water

MDPI

Article

Strategic Design and Delivery of Integrated Catchment Restoration Monitoring: Emerging Lessons from a 12-Year Study in the UK

Chris Spray [1,*], Andrew Black [2], David Bradley [3], Chris Bromley [4], Fiona Caithness [4], Jennifer Dodd [5], James Hunt [6], Alan MacDonald [7], Roberto Martinez Romero [4], Tommy McDermott [8], Hamish Moir [9], Lorraine Quinn [4], Helen Reid [4] and Hamish Robertson [10]

1 UNESCO Centre for Water Law, Policy and Science, University of Dundee, Dundee DD1 4HN, UK
2 Geography and Environmental Science, Tower Building, University of Dundee, Dundee DD1 4HN, UK; a.z.black@dundee.ac.uk
3 APEM Ltd., Riverview, Embankment Business Park, Heaton Mersey, Stockport SK4 3GN, UK; d.bradley@apemltd.co.uk
4 Scottish Environment Protection Agency, Strathallan House, Castle Business Park, Stirling FK9 4TZ, UK; chris.bromley@sepa.org.uk (C.B.); fiona.caithness@sepa.org.uk (F.C.); roberto.martinez@sepa.org.uk (R.M.R.); lorraine.quinn@sepa.org.uk (L.Q.); helen.reid@sepa.org.uk (H.R.)
5 School of Applied Sciences, Sighthill Campus, Edinburgh Napier University, Edinburgh EH11 4BN, UK; j.dodd@napier.ac.uk
6 The Tweed Foundation, Drygrange Steading, Roxburghshire, Melrose TD6 9DJ, UK; jhunt@tweedfoundation.org.uk
7 British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK; amm@bgs.ac.uk
8 Trex Ecology, Leader View, 2 Banks Crescent, Crieff PH7 3SR, UK; t.mcdermott@trexecology.co.uk
9 Cbec Eco-Engineering UK Ltd., The Green house, Beechwood Business Park North, Inverness IV2 3BL, UK; h.moir@cbecoeng.co.uk
10 Tweed Forum, Old Melrose Dairy Steading, Melrose TD6 9DF, UK; hamish.robertson@tweedforum.org
* Correspondence: c.j.spray@dundee.ac.uk

check for updates

Citation: Spray, C.; Black, A.; Bradley, D.; Bromley, C.; Caithness, F.; Dodd, J.; Hunt, J.; MacDonald, A.; Martinez Romero, R.; McDermott, T.; et al. Strategic Design and Delivery of Integrated Catchment Restoration Monitoring: Emerging Lessons from a 12-Year Study in the UK. *Water* **2022**, *14*, 2305. https://doi.org/10.3390/w14152305

Academic Editor: Ian Prosser

Received: 31 May 2022
Accepted: 21 July 2022
Published: 25 July 2022

Abstract: Despite growing interest in river and catchment restoration, including a focus on nature-based solutions, assessing effectiveness of restoration programmes continues to prove a challenge. The development of the Eddleston Water project, the Scottish Government's empirical study of the impact of implementing natural flood management measures on flood risk and habitat restoration, provides the opportunity to review restoration monitoring at a strategic and operational level for this long-running catchment restoration programme. The project has implemented an extensive range of restoration measures along the river and across the 69 km^2 catchment. This paper reviews the monitoring strategy and assesses both how the monitoring network developed meets its strategic aims and what subsequent changes were made in monitoring design and implementation. Covering hydrology, hydromorphology and ecology, we explore how all three are integrated to provide a comprehensive assessment of restoration success. Lessons to help inform other river rehabilitation monitoring programmes include the importance of a scoping study and capturing the full range of environmental variables pre-restoration; the limitations of BACI designs; and the need to focus integrated monitoring on a process-based framework and impact cascade, whilst also covering the full trajectory of recovery.

Keywords: river restoration; monitoring; aquatic ecology; natural flood management

1. Introduction

Recent years have seen a growth in interest in and calls for large-scale restoration of habitats, highlighted by the designation of 2021–2030 as the United Nations Decade on Ecosystem Restoration [1] with the aim of supporting and scaling up efforts to prevent, halt and reverse the degradation of ecosystems worldwide and raise awareness of the importance of successful ecosystem restoration. As emphasised by the United Nations, there has never been a more urgent need to revive damaged ecosystems, especially freshwaters (see World Wildlife Fund's Living Planet Report 2020 Deep Dive into Freshwaters [2]), and this has been followed by similar initiatives at national, e.g., the UK's Department for Environment, Food & Rural Affairs' Nature Recovery Network [3], and sub-national levels, including actions by signatories to the UN Convention on Biological Diversity's Edinburgh Declaration on a post-2020 global biodiversity framework [4].

Parallel to this interest in habitat restoration has been a focus on 'nature-based solutions' (and synonyms) as means of tackling the twin crises of biodiversity loss and climate change, including calls by IUCN for global standards [5]. In a UK context, the recent report by the British Ecological Society [6] has clearly demonstrated the value, importance and challenges of delivering nature-based solutions. It highlights that UK freshwater systems hold high biodiversity and that along with improved water resource management, creating habitat resilience to climate change is a high priority, which requires an integrated catchment-wide approach to restoration [7]. They call for more large-scale empirical research in this area and effective monitoring to demonstrate success.

However, assessing the effectiveness of restoration programmes on the ground has proved a challenge. Research reviews from 2005 [8] and since [9,10] have highlighted that little agreement exists on what constitutes a successful river restoration effort. Similarly, the evidence base for success in restoring catchments using natural flood management (NFM) techniques is far from conclusive [11–13]. This is as true for individual elements, such as geomorphic change within river channels [14], as it is in general. It is clear the growing interest in restoration has not been matched by parallel growth in robust, long-term, empirical and peer-reviewed studies of the effects of river [15,16] and catchment NFM [17,18] restoration. Studies that have been undertaken often only focus on individual elements or species, lack an appreciation of integration, are of short duration or, being conducted at a small experimental scale, overly rely on modelling to upscale to a wider landscape impact [11,16].

Appreciation of these challenges in monitoring has led to the production of a number of river restoration manuals [10,17], including the River Restoration Centre's Monitoring Guidance, PRAGMO [19]; the Scottish Environment Protection Agency (SEPA)'s NFM Handbook [20]; the Environment Agency (EA)'s Working With Natural Processes Review [21] and, most recently, the Construction Industry Research and Information Association (CIRIA)'s Natural Flood Management Manual [22]. One of the highlighted deficiencies is of detailed information on the design and scope of what monitoring programmes have actually been put in place, including any endpoint expectations and how these expectations fit to the (often scant) evidence available. Addressing this lack of evidence-based monitoring design and appraisal has been called for ever since Palmer's work [8] in the early 2000s and is as true for catchment NFM studies [11,17] as river restoration studies.

The ecological theory—and very much accepted wisdom—is that if there is an increase in habitat heterogeneity (the number and connectedness of habitats), driven, for example, by in-stream structural modifications such as remeandering, there should be a subsequent increase in biological diversity [23,24]. Empirical evidence for this relationship is very poorly represented in freshwater systems. In their review of published scientific studies investigating the link between river restoration and macroinvertebrate diversity, Palmer et al. [25] found that surprisingly few (two studies of 78) successfully demonstrated a positive relationship. The authors ascribed this lack of a measurable relationship not to the failure of the theory but to the difficulty of measuring the response in the macroinvertebrate community. Published reviews repeatedly call for improved study design and response metrics beyond simple measures of community change, such as richness and diversity [15,26].

Recent studies have similarly questioned the linkages, or to be more precise, the evidence for linkages, between physical interventions in rivers designed to increase structural diversity and/or to decrease flood risk and any consequent increase in habitat diversity and ultimately increased biodiversity. Analysing information from 671 restoration projects in the EU REFORM database, Angelopoulos et al. [27] showed that only 10% reported ecological outcome (9% success, 1% failure), with 5% unclear in their findings. Of the remainder, 9% were not monitored, and for 77%, no information was presented on the outcome. This interrogation of the EU meta-database supports the conclusions expressed elsewhere [19,28–32] that performance of river restoration projects is often not evaluated and therefore little is known about their effectiveness. Whilst there is less concern that many river restoration projects per se are failing, there is increasing awareness of the lack of evidence of success for these [32,33] and catchment NFM studies [17], with the suggestion that for NFM projects, less than 25% give evidence of effectiveness based on observational data [18].

Looking to meet this challenge, the aim of this paper is to describe and analyse what has been monitored during the Scottish Government's long-running empirical study of the effectiveness of restoring a river catchment to reduce flood risk and improve riverine habitats, the Eddleston Water project [34]. The objective is to examine why the selected monitoring methods were chosen and how, where, when and by whom the different strands of monitoring were designed and undertaken—and to do so within the context of whole-catchment restoration through the use of natural flood management measures and improvements to riverine and wetland habitats using nature-based solutions. We look to place our findings in the context of recent reviews and guidelines, notably England et al. [16] in this volume, which have explored success and deficiencies of restoration monitoring programmes.

The Eddleston Water project seeks to help provide the science evidence base for the use of NFM measures as part of an integrated approach to sustainable flood risk management in Scotland, a scientific challenge that was recognised by a Scottish Parliamentary Committee, which concluded that "the government establish further pilot studies to assess the contribution that natural flood management measures can make at the catchment scale" [35]. This primary focus on flood risk reduction and habitat improvement is complemented by a range of other studies addressing the catchment approach of integrated water and land management (see below), demonstrating how multiple strands of monitoring can be combined to create a comprehensive understanding of the success of the project as a whole.

The paper focusses on:

(1) The original monitoring strategy—scientific approach, project management and governance;
(2) How and to what extent the individual elements of the monitoring network combine to meets the strategic aims—monitoring programme design;
(3) Changes made in monitoring and implementation—monitoring programme delivery.

Above all, this paper is about what has been learned about integrated monitoring at a catchment scale and what has proved possible and impossible to undertake. However, this is not a guidance document for river restoration monitoring, nor does it provide a report on analyses or results from the monitoring (these can be found elsewhere). Rather, it looks to investigate the expectations and experiences of individuals who have participated in the Eddleston monitoring programme since its inception and derive lessons learned to help inform ongoing and proposed river rehabilitation programmes.

2. Materials and Methods

2.1. The Eddleston Water Project

The Eddleston Water is a 69 km^2 catchment in the Scottish Borders, the main stem of which flows north–south to join the River Tweed in Peebles. The catchment has undergone extensive changes over the last 500 years, including clearing of native woodland, land drainage, river straightening and afforestation with non-native conifers [36]. Much of the 12 km main river stem above Peebles was straightened and channelised in the early 19th century. In addition to reducing the length of channel and degrading habitats for salmonids and other species, this is expected to have led to an acceleration of surface water runoff response, increasing the risk of inundation of communities in Eddleston and Peebles.

