impacts of climate change on freshwater fisheries, with specific focus on the role of environmental flow modifications and the possible ecological consequences for stream fish ecology.

Fig. 2.2. Data buoy platform installed on Lough Sheelin in July 2021. The data logger housed inside the platform receives temperature data recorded from each thermistor and transmits data via telemetry in near-real time to a live web portal.

3. Results and Discussion

3.1. Installation of catchment-wide monitoring networks

The index ADS catchments selected were the Boyne (Counties Meath, Westmeath, Louth, Cavan, Kildare, Offaly), Inny (Counties Westmeath, Longford, Meath, Cavan) and Moy (Counties Mayo, Sligo, Roscommon) (Fig. 3.1.). These three catchments combined comprise over one third (35%) of the 647,000 acres of area benefitting from ADS throughout Ireland, with the Boyne alone accounting for 18% (119,000 acres) of total national ADS coverage. A total of 115 stream temperature loggers were deployed between April-September 2021 (Boyne n=46; Inny n=16; Moy n=53). Given the focal point of Lough Sheelin in the Inny catchment, as well as considerable difficulty accessing parts of the lower Inny River on foot, it was decided to largely consolidate monitoring efforts to the upper Inny (i.e. Lough Sheelin) sub catchment. Each temperature logger in the network will be retrieved and replaced with a newly calibrated logger in 2022, at which point the first dataset of water temperatures can be analysed.

3.2. Lough Sheelin Data Buoy

Owing to the capacity for near real-time data retrieval from the Lough Sheelin data buoy, the thermal regime of the lake during the latter half of 2021 can now be characterised. Lough Sheelin can be classified as a large shallow polymictic lake which undergoes intermittent periods of water column stratification and mixing during the summer period (Fig. 3.2). Warm, calm periods of weather such as occurred throughout July, late August, September and even as late as mid-October 2021, allowed the development of brief periods of thermal stratification with warm, buoyant surface layers heated by solar radiation overlaying cooler, dense bottom layers. Even short periods of cooler or unsettled weather disrupted stratification with breakdown and homogenisation of thermal gradients apparent. It is likely that the shallow nature and large surface area of Sheelin cannot support a continuous uninterrupted period of summer stratification as *convective mixing* (due to cooling surface temperatures) and wind shear cause full water column overturns in between warm, calm periods of weather. It should however be noted that applying the density difference criteria between surface and bottom water, Sheelin was classified as stratified for 77% of the days between July 01 and September 30.