The Eddleston Water project is managed by the Tweed Forum on behalf of the Scottish Government and SEPA, and it was brought about by a partnership including the University of Dundee, the British Geological Survey (BGS), the Scottish Borders Council (SBC) and, most importantly, local landowners and land managers. Working with 21 farmers across the catchment, since 2012, the Tweed Forum and partners have been able to install a wide range of habitat restoration and NFM measures, including:

- 207 hectares of woodland planting, with over 330,000 native trees;
- 116 high-flow log structures, positioned on upper tributary streams;
- 36 flow-attenuation ponds located in the headwaters and 2 larger ones on the lower floodplain;
- 3.0 km of previously straightened river channel remeandered, with adjacent flood banks removed.

The majority of these measures were implemented between 2013 and 2015, but some have occurred since, and more are planned (Figure 1).

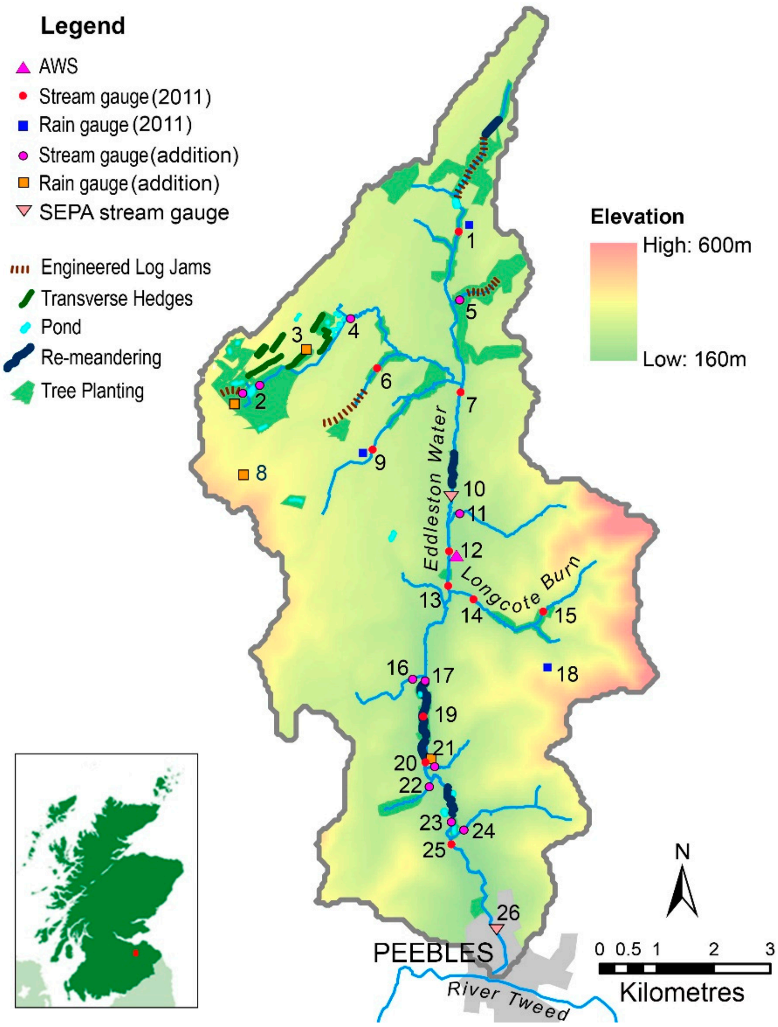

Figure 1. Eddleston catchment map showing location in Scotland (inset), NFM measures and numbered locations of hydrology monitoring instruments: (1) Craigburn, (2) Ruddenleys, (3) Wester Deans, (4) Cowieslinn Burn, (5) Westloch Burn, (6) Middle Burn, (7) Earlyvale, (8) Cloich Forest, (9) Shiplaw Burn, (10) Signal Cottage/Shiphorns/SEPA Shiplaw GS, (11) Harcus Burn, (12) Darnhall, (13) Eddleston Village, (14) School, (15) Middle Longcote, (16) Wormiston Burn, (17) Lake Wood, (18) Burnhead, (19) Cringletie (replaces Milkieston Toll), (20) Nether Kidston, (21) Windylaws Burn, (22) Kidston Burn, (23) Kidston Central, (24) Winkston Burn, (25) Kidston Mill/Rosetta Bridge, (26) SEPA March Street GS.

The Eddleston Water project has three main aims:

1. To reduce the risk of flooding to downstream communities through the utilisation of NFM measures;
2. To improve habitats for wildlife and raise the 'ecological status' of the river (as originally defined in the EU Water Framework Directive (WFD);
3. To work with landowners and farmers to maximise the benefits of the work, whilst sustaining their businesses and farming practices.

In seeking to deliver these objectives, the project took an empirical approach from the outset. This was based on detailed data collection, measurement and monitoring, in order to generate robust evidence of the impact, cost and benefits of working with natural processes at a catchment scale [37,38]. The later development of a combined hydraulic–hydrological catchment model [39] has enabled further analyses and testing of scenarios, as well as enhancing transferability of results to other catchments [40].

Developed as part of the project scoping study [37], the monitoring strategy set three aims:

(a) Develop a comprehensive hydrometry network to form the underpinning hydrological dataset for the whole study;
(b) Identify locations for monitoring associated changes in groundwater, fluvial hydrogeomorphology and ecology, with reference to existing and proposed monitoring programmes at both catchment and individual reach scales;
(c) Establish protocols on methodologies, data capture, quality control and data archiving.

2.2. Methods

Information relating to the objectives, proposals and outputs from monitoring was collected by those involved in the study at a workshop in 2020, reviewed and synthesised online and collated by the lead author. Further commentary on governance issues was provided through review by partners in the EU Interreg North Sea Region Building with Nature programme. As well as reviewing the strategy itself, authors focussed on the suite of elements that *a priori* were expected to show a response to river rehabilitation:

- Surface water hydrology;
- Groundwater studies;
- Catchment fluvial audit;
- Channel fluvial geomorphology;
- Fish populations;
- Aquatic macroinvertebrates;
- Aquatic macrophytes.

In order to focus on generic learning from a multidisciplinary approach, rather than present details on the individual monitoring programmes in this paper, full details for each and, where relevant, links to specific method statements and locations are available on the Eddleston Project website at https://tweedforum.org/our-work/projects/the-eddleston-water-project/. Information recorded covers the choice of parameters to be measured, analyses undertaken and indicators derived. Along with strategic project design, this paper specifically focuses only on the detailed monitoring strategy, the parameters monitored and the methodologies used.

3. Results

3.1. The Monitoring Strategy: Scientific Approach, Project Management and Governance

An overview of the project research design is presented in Figure 2, showing the cascade of intervention and response monitoring.

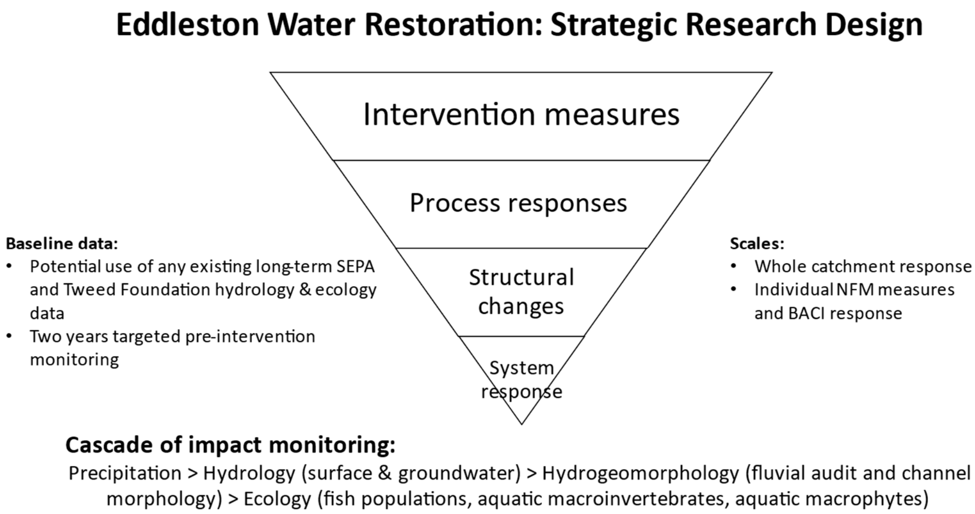

Figure 2. Eddleston Water Strategic Research Design.

The methods used to determine restoration success, criteria chosen and scale of area covered are shown in Figures 3 and 4.

Catchment characteristics	Main restoration interventions
Precipitation – automatic weather stations	Woodland planting – 207 ha
Surface geology – geological mapping	High flow log structures – 116
Land cover – aerial photographic survey	Flood storage ponds – 38
Fluvial audit – catchment fluvial walk over survey	Re-meanders – 3km

Impact measures	Main restoration success criteria – significant changes in:	Scale (Cat /Sub /Site) - BACI
Hydrology - surface water	Flood flows – Flood levels – Flood event frequency – Lag time to peak flood	Catchment - BA Subcatchment - BACI
Hydrology - groundwater	Timing and extent of levels recorded in groundwater wells – hydraulic conductivity – stable isotope ratios in groundwater	Site transects - BA
Fluvial audit	Distribution of meso-scale morphological/habitat units & alluvial bar forms	Catchment - BA
Channel hydromorphology	Geomorphic diversity, & whether the geomorphic units present in restored sites display distinct differences in sediment grain size distribution	Sites (meanders) - BACI
Ecology - river habitats	Occurrence of river habitat types (riffle, run, glide, slack, pool) in restored reaches	Sites (meanders) - BACI
Ecology - fish populations	Semi-quantitative spot sampling results from catchment electro-fishing for salmonids Fully quantitative electro-fishing, with length & weight of salmonids & habitat data	Catchment - BA Sites (meanders) - BACI
Ecology - macroinvertebrates	Biotic indices & metrics of abundance, diversity & taxon richness of macroinvertebrate populations at family level, at catchment and site scales	Catchment - BA Sites (meanders - BACI
Ecology - macrophytes	Biotic indices & metrics derived from standard species-level LEAFPACS surveys of 100m reaches covering two pool-riffle sequences	Catchment – BA Sites (meanders) - BACI

Figure 3. Eddleston Water restoration monitoring success criteria.

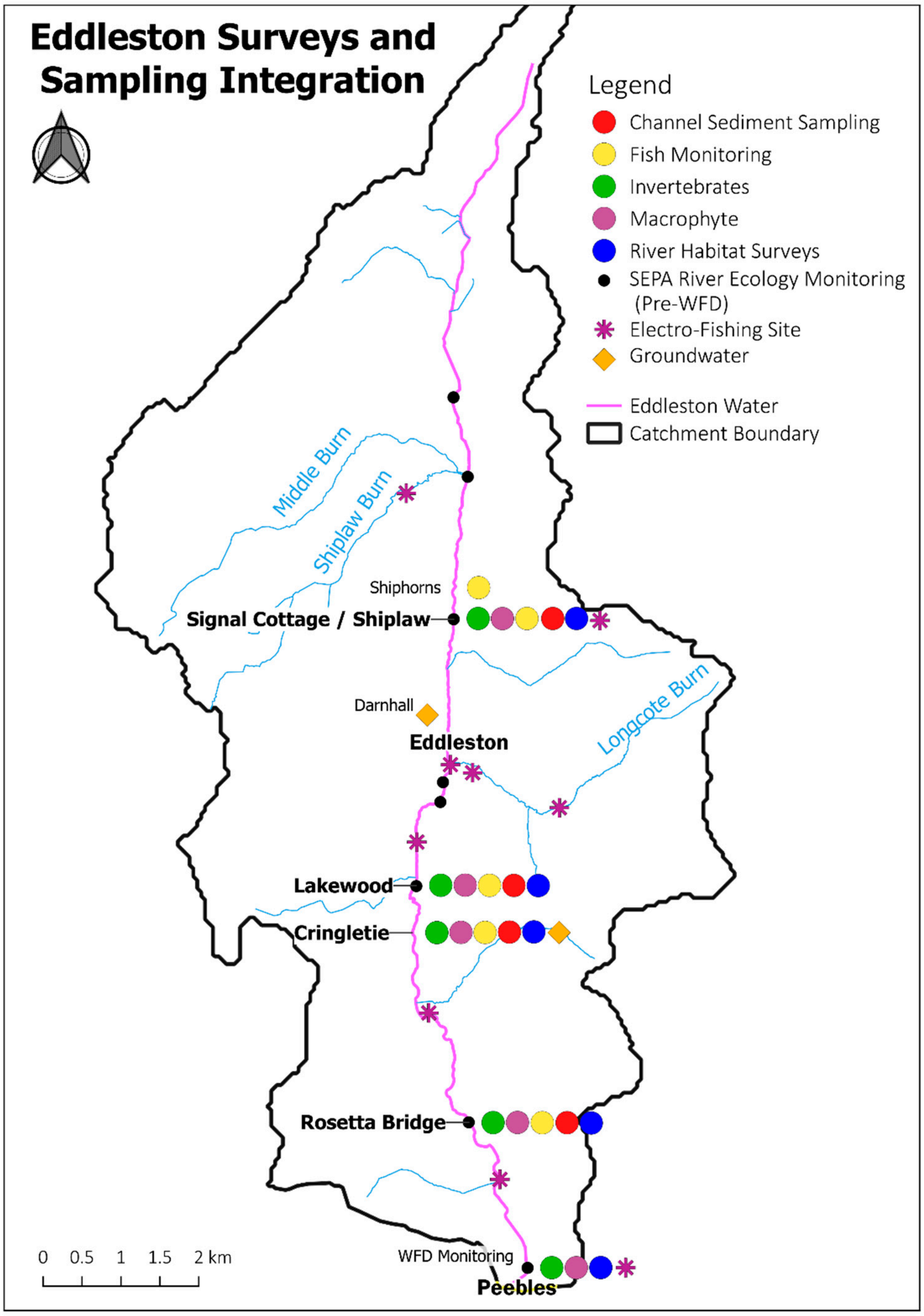

Figure 4. Eddleston Water integration of catchment restoration monitoring networks.

The strategic design took a process-based approach to assessing the impact of catchment restoration measures, including the integration of scientific disciplines and monitoring locations. This impact cascade places a focus on the requirement to establish a robust and dense hydrological network capable of providing a fine-scale spatial platform upon which all other monitoring programmes can be built. This is complemented by the co-location of monitoring sites for different parameters and taking opportunities to compare the response to restoration measures from sub-catchments having contrasting hydrological and environmental characteristics. Figure 4 shows how this was achieved for the main areas of research.

The strategy looked to build on existing programmes, including the potential use of locations where historic measurements of hydrology or ecology could act as extensions of baseline data for assessing change (e.g., SEPA stream gauges, Figure 1; ecology sites,

Figure 4). However, existing data on hydrology proved sparse, and whilst more ecological data were available, they too were of variable relevance to the study's aims and potentially not of fine enough spatial resolution to explore change from restoration measures. Utilising historic data, though, presents challenges that arise from either continuing existing practices or modifying, extending or replacing them. For each parameter, this necessitated assessing the advantages of integrating past data collection procedures and analyses originally designed for other purposes compared to the potential gains to be had from adopting new monitoring methodologies better able to detect change, though with only a two-year pre-intervention monitoring period.

Changes arising from restoration measures needed to be assessed at two scales: the catchment scale, to examine cumulative impact of measures introduced across the landscape, and the individual scale, to assess the effectiveness of different types and designs of measures in different locations within the catchment. To investigate change, either a Before-After-Control-Impact (BACI) research design was utilised or, where this was not feasible, other approaches were identified that could effectively measure change [41].

In terms of governance and approach, the Eddleston monitoring strategy is essentially an investigative one [16], but unlike many research projects, there is no single Project Investigator (PI) with direct oversight or 'control' of research, resources and staff deployment. Instead, decisions as to the overarching direction of research and objectives of monitoring are made largely through consensus at the Project Board led by the Tweed Forum as project managers, along with the Scottish Government and SEPA. Advice is also available from the long-term primary science providers the University of Dundee and the British Geological Survey.

Recognising the need to coordinate monitoring undertaken by established partners, the role of Science Coordinator was established. Reporting to the Project Board through the Tweed Forum, and currently held by the lead author, this role looks to encourage a total ecosystem approach to research, placing it within IUCN's integrated project framework [32], including hydrological, hydromorphological and ecological components [42], while also recognising socio-economic and other contexts. In addition, an important practical challenge is ensuring that all elements of the different monitoring programmes and instrumentation are in place, integrated and operational with reference to the precise timing, location and types of restoration measures planned or anticipated. As the exact timings and locations are dependent on landowner agreements and other external drives, this is a challenge for effective and integrated monitoring.

Being an open research platform funded largely by the Scottish Government, a growing number and diversity of researchers are attracted to the site. The Science Coordinator role therefore also includes appraisal and subsequent facilitation of new projects, such that they can be integrated with current monitoring and seek mutual benefits through coordination of fieldwork and other activities, whilst recognising and protecting the interests of existing researchers and the local community. This last is key, as any accidental incidents or risks of stakeholder fatigue resulting from the actions of any researcher could lead to a landowner withdrawing their involvement and so jeopardising the whole monitoring programme. Liaison with landowners has thus been identified as a specific role for the Tweed Forum as locally trusted experts in participative engagement with catchment stakeholders [43].

One aspect that was not fully recognised at the outset was the need to have an overarching project data management and archiving system and not rely on individual processes. Thus, whilst the hydrology data were quality assured and archived on remote systems within the University of Dundee, and similar rigorous data management backups and protocols were followed by BGS, the cyber-attack that hit all SEPA's systems in December 2020 exposed the project to unforeseen risks. This has included loss of access to SEPA's in-house data systems for well over a year, serious delays in data management and a loss of a small amount of ecological data that had not been copied to co-workers in other institutes.

The challenges with data management highlight the wider issue that without a PI in place, especially if they bring in their own funding, some research can effectively proceed independently of overarching project aims, such that monitoring details are not readily visible or coherent with existing monitoring strategies, and opportunities for integration can potentially be lost. Ultimately, what is monitored depends on the impetus for the restoration scheme but equally that of individual 'one-off' researchers attracted to the platform.

3.2. How the Individual Monitoring Networks Meet the Strategic Aims

3.2.1. Surface Water Fluxes

A surface-water-gauging network was designed and built to provide a comprehensive picture of flow rates from principal tributaries and at intervals along the main stem of the Eddleston Water (Figure 1). The opportunity to extend the pre-intervention baseline monitoring record was taken with the use of historic information from two uncalibrated water level sites run as part of SEPA's flood forecasting network:

- An upstream site (Shiplaw) providing water level and discharge data from 2002, as well as continuation precipitation records from 1990;
- A downstream site at the catchment foot (Peebles) providing water levels from 2009.
- To meet project aims, these were integrated with new elements including:
- An automatic weather station (for determination of a catchment water balance);
- Recording and storage rain gauges at eight additional sites (to characterise spatial variation in precipitation across the catchment);
- 12 additional streamflow-gauging stations (to measure the contributions of tributaries to the main stem and changes in discharge along the main stem downstream), plus 12 additional water level gauges subsequently installed to fill the gaps;
- 11 water gauges located on ponds to specifically monitor their response to runoff.

The resulting gauging network of 24 new stream gauges plus two existing SEPA sites is one of the densest in the UK (one gauge per 2.65 km^2), ensuring not only the generation of high-quality precipitation input and stream flow data but also that sites have been located in the 'right place', not only for hydrological monitoring purposes but also for other monitoring disciplines reliant on this underlying network.

The network is designed to assess the effectiveness of measures at different scales: whole catchment, tributary areas and individual measures. By separating and comparing results from adjacent gauges, it is possible to measure the response to specific measures introduced on the main stem, such as remeandering, as well as interventions in specific sub-catchments. Thus, the provision of 11 monitoring sites along the main stem enables the flood response of the catchment as a whole and of additional sub-catchments to be monitored through assessment of travel times and analyses of the shape of flood hydrographs from the different sites as water passes down the valley (Figure 5).

The scoping study identified sub-catchments that have contrasting topography, soil and land cover, and as these factors might be expected to affect stream-flow responses to rainfall inputs, monitoring sites were therefore located to capture the runoff generated by these different tributaries, enabling source areas to be isolated and their contributions to runoff along the main stem to be assessed. This integrated location pattern of individual gauges allows the assessment of different measures through the creation of 'experimental' and 'control' units to better explore changes in hydrology as well as any associated ecological responses. This is particularly well demonstrated in the work investigating the effectiveness of leaky wood structures and pond construction in the Eddleston headwaters, comparing before and after periods of data between experimental and control sub-catchments [38].

Although identified as a possibility in the scoping study, no detailed project work was undertaken on evapotranspiration, though continuous evapotranspiration data have been calculated from the weather station, and a parallel study was initiated by University of Dundee on infiltration beneath different land use types (see next section).