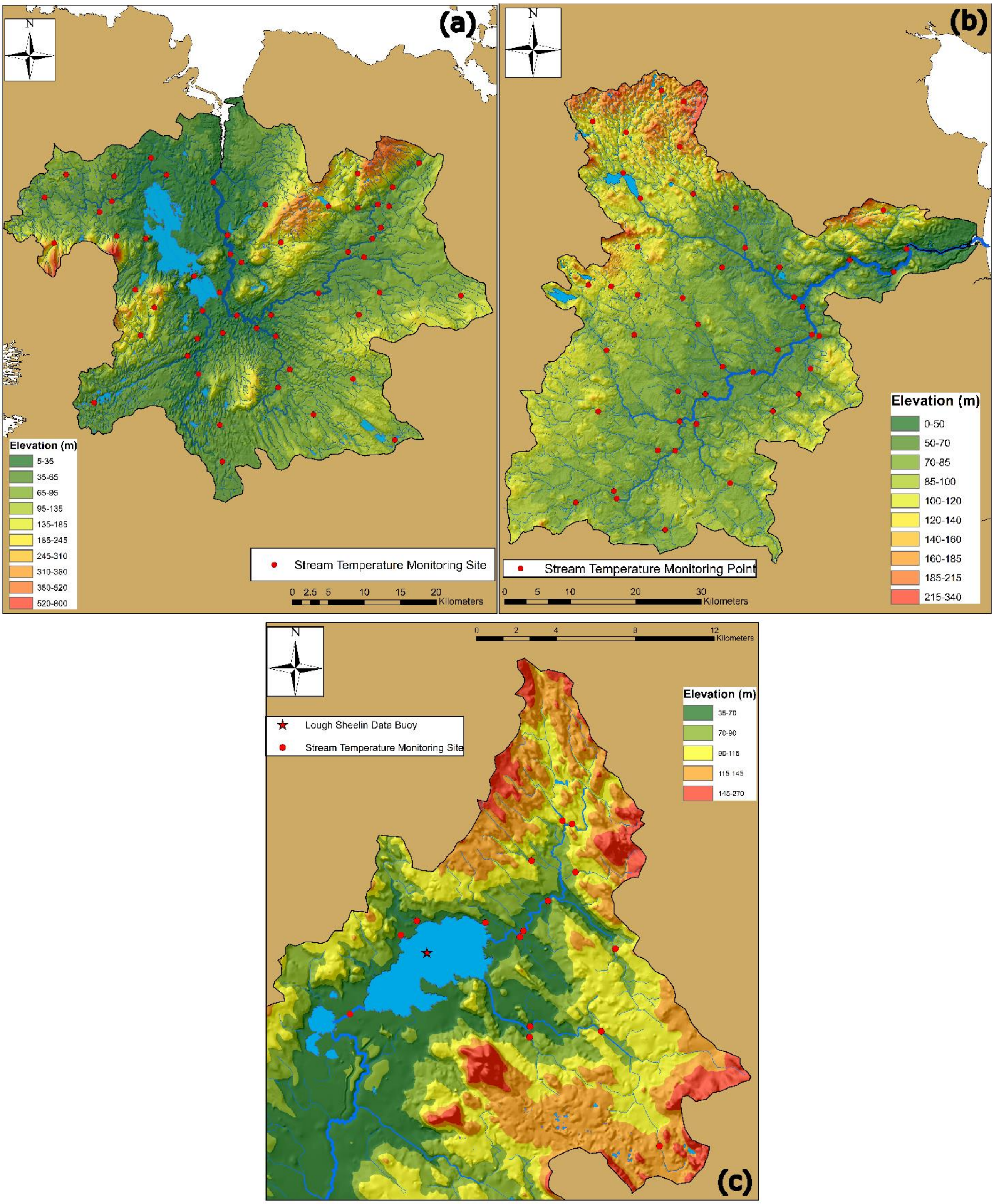

Figure 3.1. Selected index catchments showing water temperature monitoring sites. (a) River Moy catchment, (b) River Boyne catchment and (c) Inny/Lough Sheelin sub catchment.

The heatwave event that occurred between 15th and 25th July 2021 led to anomalously warm conditions throughout Ireland. During the heatwave, the upper 4-5 metres of the water column generally experienced temperatures in excess of 20 °C and the surface temperatures occasionally exceeded 25 °C. Significant thermal stress occurs in salmonids at water temperatures at and above ~20 °C, with temperatures beyond 24.7 °C potentially lethal for brown trout (Elliott and Elliott 2010). This implies that usable lake habitat during such warm events could compress suitable thermal habitat significantly. Using the bathymetry of Lough Sheelin and neglecting horizontal thermal gradients (with the caveat that in a large shallow lake such as Sheelin these are likely to be significant at times), the volume of water with temperatures consistently below 20 °C during the July heatwave event (Fig. 3.3.) was only 7.0 x 10^6 m^3 or ~11.5 % of the total available lake volume. Precisely how the resident lacustrine trout population adapt during such events requires further assessment and whether they could tolerate a more prolonged exposure to such stressful conditions is unknown. An additional factor is whether oxygen concentrations near the lakebed are amenable to fish during stratified conditions, which likely impinges on suitable habitat even further. Developing a mechanistic understanding of the meteorological and limnological drivers of oxythermal lake habitat is an area of planned experimental work for the project during 2022.