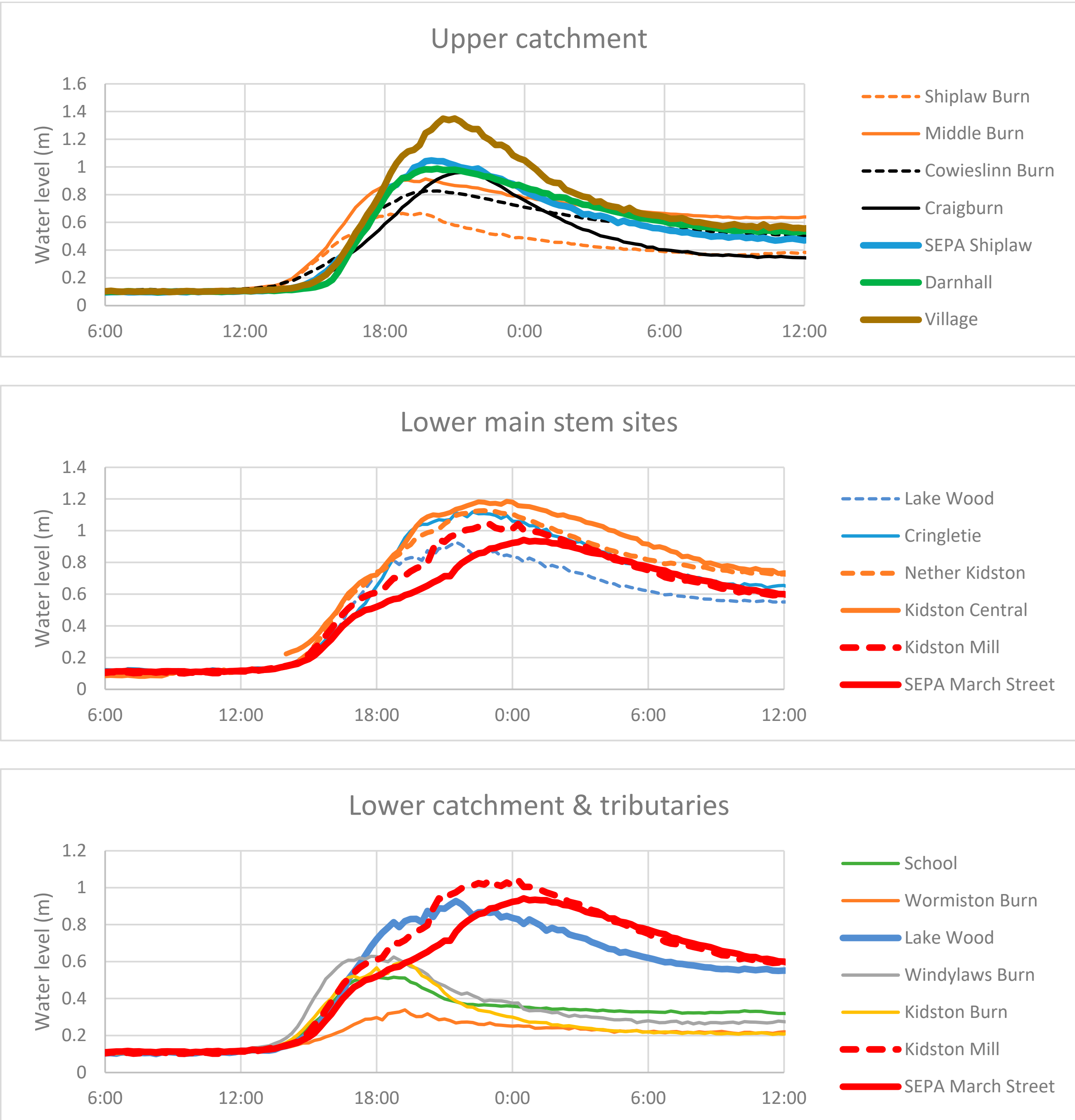

Figure 5. Water level hydrographs for main stem and tributary gauges, 4–5 December 2020 (levels shown relative to a common starting level for display purposes). See also Figure 1 for location of individual gauging stations.

3.2.2. Groundwater Monitoring

In comparison to the spatial network developed for surface water monitoring, the in situ groundwater monitoring was originally focussed on one location—the floodplain and adjacent hillslopes upstream of Eddleston village (Figure 4)—and designed specifically for the project. With no prior data to build on, and as little is known about how groundwater dynamics in floodplains might respond to catchment restoration measures such as remeandering or floodplain storage, the aim was to measure variations in groundwater level and temperature at various depths along a representative lateral transect from the river across the floodplain and up the hillslopes. The general hypothesis was that the introduction of measures would result in an increase in groundwater/surface-water interactions.

To this end, in 2011, BGS installed equipment to enable long-term monitoring of soil moisture, groundwater levels and groundwater temperature. The geology of the site was fully characterised in three dimensions and studied using a variety of techniques, measures and models, including geological re-surveying, trial pitting, geophysical surveying and drilling; the development of a three-dimensional geological model; and the monitoring of ten drilled piezometers of depths from 1–10 m running from the river up the adjacent hillslope [43]. However, due to a change in land owner agreement, no NFM measures were installed on this part of the floodplain, so although new insight was gained on the role of small floodplain aquifers in coupling hillslope flow and rivers [44], the experimental setup could not be used to directly examine the impact of NFM restoration measures.

Meanwhile, additional groundwater monitoring has been able to explore other strategic aims of the project in an integrated manner, highlighting the important influence of land use, soils and surface geology on the effectiveness of catchment restoration measures. In 2016, a new site was introduced to monitor groundwater and soil flow on an adjacent hillslope comparing flow in grassland and beneath a forest strip. Additionally, a third monitoring programme from 2015–2017 looked to quantify groundwater– surface-water interactions through measuring stable isotopes and alkalinity across all the Eddleston sub-catchments. These have quantified the impact of potential restoration measures such as plantation planting on storm flows [45] and the influence of transverse planting on hillslopes [46]. Additionally, in a related study, the impact of land cover, superficial geology and soil types on permeability was examined in woodlands of different ages and under grassland, with the differences between results in different land covers used to infer areas of runoff generation and areas with increased capacity for rainfall infiltration [47].

3.2.3. Ecological Monitoring

Ecological monitoring sought to take advantage of past work by building on existing high-quality data collected by SEPA to fulfil the statutory requirements for reporting on ecological status of the Eddleston Water and on site condition monitoring by Scottish Natural Heritage (SNH) for assessment of condition of notified features of the EU Special Area of Conservation (SAC). Results would thus be directly comparable with other sites and provide the opportunity to understand ecological changes over a much longer time period. At the catchment level, therefore, SEPA continued aquatic macroinvertebrate and macrophyte monitoring at the same single downstream location used for WFD monitoring purposes in Peebles (Figure 4), using their standard methodologies for sampling and allied habitat recording. No WFD monitoring data are presented for fish by SEPA prior to 2013, but the Tweed Foundation undertook fish monitoring for many years, including spot sampling every three years for salmonid fry at sites along the Eddleston Water, and this programme also continued.

However, whilst SNH continued their condition monitoring of the Tweed SAC, this did not involve any surveys on the Eddleston, so this was not covered. With the exception of Atlantic salmon (*Salmo salar*), no separate monitoring was undertaken of species designated within the SAC, such as otters (*Lutra lutra)* or lampreys (*Lampetra* and *Petromyzon*), or to monitor non-native invasive species (INNS), water voles (*Arvicola amphibius*) or other species of conservation concern. Even if changes occurred, it would not be possible to link these with the introduction of restoration measures. For assessment of impact of individual measures, integrated ecological and hydromorphological monitoring focussed on the impact of channel reconfiguration, 'remeandering' being one of the most widespread features of river restoration projects. A BACI design was developed centred on the remeandering of two stretches of channel combined with the identification and monitoring of two control stretches, upstream and downstream (Figures 6 and 7). In each case, a 'site' was c. 100 m long, enough to encompass at least two full pool-riffle sequences and the standard LEAFPACS survey reach length for macrophytes.

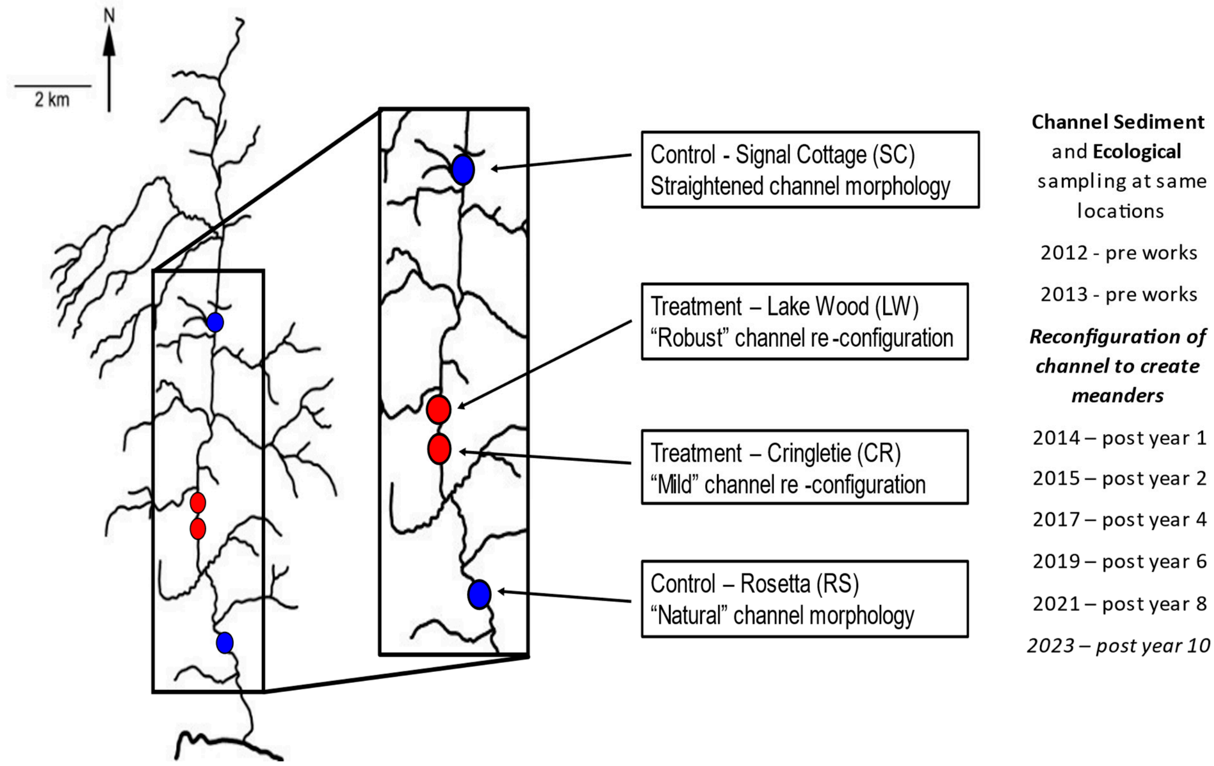

Figure 6. BACI design for Eddleston Water ecology and channel morphology monitoring and trajectory of recovery.

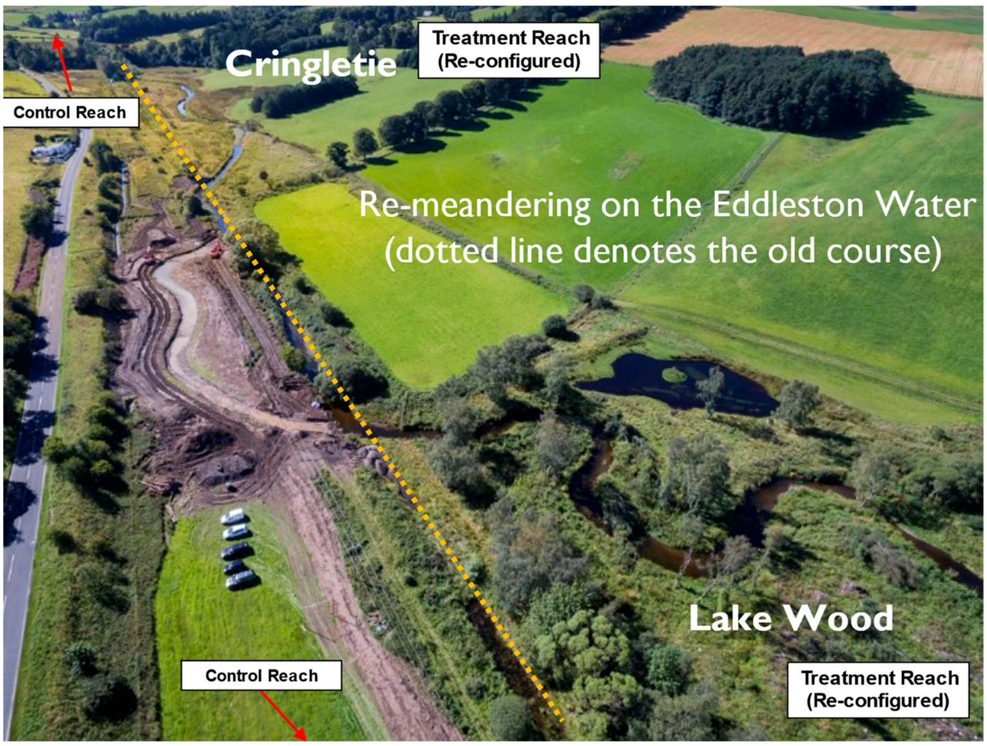

Figure 7. Aerial photograph of Eddleston Water restoration 2018—remeanders at Lake Wood and Cringletie looking south downstream.