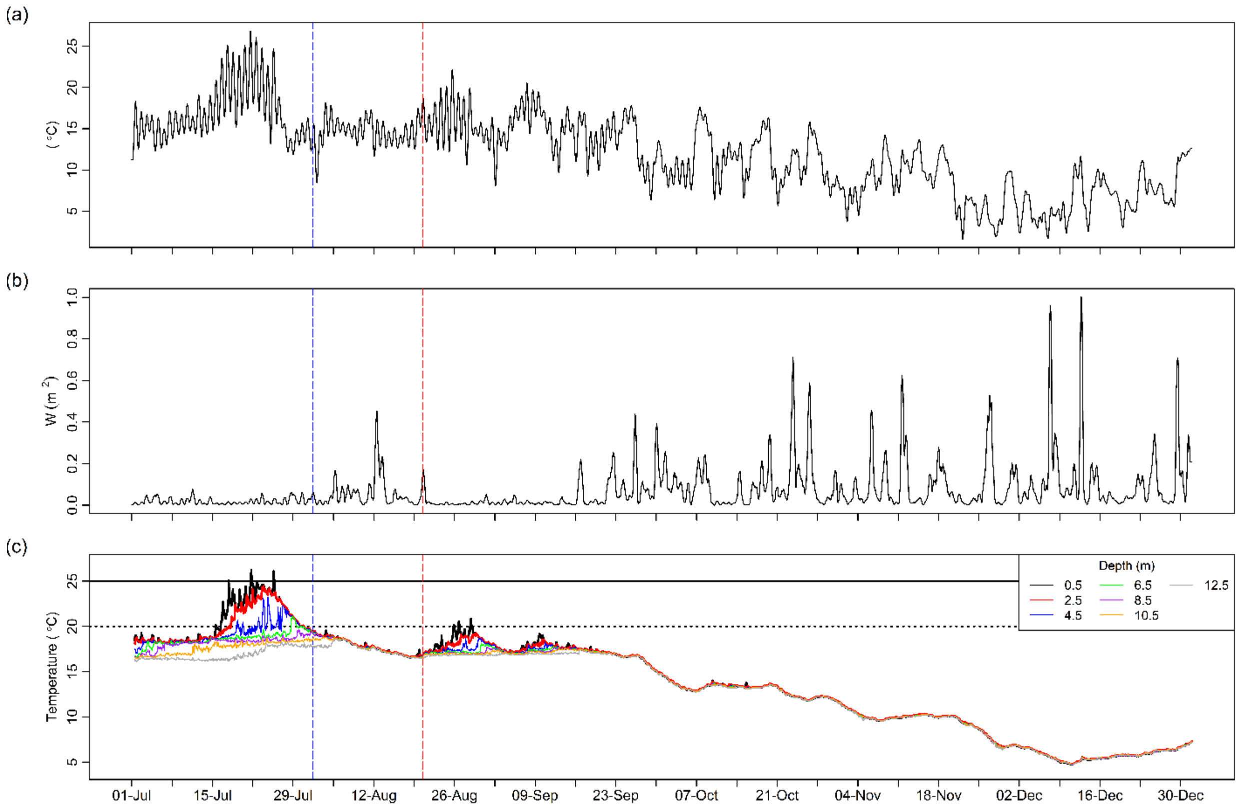

Figure 3.2. Timeseries of (a) air temperature (°C), (b) rate of work per unit area by wind stress (W m^{-2}) and (c) water temperatures (°C) at different depths in Lough Sheelin. (a) and (b) show 12-hour rolling averages of data taken from the Met Éireann synoptic station at Ballyhaise (approx. 24 km from Sheelin). Separation of temperature lines in (c) indicate periods of stratification. Dashed vertical lines highlight an example of stratification breakdown due to cooler surface temperatures and increased wind stress (blue line), followed by a fully mixed period and then a brief re-stratification event (red line) as maximum daily temperatures increased and weak wind events prevailed. Black horizontal lines in (c) denote 20 °C (dashed) and 25 °C.