The choice of experimental sites was informed by the hydromorphological surveys in the scoping study [37], which identified the reaches most severely impacted by historical alterations to the banksides and channel, and enabled by landowner agreement to the remeandering proposals. The choice of control locations was based on co-location with SEPA's original aquatic macrophyte survey locations and pre-WFD ecology sites (Figure 4): upstream at Signal Cottage and downstream at Rosetta Bridge (Figure 6). Consideration was given to locating controls completely outside the Eddleston catchment, to ensure no influence could occur from the implementation of measures, but it was considered better to choose control sites as far up/downstream as possible within the same catchment, so that each was subject to the same weather patterns and other potential catchment perturbations unrelated to restoration activities.

Consideration was given to novel quantitative sampling methods, for example, Surber sampling for macroinvertebrates, but the use of the existing methodology of three-minute pond-net kick samples in spring (summer) and autumn was preferred to maintain consistency and enable comparison with other studies. To describe the trajectory of recovery, sampling occurred one or two years pre-meandering, each year immediately following and then in alternate years. Laboratory analysis and taxonomic resolution followed standard SEPA protocols, as did production of standard biotic indices and metrics of abundance, diversity and taxon richness, with multivariate analysis used to map changes to macroinvertebrate populations in response to restoration. Monitoring of aquatic macrophytes used the standard LEAFPACS surveys; however, WFD habitat monitoring was seen as too coarse to establish the linkage between morphological changes to the channel and biological response, so this was expanded to include a detailed survey of hydrogeomorphology (see below).

At the outset, the Tweed Foundation advised that on the scale proposed, remeandering was unlikely to offer significant benefits to juvenile salmon (*Salmo salar*) and trout (*Salmo trutta*) populations. Sites previously sampled in the canalised sections identified for remeandering were already productive for both species, with the highest abundance of fry and parr found in shallow fast-flowing riffle and run habitats. A second concern was that even with a much longer-term baseline, it could prove impossible to distinguish between changes in salmonid populations that could be attributed to the impact of remeandering from other factors operating at a catchment or wider scale, especially given the large annual variability seen in fish densities. Fish monitoring was therefore not initially undertaken at remeander locations, a decision later reviewed in response to wider considerations about fish ecology responses to restoration more generally. Additionally, meanwhile, the Tweed Foundation undertook semi-quantitative sampling of salmonid fry by electrofishing at 12 locations in the Longcote and Shiplaw sub-catchments (Figure 4), working with Forest Research to assess impacts on fish from riparian habitat fencing and native tree planting.

3.2.4. Water Quality

Failing water quality has not been an issue for the Eddleston and was not considered a priority for monitoring (unlike other waters impacted by diffuse pollution), so SEPA just continued standard water quality monitoring at their downstream sampling site. To explore if remeandering had any impact, a number of measures of water quality were identified alongside the ecological parameters as potentially being important, including temperature, pH, suspended solids, biological oxygen demand, nitrates and phosphorus, with the plan to collect these at the same time and location as ecological samples.

3.2.5. Sediment Fluxes

Despite identification in the strategy, no monitoring was undertaken of sediment fluxes, though background information was available. In 2014, Environment Systems Ltd. ran the SCIMap programme as part of ecosystem services mapping of the catchment, which focussed on fine sediment and the accumulated erosion risk from different land uses. In 2013, SEPA undertook STREAM modelling [48,49] for Scottish baseline rivers, including the Eddleston, which delineates homogenous reaches and predicts potential erosional and depositional reaches for coarse sediment in the channel using QMED (median annual flood), slopes and channel width.

Independently, a pilot study was begun by BGS, running for two years from 2016, to explore suspended sediment sources, mobilisation, transport and deposition. This involved looking at sediment flux in different sub-catchments and the geochemical signatures of stream sediment samples collected from the main stem and two tributaries, complemented by GIS geomorphometric analysis of the catchment, based on topography, geology and land use. However, like other sediment flux measurements, this has not been integrated into restoration monitoring.

3.2.6. Catchment Fluvial Audit, LiDAR and Channel Fluvial Geomorphology

At the catchment level, the opportunity to build on existing data was explored through consideration of utilising SEPA's Morphological Impact Assessment System (MImAS) to monitor change. However, this is not a monitoring system per se; rather, it assesses the 'morphological status' of the river channel by determining the capacity of a river to absorb morphological impact without degrading ecological performance. As this is achieved through assessing the likely morphological impact resulting from existing or historic activities (such as artificial bank protection or straightening), it could potentially be used 'in reverse' to monitor improvements achieved by river restoration measures that remove such impediments. For the Eddleston, much of this is a legacy from channel realignment 200 years ago, but results from using MImAS have so far proven to be limited in terms of monitoring restoration as such. Channel morphology was initially described as 'Poor status' in 2007, reassessed as 'Moderate' in 2008, downgraded to 'Bad' in 2012 following a detailed field-based resurvey, but then improved to 'Poor', and is now only measured in terms of its potential impact.

More specifically, therefore, as part of the scoping study, a fluvial audit was undertaken in 2009 by cbec Ltd. [37] to provide a detailed baseline condition assessment more specific to project aims. Covering 12 km of the main stem of the river, it provided semi-quantitative data on the physical condition of the river expressed in terms of reach-scale morphology (pool-riffle, plane bed, etc.) and meso-scale geomorphic units (individual pools, riffles, runs, etc.), along with mapped information on depositional sedimentary features (type and extent of alluvial bar forms, substrate texture, etc.); sediment sources (extent and degree of bank erosion, tributary inputs); vegetation features (riparian tree cover, in-channel large wood, macrophytes); and a record of human impacts (hard engineering such as bank protection, weirs, and bridges and softer impacts such as bank poaching by livestock). This highlighted reaches where impacts were most severe and restoration might be targeted for maximum impact.

A second full fluvial audit was undertaken in 2018 in conjunction with a partial re-survey in 2015/2016, the latter to capture the physical condition of sites where restoration had been undertaken and those used for a sample control. Using the same methods and surveyor, this enables change in distribution of such features as meso-scale morphological/habitat units and alluvial bar forms to demonstrate how the channel had adjusted since 2009. All of the fluvial audits were accompanied by a detailed photographic record.

Unknown when the project began, the main stem of the lower part of the Eddleston Water was flown using LiDAR in 2003, at a one-metre resolution. Further investigation revealed that the whole catchment had also been flown in 2016, providing data that cover the period shortly after the introduction of many of the NFM interventions and is of very high resolution (25 ppm^2) and imagery (6cm ground sampling distance). More recently, as part of the Scottish Government's Public Sector phase III programme (2015–2016), other LiDAR data at 0.5 m resolution has also become available, which, together with earlier surveys, can be utilised to monitor change, as well as for developing restoration designs.

Looking to assess restoration at the site level, fluvial geomorphological monitoring was integrated in a BACI design with ecological monitoring at the two remeandered and control reaches. By co-locating sample sites with those for aquatic macroinvertebrates, the aim was to test the causative link between physical interventions to improve channel structure (remeandering) and biotic response to these interventions. Monitoring focussed on whether restored sites had greater geomorphic diversity than unrestored sites and whether the geomorphic units present in the restored sites displayed distinct differences in sediment grain size distribution. Sediment sieving was used to determine the distribution of grain sizes between and within the five main types of habitat in each stretch: slacks, pools, glides, runs and riffles. Sampling was carried out in 2013 prior to restoration and 1, 3, 5 and 7 years following restoration. These techniques combined were used to assess how the grain size changed for each geomorphic unit over time, as a proxy for the condition of these units, and to see whether units become more sedimentologically different or similar over time.

Using the topographical surveys of the four channel sections undertaken by cbec in 2018 as a basis, combined with additional GIS layers and detailed modelling, distinct geomorphologic units were identified and mapped using the Geomorphic Unit Toolbox (http://github.com/Riverscapes/pyGUT accessed on 25 May 2022). This is a more objective approach to assessing changes in diversity of geomorphic units compared to the more qualitative approach employed in most fluvial audits. This provides three-dimensional geometry of the river bed four years after the channel was restored (i.e., remeandered), from which channel diversity can be quantified using the Shannon diversity index [50].

3.2.7. Other Monitoring and Modelling Undertaken in the Eddleston as a Research Platform

As the project developed, the increasing value of the Eddleston as a research platform has attracted many other researchers across different disciplines. Unsurprisingly, most only collect data for a short time period (either one-off or 3 years maximum) and, significantly, are not in themselves part of the Eddleston monitoring programme. However, wherever possible, these have been integrated with ongoing monitoring locations, so that this information could be directly related to existing and future studies, including:

Habitat mapping from air photography—detailed habitat maps of the Eddleston catchment were produced by Environment Systems Ltd. for SBC from air photographs taken in 2009 and as part of Dundee University research from 1946 photographs, which also compared the two periods [51].

Pond ecology—in 2021, a study of the aquatic macroinvertebrates of 18 of the c. 100 ponds across the catchment was undertaken to assess their individual ecology and the contribution of NFM ponds to overall catchment wetland biodiversity [52].

Environmental-DNA—in 2021, comparative studies were undertaken of aquatic invertebrates from river habitats and ponds by NatureMetrics Ltd., SEPA and the Universities of Dundee and Edinburgh Napier to assess differences in habitats and methodologies as determined by environmental DNA and standard sampling methods.

Ecosystem Services—Environment Systems Ltd. produced ecosystem services maps for the Eddleston catchment in 2009 as part of the Scottish Government's Land Use Strategy pilot in the Borders, a selection of which were later compared with ecosystem service maps for the Eddleston in 1946 [51].

Farmers' attitudes to NFM—interviews have been conducted with farmers to assess their attitude to the use of NFM measures, and the latter study assessed the financial impact of implementing different NFM measures on farm businesses [53,54].

Community responses to NFM and flood risk management—detailed interviews in Eddleston and Peebles looked at community knowledge and perception of flood risk, including the use of NFM [55–57].

Cost–benefit analyses of NFM measures—detailed assessments of the flood damages avoided by the use of NFM measures across the Eddleston catchment, alongside the additional economic value of other ecosystem services co-delivered by measures, were produced in 2020 [58,59].

Hydrological and Hydraulic Modelling—as a direct extension to the monitoring programme, a number of hydrological and hydraulic models have been developed for the

Eddleston catchment, including HEC-RMS, MIKE SHE/MIKE II [60] and HEC-RAS 2D [39], and used to extend learning to other locations [40]. In addition, studies have utilised the Eddleston for development and running of other models, such as SHETRAN, to assess the hydrological impact of leaky wood structures [61].

3.3. Changes in Monitoring Design and Implementation

In reviewing changes in monitoring that have occurred since project initiation, key topics were brought together under a series of generic themes. Unless noted, other monitoring has largely continued as agreed.

3.3.1. Changes in Choices of Parameters

The key parameters that underpin the surface water hydrological network remain, with the focus on water level measurements as a surrogate for flow now enhanced by improved calibration through achievement of successful measurements at high and low extremes, alongside the development of catchment-specific hydraulic and hydrological models.

The main change has been increased focus on the role ponds can play in catchment restoration [62,63], with moves to monitor hydrological capacity and biodiversity of newly created wetlands. With 38 ponds providing temporary flood storage, this has necessitated additional monitoring of water levels. Alongside this, interest in flood ponds as contributors to catchment wetland biodiversity has resulted in new surveys of aquatic invertebrates and exploration of environmental DNA as a monitoring tool [52].

A significant change in ecological monitoring was the introduction of fish community surveys in 2017 to assess the impact of the remeandering. Earlier advice highlighted the challenges of using salmonid fish populations to monitor changes in abundance, but a re-evaluation of this concluded that salmonid life stages might be influenced by the specific changes in channel structure introduced by remeandering. In addition, Atlantic salmon are an iconic species, the presence of which is economically, culturally and socially important in the Tweed catchment and as such likely to be perceived as an important indicator of restoration success. Consequently, fish were added to the parameters surveyed (see below) to assess their potential response to remeandering in the context of the other detailed ecological and hydromorphological surveys already underway.

3.3.2. Changes in Methodologies (Including Timing and Frequencies)

Hydrological methodologies and precipitation recording remain the same except for technical process enhancements, such as deploying new electromagnetic current meters to improve accuracy of flow calibrations and increasing use of solar-powered telemetry at rainfall- and headwater-monitoring sites.

Where changes have been made, they reflect challenges and opportunities, including the emergence of new techniques, the need to simplify sampling due to resource and time constraints, and requirements to better align different monitoring elements and/or to improve accuracy of site location and habitat definition. Sediment sampling, for example, which initially involved taking a sample from every habitat unit along the 100 m control and restoration sites was changed to sediment sampling for the most representative of these habitat units, due to the time needed to undertake this and the resources available. A useful addition in subsequent years, though, was detailed habitat mapping, enabling changes in habitats to be assessed prior to sample collection.

For aquatic macroinvertebrates, it quickly became apparent that sampling three times a year was too onerous, particularly due to the time and resources needed for identification. As it was unclear if this was adding significant value, this was reduced to just spring and autumn surveys. The sampling methodology was also refined so that locations better matched the individual habitat types and more precisely matched those used for the hydromorphological and sediment sampling. Instead of taking three-minute pond-net kick samples over 100 m, 20 x individual samples were split between flow habitats (run, riffle, glide, slack, pool) in proportion to their occurrence within the 100 m section, with three replicates collected from each reach and each sampling occasion. Although not a quantitative methodology, such as Surber sampling, this means samples from each habitat type can be preserved separately on site for subsequent independent analyses.

A move to more quantitative monitoring was included in the changes to fish monitoring begun in 2017, with electrofishing surveys carried out in August from 2017–2019 at three remeandered sites (Cringletie, Lake Wood and Shiphorns) and associated control locations. At each location, approximately 100 m^2 of channel was fished in a triple-run fully quantitative fashion, with habitat data recorded as per the Scottish Fisheries Co-ordination Centre recording protocol, along with length and weight of a sample of Brown trout, chosen because, unlike Atlantic salmon, they were more likely to be resident and less influenced by potential factors external to the local channel. Redd surveys were undertaken covering all areas adjacent to sampling locations in late November/early December.

The adoption of novel techniques has included the trial use of environmental DNA in 2021 as a means to survey macroinvertebrates in both pond and river habitats, results from which are in preparation. Finally, the emergence of the Geomorphic Unit Tool (GUT) as a technique for rapid and robust identification of geomorphic units on the river bed [50] enabled us to add this technique to enhance the analytical work on hydromorphology. GUT is able to provide a robust and independent way to consistently identify distinct habitat units in the stream channel that is not influenced by discharge on the day of sampling; a source of uncertainty otherwise present due to lack of consistency in the way ecologists and geomorphologists sometimes classified units. Similarly, we took advantage of the existence of the LiDAR surveys mentioned above, which could be used to assist monitoring change in the river channel environment.

3.3.3. Changes in Locations

From the outset, it was recognised that the gradual inclusion of additional NFM measures as opportunities arise, the emergence of new research questions, the arrival of new research partners and the development of new techniques might require changes in the location and/or development of additional monitoring sites, as indeed has occurred for these reasons.

To better understand the impact of restoration measures on stream flow and the interaction between main stem and tributary flows, a number of new river gauges have been added to the hydrological monitoring network. These include one on the main stem ahead of remeandering and the creation of a new pond downstream in 2020, with six more upstream on tributary channels. Additionally, to support a PhD study on the impact of remeandering on flood attenuation [64], a new water level gauge was installed upstream of the Lake Wood remeander. Similarly, new rain gauges to inform studies on soil moisture were added in Cloich forest (2016) and at Wester Deans (2019).

As noted, interest in the assessment of temporary flood storage in ponds, which had seen intermittent recording of water levels at a small number of sites across the catchment, have been increased. This includes installation of a new river gauge in the upper catchment in 2019 following the construction of large ponds there, as well as telemetry to record water temperature and rainfall. Monitoring focusses on water level as a means of volumetric assessment. More recently, the measurement of hydrological flux for a range of ponds has become the focus of new research and monitoring by BGS and the University of Dundee.

4. Discussion

The Eddleston Water study can be described as 'learning by doing'. Whilst the multiplicity and diversity of project elements, disciplines, institutions and researchers attracted to the Eddleston as a research platform creates its own challenges, the project's very existence relies entirely on the voluntary cooperation of the many landowners across the catchment. As such, ideal research design and implementation focussed on the provision of a robust science-evidence base has to be balanced with practical constraints, many out of control of the project, which ultimately determine what can be done on the ground. In assessing the aims of this paper, the restoration measures that have been implemented and the programmes established to monitor them, some key themes emerge reflecting many of those identified in England et al. [16].

4.1. Scientific Approach, Project Management and Governance

Whilst the governance and management process put in place seeks to direct research focus, coordinate monitoring, and ultimately ensure reporting on implementation, in many instances, monitoring details and publication of outputs remain the choice of the respective researchers involved. Therefore, despite agreement on the development of target outcomes [65], actual implementation of monitoring and successful delivery of quantified expectations [27] remains at risk due to changing staff, funding constraints and alternative priorities within each institution.

With complex, multiple-partner research programmes, this can threaten the integrity of overall monitoring design and, over the length of this study, has led to a number of governance 'failures', notably around missed communication and research delivery. These have included lack of awareness of precise timing and location of restoration measures, missing invertebrate samples, lengthy delays in provision of ecological results, development of parallel hydrological models, inaccessibility of data, differing views on the potential value of specific elements of fish ecology monitoring and loss of outputs as research studies remain unpublished. In addition, the temporary and long-term loss of access to data systems from a cyber-attack on SEPA exposed weaknesses in data management and archiving. Learnings from these challenges such as the necessity for a single project-wide data management protocol can be identified and acted upon. On the other hand, the positive gains from the governance adopted, including resources and support for monitoring and analyses provided 'in-house', especially by SEPA, but also BGS, the University of Dundee and the Tweed Forum as the main partners, are of greater value and stand in contrast to some more directly controlled research contracts. Mutual partner support and trust are seen as key components, leading to widespread sharing of resources, advice and access to networks.

A key challenge to effective monitoring in this study is provided by the reliance on voluntary engagement by each landowner in the implementation of measures on their land and, additionally, the simultaneous availability of relevant funding streams for monitoring, especially long-term. As a consequence, restoration and monitoring of individual reaches has not necessarily proceeded in an ideal scientific or 'logical' manner, spatially or temporally [66], but relied on negotiation and good will. The location and timing of remeandering of the BACI sites, for example, reflects differences in landowner willingness to participate. Similarly, with the groundwater studies, we saw changes from the original monitoring design as a consequence of the relevant landowner deciding not to permit the proposed remeanders at the chosen location. However, whilst as a consequence the original groundwater monitoring set up could not be used to directly examine the impact of NFM measures, a key lesson was that BGS was able to be dynamic and respond, such that excellent results were still obtained of direct relevance to strategic project aims but not for the remeander restoration measures originally targeted [44–46].

Finally, the organic manner in which some elements were developed and came online meant there was little opportunity for site-specific baseline measures, such as the creation of new meanders in 2021 downstream at Nether Kidston. Additionally, the ongoing availability of funds for long-term monitoring provides a challenge, especially for connectivity to wider wetland ecology and for establishing the trajectory of recovery [67], but through the support of the Scottish Government, this long-term approach remains a strong feature of the Eddleston study.

4.2. Monitoring Programme Design

Like other monitoring programmes, the twin challenges of scale and time, as well as the challenge of demonstrating cause and effect, underpin project design and delivery [15,25]. In establishing Eddleston as an empirical study covering 69 km^2, it was recognised this created two overarching challenges: it would take longer to start to deliver results than for an approach based largely on modelling [38], and results at this scale might be 'messy' due to the influence of other environmental drivers operating across such a large catchment outside research design control [15,31]. These factors combined with the need to obtain voluntary participation by individual land managers emphasised the importance of conducting a scoping study, so as to be able to identify factors causing variability within the system and focus efforts on areas and methods most likely to deliver significant results [16].

The scoping study enabled the identification of the most degraded sections of channel, where approaches to individual landowners to allow reconfiguration were therefore targeted. It showed the existence of sub-catchments that have contrasting topography, soil and land cover, which enabled restoration monitoring of individual and potentially paired catchments to be developed. Additionally, discovering previous data sources and their respective monitoring methods enabled consideration of alignment of monitoring locations and methods so as to extend the baseline for assessment of change [8,16]. However, attempts to persuade landowners to participate in specific types of NFM measures on their land were not always successful, even where schemes were developed and costed, so some of the best experimental designs and opportunities for monitoring remain unfulfilled. Even where measures were introduced, the exact location and extent was a compromise between academic ideal and farm business plans; for example, the degree of channel sinuosity accepted in remeandered reaches varied among different farmers (8–46%), which makes monitoring of their impact more complex. However, it also provided an opportunity to assess the morphological effect of a higher/lower-sinuosity meander design and take into account different historical constraints on channel development.