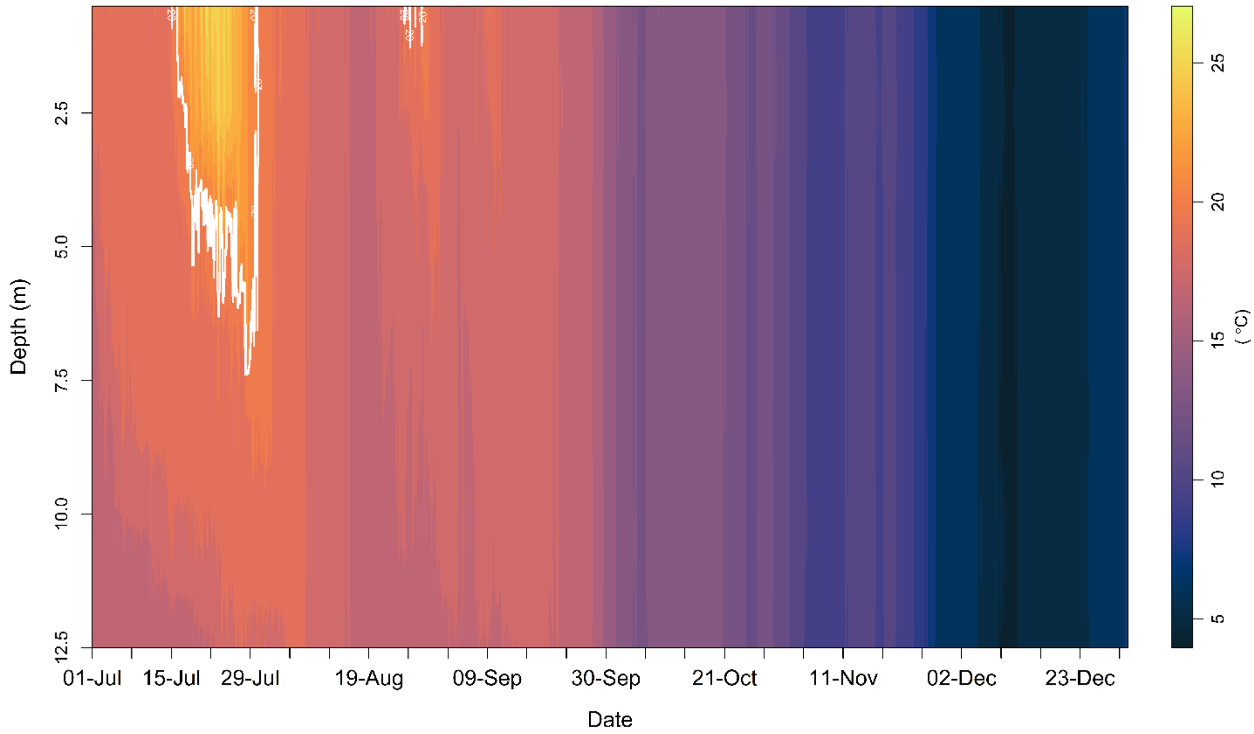

Figure 3.3. Contour lines of water temperature (°C) derived from temperature measurements at different depths in the water column from July 01 until December 31 2021. The white line denotes the 20 °C isotherm, which was prevalent during the heatwave event in July. By assuming that brown trout will generally avoid water temperatures in excess of 20 °C in order to feed, lake trout would mainly have been confined to depths greater than ~6 metres during this period. Interpolating volume from the lake bathymetry, this would have left only ~11% of the total lake volume as thermally suitable trout habitat.

3.3. Lough Sheelin catchment oxythermal dynamics during July heatwave

The installation of dissolved oxygen and water temperature data loggers at index sites as part of a pilot study around the Lough Sheelin sub-catchment revealed temporal dynamics of dissolved oxygen driven by hydro-climatic conditions. In particular, data loggers installed along the Mount Nugent and Upper Inny rivers, two major Lough Sheelin tributaries, during and after the July heatwave event showcased the relative importance of flow and local riverscape features on water temperature and dissolved oxygen (Fig. 3.4).

Notably, periods of low flow and warm, sunny weather stimulate daytime primary productivity by photosynthesising organisms. This increases oxygen concentrations considerably during the day. However, at night-time, aerobic respiration by primary producers and consumers utilises dissolved oxygen, incurring an oxygen debt. This leads to pronounced day-night differences in both temperature (due to solar radiative heating) and oxygen (largely due to biological production and respiration). In eutrophic streams at locations without riparian cover such as the Mount Nugent River monitoring site, *stream metabolism* is heightened during such warm spells as light and nutrients are typically not limited and photosynthetic primary production is enhanced. This can ultimately lead to a risk of night-time hypoxia for stream fish. The combination of high water temperature and low oxygen are extremely stressful to fish such as brown trout. Even dissolved oxygen saturations as low as 70% can negatively affect trout swimming performance when combined with water temperatures higher than 22 ^{o}C (Nudds *et al*,. 2020). Alarmingly, at night-time during the July heatwave in the Mount Nugent stream, dissolved oxygen saturation dropped below 40%, with concurrent night-time water temperatures remaining elevated above 20 °C (Fig. 3.4). In addition daytime water temperatures at this site reached 23.82 °C (Fig. 3.4) encroaching on the incipient lethal temperature for trout of 24.7 °C (Elliott 2000). A rainfall event and subsequent increase in streamflow following the heatwave disrupted the large diel oxygen signal and more favourable oxythermal fish habitat conditions reoccurred. However warm, relatively dry spells again in August and September once again led to enhanced stream metabolism. In contrast to the more degraded Mount Nugent site, the Upper Inny River site has good riparian cover along the reach where oxygen measurements were taken and the underlying geology predominantly comprises karstified aquifer. This resulted in generally higher night-time oxygen concentrations (perhaps owing to shading affects on primary productivity) and maximum water temperatures that remained 5 °C cooler on average during the July heatwave, despite both sites being less than 5 km apart in distance and exposed to the same climatic conditions (Fig. 3.4).