The decision to follow established methods for monitoring catchment restoration, as opposed to developing project-specific methods, and, where relevant, to 're-use' past sample locations has clear benefits, notably in the 'extension' of the flood record taken from SEPA's two gauging sites. Similarly, strict adherence to SEPA's macrophyte survey procedures and macroinvertebrate sampling protocols, along with robust quality assurance for identification and analyses of samples, removed a lot of potential uncertainties. SEPA were also able to deploy the same ecological sampler for all surveys, thus removing sampler variability as another source of uncertainty. However, whilst in theory enabling direct comparison with previous data and other monitoring locations, these advantages remain to be effectively utilised in analyses to date. An added disadvantage was that it ruled out the potential use of alternative methods, such as the use of a Surber sampler in order to obtain better quantitative assessment of aquatic macroinvertebrates, which, for experimental BACI style and focused long-term studies, may be an alternative for consideration.

A key challenge that arises for monitoring empirical studies is the reliance on natural events, the timing and scale of which cannot be predicted [68], and the presence of habitats and communities of target species in the locations and numbers desired for investigation. This also impacts the length of time needed to cover the full range and amplitude of pre-restoration events, as well as to encompass a similar diversity of events to monitor recovery. This can impact quality of data, as, for example, the empirical assessment of the effectiveness of different restoration measures will rely on observing their response to different events but is also influenced by underlying variability in the nature of those events (rainfall intensity, location and duration) and of local antecedent moisture conditions—unknowns difficult to plan for in monitoring timetables. Finally, the trajectory of recovery from change, such as the ecological response to channel realignment, cannot be expected to be linear or immediate and may differ between biota, again requiring monitoring for longer time periods than is available for most studies [69].

To meet these challenges, the project planned 2 years of baseline data collection, rare in itself but not the 3-year ideal recommended [67,70]. However, by chance, this encompassed a period of 7 successive months each exceeding 100 mm of rainfall, a record yet to be surpassed, giving a valuable hydrological baseline against which to assess future change. Describing the trajectory of recovery is an integral part of restoration monitoring, which, for the BACI work on remeandering, has seen the collection of data seven years after implementation. It is clear that recovery of both channel structure [71] and ecology [72] is still in progress, mirroring observations on the trajectory of recovery seen on the river Nith [73].

As noted, monitoring to 'prove' cause and effect has involved paired catchment [38] and BACI designs, but where real reaches are concerned, none are a perfect comparative fit, so unknown variables are introduced. The control reaches lie on the same watercourse as the experimental impact reaches, which raised questions as to independence, not least from the possible influence of measures introduced upstream, but locations in alternative catchments were deemed too different and variable. Additionally, neither meandering control section was as static over time as hoped for; works to a road bridge upstream of one and works to the channel upstream of the other could potentially have impacts on the hydraulic controls downstream. Similarly, whilst the meandering BACI design was intended to cover paired experimental reaches undergoing the same treatment, the extent of remeander in the two impacted sections differs, one being more sinuous (46% added length) than the other (8%). This highlights the importance of the BACI monitoring framework, which still enables analysis of mesohabitat- and reach-level data on macroinvertebrate communities from control and impact sites, thereby demonstrating the ecological response to the physical intervention of remeandering a channel.

A particular challenge for river and wider catchment restoration projects that look to assess the impacts of channel and floodplain reconfiguration is that few recognise the three-dimensional nature of water flow through a catchment, and even fewer are able to include and integrate this within their monitoring strategy. The importance of the interplay of hydrology and community ecology in the hyporheic zone of rivers has been highlighted by a number of studies [74], particularly in times of drought [75], focussing on the potential impacts this can have on invertebrate populations. Whilst the ecological impacts are not covered by the research at Eddleston, groundwater and ongoing soil studies have been integrated with surface water hydrology as far as possible. Such integration is rare, but the linkage can be vital to understanding the success or otherwise of the introduction of restoration measures. Geological structure and groundwater dynamics can have an important function in regulating river flows [43], whilst soil characteristics and land cover can affect hydraulic conductivity and impact local surface runoff and flood management [45–47].

4.3. Monitoring Programme Delivery

Annual monitoring planning meetings are used to promote integration and review delivery, and the hydrological monitoring proceeded much as planned, with the main challenges around monitoring of ecological and hydromorphological responses. Part of this reflected the use of 'in-house' expertise and resources from SEPA, the ultimate deployment of which is influenced by other priorities. Consequently, some found sampling and analyses could not occur or had to be outsourced at extra costs, or provision of results was extremely late. In comparison, the use of consultants delivered monitoring requirements to specification and time but significantly lost out on flexibility, value of in-house contributions and expertise, integration and longevity of engagement, all of which extend beyond bounds of contractual limits. Similarly, whilst some academic partners and students proved effective, their aims and outputs were frequently related to their own research interests and their timings to individual calendars, not necessarily fitting with project aims.

At the catchment level, ecological monitoring following WFD and Habitats Directive methods has delivered little in terms of information on change potentially happening. Despite being part of the Tweed SAC, SNH undertakes no monitoring of the Eddleston, and whilst SEPA maintained their regulatory monitoring, results from the single site at the bottom of the catchment proved too coarse and remote to be of value for this project's aims. Both experiences highlight the need to ensure planned monitoring fits project aims and can deliver results at the right resolution. For fish, spot sampling of salmonids undertaken by the Tweed Foundation continued, but as noted above, they considered river restoration would not necessarily significantly improve salmonid populations. Additionally, as with the continuation of other historic WFD monitoring, detection of change following restoration was not possible at the catchment scale. In addition, a missing element was the potential impact on other native fish species, including eels (*Anguilla anguilla*), sticklebacks (*Gasterosteus aculeatus*) and lampreys, each of which present their own diverse challenges for sampling.

The decision not to include any element of fish monitoring alongside the BACI surveys of hydromorphology and macroinvertebrates could be seen as a missed opportunity to address change at the small in-channel mesohabitat scale, one of the specific interests of the project. In hindsight, the accurate mapping of instream habitat units, as later undertaken through GUT, could provide information on changes in unit area, distribution and quality of fish habitat consequent upon remeandering. A recently developed new method, the National Electrofishing Programme for Scotland [76], based on a randomised sampling design covering all fish habitats (as opposed to a focus on productive habitats as in this and other studies), could be modified as a stratified sampling approach for different habitats to estimate total production and allow direct comparison between remeandered and neighbouring channelised reaches.

For aquatic macroinvertebrates, the reduction from three- to two-season sampling and the modification to collect replicate samples at the much finer individual habitat-type scale was enacted in the first year, therefore allowing comparison to still be made. However, monitoring in this detail is very expensive, and a stand-alone focussed quantitative approach may have been more effective. Were historic data, analyses and indices not available, along with experienced SEPA staff and resources, starting afresh, we would probably take the quantitative route and set up a better design for identifying predicted change.

Using the Geomorphic Unit Tool provides a more objective method of assessing changes in geomorphic units to enhance the analytical work on hydromorphology, particularly for small reaches. However, this is expensive and requires high-resolution topographical data. If the project site is over 500 m and/or has not undergone significant change, a detailed fluvial audit would be a better monitoring technique, as it is quicker to perform and still provides a measurement of geomorphic change within the study area. Meanwhile, we recognise that using SEPA's MImAS tool for measuring change in morphological response has its limitations for restoration monitoring, not least as it was not originally designed as such, and there is ongoing uncertainty around its future utilisation anyhow.

The study is still in progress, which means that important elements such as the analysis of the individual and collective trajectory of river recovery will take time to emerge. We also recognise that this will provide the opportunity to gain added value from the attempts not solely to co-locate sampling but to effectively combine the different sampling approaches and parameters that are embedded in the overall monitoring strategy. The aim ultimately is to be able to present a comprehensive synthesis at a systems level, using the data together in such a way as to be able to demonstrate greater understanding of how physical perturbation of the river environment can and has led to hydromorphological and ultimately biological responses at the habitat unit, reach and catchment scales.

5. Conclusions

A number of lessons have emerged from this review of monitoring, which may help inform ongoing and proposed river rehabilitation programmes. In respect to the main aims of the paper, key amongst these are:

Scientific approach, project management and governance:

- Trying to monitor integrated catchment restoration across disciplines at a landscape scale requires a mature form of governance and flexible project management. On the one hand, this needs to set the direction and bounds of implementation and research monitoring, but on the other, it needs to look to attract, integrate and enable individual areas of assessment and monitoring, recognising their respective challenges and opportunities.

- Good governance and project management need to both encourage new initiatives and cooperative working and also ensure ongoing research is not compromised. In a long-term empirical study where landowner consent to monitoring is entirely voluntary, the consequences of alienating key landowners and co-workers could be disastrous for research continuity.
- A publicly funded research platform such as the Eddleston, which has the advantage of providing an ongoing field-based experiment, is open to increasing pressures from competing external research interests. Integrating these with the strategic aims and ongoing research programmes remains a challenge and may not always be possible.
- With all aspects of catchment restoration ecology ultimately being linked back to hydrological and hydromorphological change, the importance of developing a process-based impact assessment framework, underpinned by a dense and strategically located hydrological monitoring network, is paramount, as is co-locating monitoring of different elements and disciplines.

Monitoring programme design and combining the individual elements of the monitoring network to meet the strategic aims:

- The production of a restoration scoping study to characterise catchment hydrology and identify key habitats can greatly assist in focussing on priority drivers and identifying monitoring methods and sites for assessing change. This is especially relevant where empirical data are used as the basis for restoration monitoring, holding both for natural sub-catchment comparisons and experimental BACI designs where null hypotheses can be tested.
- Working on larger scales temporally and spatially brings challenges in terms of increasing complexity and 'noise' from external drivers of environmental change unrelated to restoration per se. Whilst a BACI design may be able to mitigate these pressures, even control sites may show significant change over time, and their location within the same or different study catchment needs to be assessed. If, as here, controls are located within the same catchment, future studies might wish to extend the monitoring for several 100 m downstream of restoration.
- The importance of capturing the full range of baseline and natural events is well demonstrated, with pre-implementation data needing to cover the full range of habitats, species and events of different size and frequency.
- Co-location of monitoring sites will not be enough on its own to distinguish the responses at a systems level, so there is a need to understand the linkages and process changes at the geomorphological unit scale, at the reach scale and at the whole-systems level of the catchment.
- Assessment of restoration success needs to include the often overlooked three-dimensional nature of water flow through the catchment surface and groundwater environments in terms of both ecological response and hydraulic connectivity.

Monitoring programme delivery and changes made in implementation:

- For effective quality assurance, not only is repeating the use of recognised monitoring methodologies and associated QA important in enabling comparisons and reducing uncertainty, so is using the same surveyors and locations over extended time periods
- However, gains from continuing with historic measures may divert from quantitative and novel approaches that could potentially yield more focussed results. The emergence of new monitoring techniques should be kept under review and, as with new research questions, consideration of their integration into current monitoring should be prioritised.
- Ecological responses to hydromorphological perturbations may still be occurring many years later, which highlights the need for consistent long-term observations to

cover the complete trajectory of change due to restoration measures, something few studies have either time or resources to undertake.