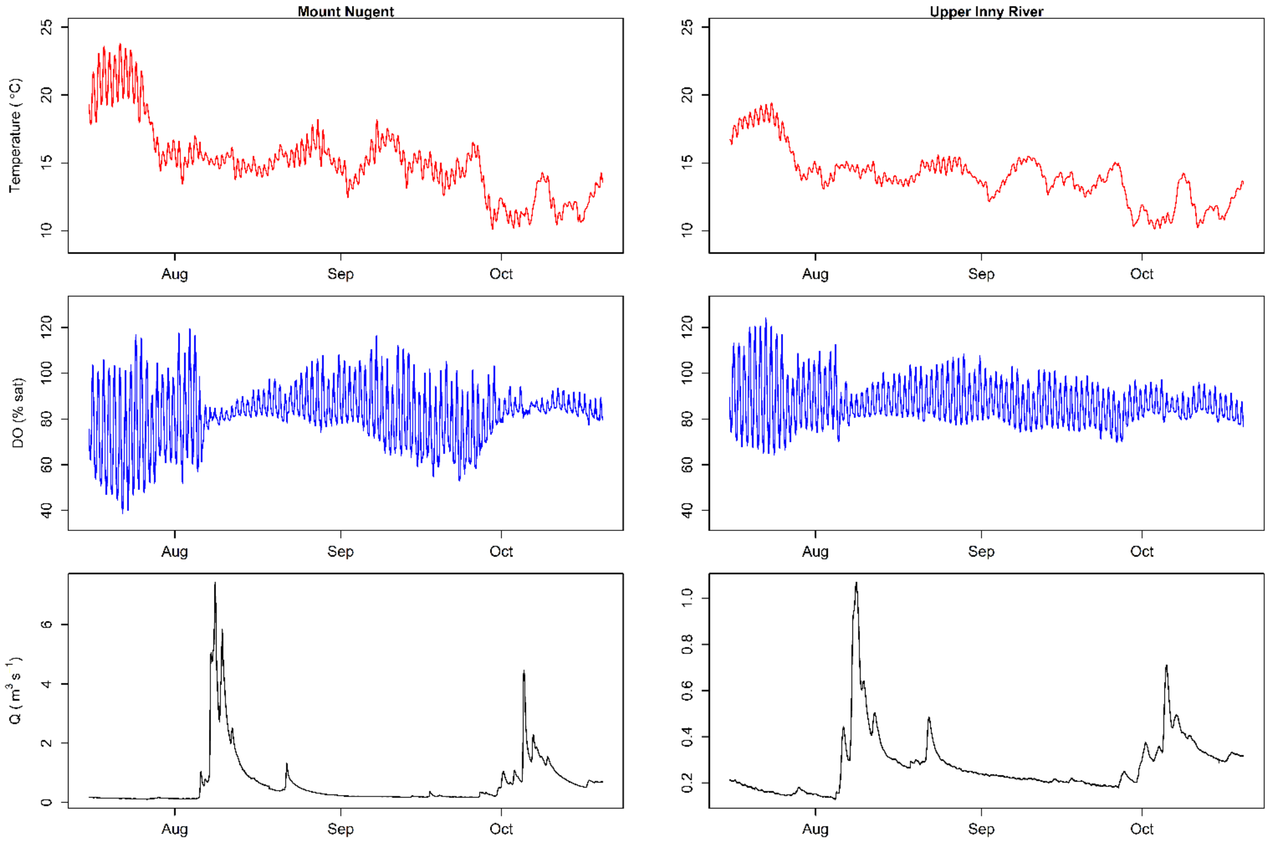

Figure 3.4. Timeseries of (a) water temperature (°C), (b) Dissolved oxygen saturation (%) and (c) stream flow (Q m^3 s^{-1}) at 10-minute intervals between July 16th to October 19th 2021 for the Mount Nugent River (left panels) and the Upper Inny River (right panels). (Note that the y-axis scales are equivalent except for streamflow).

4. Conclusion

The inaugural year of the OPW Climate Resilience Research Project saw three important index catchments instrumented with water temperature monitoring networks as a first step toward developing an understanding of the spatio-temporal thermal response of fish habitat to climate variability in drained catchments. How channelisation, carried out as part of flood relief schemes in these systems, interacts with atmospheric influences on stream thermal regimes will also be assessed following a sufficiently long period of data collection, which will inform modelling techniques such as stream network analysis (e.g. Peterson *et al*., 2013).

A state-of-the-art data monitoring buoy was installed in Lough Sheelin and has already begun to inform on the physical limnology of this important fishery resource and how it potentially may respond to climate change. A substantial increase in the scope of this lake monitoring system aimed at capturing climate effects on lake biogeochemistry (specifically dissolved oxygen dynamics) and lake fish ecology has been developed. This experimental work will be implemented during the 2022 field campaign.

Targeted measurements in the Lough Sheelin catchment, which forms the upper part of the Inny system, have revealed climate influence on disturbed rivers, particularly systems draining intensively agriculturalized watersheds with additional industrial inputs. This experimental work will continue in 2022 and provide a full year of high-frequency measurements of flow, water temperature and dissolved oxygen in critical trout spawning tributaries of Lough Sheelin.

Finally, a substantial review of the literature on climate change and freshwater fisheries was completed and an abridged synthesis formed the basis of a book chapter publication in the upcoming edition of the 'Encyclopedia of Inland Waters' (Kelly *et al*., 2021). This work will provide a reference to inform the future experimental work of the project aimed at assessing pragmatic mitigation strategies toward increasing resilience of Irish freshwater fish habitat in drained catchments and channelised rivers.

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