Author Contributions: Conceptualisation, C.S., A.B. and J.D.; Methodology, C.S., A.B., D.B., C.B., F.C., J.D., J.H., A.M., R.M.R., T.M., H.M., L.Q. and H.R. (Helen Reid); Writing—original draft, C.S., A.B., F.C., J.H., A.M., T.M., H.M. and H.R. (Helen Reid); Writing—review and editing, C.S., A.B., D.B., C.B., F.C., J.D., J.H., A.M., R.M.R., T.M., H.M., L.Q., H.R. (Helen Reid) and H.R. (Hamish Robertson); Visualisation, C.S., A.B., J.D. and H.R. (Hamish Robertson). All authors have read and agreed to the published version of the manuscript.

Funding: The Eddleston Water study is funded by the Scottish Government both directly and through relevant funding streams, such as the Scottish Rural Development Programme. For the period 2016–2020, it was the recipient of funding through participation in the EU North Sea Region Interreg programme Building with Nature. In addition, very significant contributions have come from the Scottish Environment Protection Agency itself and from key partners, including the University of Dundee and the British Geological Survey, not least in terms of in-house monitoring, research, analyses and advice. Other organisations, including the Scottish Borders Council, Scottish Natural Heritage (now NatureScot), Forestry and Land Scotland, Forest Research, CEMEX, Scottish Power, Forest Carbon and Woodland Trust, are also important funders and supporters, as indeed are the land owners and land managers themselves.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Further information on specific elements of monitoring is available on the Eddleston Water Project website at: https://tweedforum.org/eddleston-project-database/.

Acknowledgments: The project is managed by the Tweed Forum and directed by a small Project Board chaired by the Scottish Environment Protection Agency and the Scottish Government, with additional contributions from the Scottish Borders Council and the two main science providers, the British Geological Survey and the University of Dundee, all of whom we thank for their comments and contributions. Acknowledgement is gladly given to Luke Comins (Tweed Forum), Debi Garft (Scottish Government), Heather Forbes and Roy Richardson (SEPA) not only for comments on the draft but for their many contributions throughout the life of the study. Alan Werritty (University of Dundee), Richard Williams (Glasgow University), Colin Adams (Glasgow University) and Jo Girvan (Forth Rivers Trust) are also thanked for their contributions to the study and to this monitoring review. The partnership effectively also includes the local farmers and landowners in the Eddleston valley and the communities with whom we work, as they are key to all aspects of project design and delivery. We are pleased to acknowledge their participation and support for the introduction of NFM measures and associated monitoring. The views expressed within this paper are those of the authors and not necessarily those of their organisations.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations Decade on Restoration. Available online: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N19/060/16/PDF/N1906016.pdf?OpenElement (accessed on 25 May 2022).
2. World Wildlife Fund. Bending the Curve of Biodiversity Loss: A Deep Dive into Freshwater. In *Living Planet Report 2020*; Almond, R.E.A., Grooten, M., Petersen, T., Eds.; WWF: Gland, Switzerland. Available online: https://wwfin.awsassets.panda.org/downloads/lpr_2020___deep_dive_into_freshwater.pdf (accessed on 25 May 2022).
3. Department for Environment, Food & Rural Affairs. Nature Recovery Network. Policy paper. April 2022. Available online: https://www.gov.uk/government/publications/nature-recovery-network/nature-recovery-network#:~{}:text=Defra%20and%20Natural%20England%20are,enhancing%20England%27s%20wildlife%2Drich%20places (accessed on 25 May 2022).
4. UN Convention on Biological Diversity & Scottish Government. Edinburgh Declaration on Post-2020 Global Biodiversity Framework. 2021. Available online: https://www.gov.scot/publications/edinburgh-declaration-on-post-2020-biodiversity-framework/pages/current-signatories/ (accessed on 25 May 2022).
5. International Union for the Conservation of Nature. *IUCN Global Standard for Nature-Based Solutions*, 1st ed.; IUCN: Gland, Switzerland, 2020. Available online: https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf (accessed on 25 May 2022).

6. Stafford, R.; Chamberlain, B.; Clavey, L.; Gillingham, P.K.; McKain, S.; Morecroft, M.D.; Morrison-Bell, C.; Watts, O. (Eds.) Nature-Based Solutions for Climate Change in the UK: A Report by the British Ecological Society. BES: London, UK, 2021. Available online: www.britishecologicalsociety.org/nature-based-solutions (accessed on 25 May 2022).
7. Spray, C.J.; Maltby, E.; Clavey, L. Freshwater Systems. Chapter 6. In *Nature-Based Solutions for Climate Change in the UK: A Report by the British Ecological Society*; Stafford, R., Chamberlain, B., Clavey, L., Gillingham, P.K., McKain, S., Morecroft, M.D., Morrison-Bell, C., Watts, O., Eds.; BES: London, UK, 2021; pp. 89–106.
8. Palmer, M.A.; Bernhardt, E.S.; Allan, J.D.; Lake, P.S.; Alexander, G.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.N.; Follstad-Shah, J.; et al. Standards for ecologically successful river restoration. *J. Appl. Ecol.* **2005**, *42*, 208–217. [CrossRef]
9. Beechie, T.J.; Sear, D.A.; Olden, J.D.; Pess, G.R.; Buffington, J.M.; Moir, H.; Roni, P.; Pollock, M.M. Process-based Principles for Restoring River Ecosystems. *BioScience* **2010**, *60*, 209–222. [CrossRef]
10. England, J.; Naura, M.; Mant, J.; Skinner, K. Seeking river restoration appraisal best practice: Supporting wider national and international environmental goals. *Water Environ. J.* **2020**, *34*, 1003–1011. [CrossRef]
11. Dadson, S.; Hall, J.; Murgatroyd, A.; Acreman, M.; Bates, P.; Beven, K.; Wilby, R. A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proc. R. Soc. A* **2017**, *473*, 2199. [CrossRef] [PubMed]
12. The Parliamentary Office of Science and Technology. POSTNOTE 623 Natural Mitigation of Flood Risk. May 2020. Available online: https://post.parliament.uk/research-briefings/post-pn-0623/ (accessed on 25 May 2022).
13. Environment Agency. Working with Natural Processes to Reduce Flood Risk. The Evidence Base for Working with Natural Processes to Reduce Flood Risk. 2021. Available online: https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/working-with-natural-processes-to-reduce-flood-risk (accessed on 25 May 2022).
14. Kondolf, G.M.; Micheli, E.R. Evaluating stream restoration projects. *Environ. Manag.* **1995**, *19*, 196–214. [CrossRef]
15. Al-Zankana, A.F.A.; Matheson, T.; Harper, D.M. How strong is the evidence–Based on macroinvertebrate community responses–That river restoration works? *Ecol. Hydrobiol.* **2020**, *20*, 196–214. [CrossRef]
16. England, J.; Angelopoulos, N.; Cooksley, S.; Dodd, J.; Gill, A.; Gilvear, D.; Johnson, M.; Naura, M.; O'Hare, M.; Tree, A.; et al. Best Practices for Monitoring and Assessing the Ecological Response to River Restoration. *Water* **2021**, *13*, 3352. [CrossRef]
17. Lane, S.N. Natural flood management. *Wiley Interdiscip. Rev. Water* **2017**, *4*, e1211. [CrossRef]
18. Kay, A.L.; Old, G.H.; Bell, V.A.; Davies, H.N.; Trill, E.J. An assessment of the potential for natural flood management to offset climate change impacts. *Environ. Res. Lett.* **2019**, *14*, 044017. [CrossRef]
19. Roni, P.; Beechie, T.J. *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats*; John Wiley and Sons Ltd.: Chichester, UK, 2013; pp. 1–300. ISBN 9781405199551.
20. River Restoration Centre, Practical River Restoration Appraisal Guidance for Monitoring Options (PRAGMO). 2011. Available online: https://www.therrc.co.uk/monitoring-guidance (accessed on 25 May 2022).
21. SEPA. Natural Flood Management Handbook. 2015. Available online: https://www.sepa.org.uk/media/163560/sepa-natural-flood-management-handbook1.pdf (accessed on 25 May 2022).
22. Wren, E.; Barnes, M.; Janes, M.; Kitchen, A.; Nutt, N.; Patterson, C.; Piggott, M.; Robins, J.; Ross, M.; Simons, C.; et al. Natural Flood Management Manual, CIRIA 2022. 423 pages. Available online: https://www.ciria.org/ItemDetail?iProductCode=C802F&Category=FREEPUBS&WebsiteKey=3f18c87a-d62b-4eca-8ef4-9b09309c1c91&msclkid=bc6575dcd12411ec9f60951db9f11433 (accessed on 25 May 2022).
23. MacArthur, R.H. Patterns of Species Diversity. *Biol. Rev.* **1965**, *40*, 510–533. [CrossRef]
24. Palmer, M.A.; Ambrose, R.F.; Poff, N.L. Ecological Theory and Community Restoration Ecology. *Restor. Ecol.* **1997**, *5*, 291–300. [CrossRef]
25. Palmer, M.; Menninger, H.L.; Bernhardt, E. River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? *Freshw. Biol.* **2010**, *55*, 205–222. [CrossRef]
26. Feio, M.J.; Hughes, R.M.; Callisto, M.; Nichols, S.J.; Odume, O.N.; Quintella, B.R.; Kuemmerlen, M.; Aguiar, F.C.; Almeida, S.F.P.; Alonso-EguíaLis, P.; et al. The Biological Assessment and Rehabilitation of the World's Rivers: An Overview. *Water* **2021**, *13*, 371. [CrossRef] [PubMed]
27. Angelopoulos, N.V.; Cowx, I.G.; Buijse, A.D. Integrated planning framework for successful river restoration projects: Upscaling lessons learnt from European case studies. *Environ. Sci. Policy* **2017**, *76*, 12–22. [CrossRef]
28. Downs, P.W.; Kondolf, G.M. Post-Project Appraisals in Adaptive Management of River Channel Restoration. *Environ. Manag.* **2002**, *29*, 477–496. [CrossRef]
29. Bernhardt, E.S.; Palmer, M.A.; Allan, J.D.; Alexander, G.; Barnas, K.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.; Follstad-Shah, J.; et al. Synthesizing, U.S. river restoration efforts. *Science* **2005**, *308*, 636–637. [CrossRef]
30. Roni, P.; Hanson, K.; Beechie, T. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North Am. J. Fish. Manag.* **2008**, *28*, 856–890. [CrossRef]
31. Wohl, E.; Lane, S.N.; Wilcox, A.C. The science and practice of river restoration. *Water Resour. Res.* **2015**, *51*, 5974–5997. [CrossRef]
32. IUCN (UK). Available online: https://iucn-nc.uk/projects/river-restoration-and-biodiversity/ (accessed on 25 May 2022).
33. Addy, S.; Cooksley, S.; Dodd, N.; Waylen, K.; Stockan, J.; Byg, A.; Holstead, K. *River Restoration and Biodiversity: Nature-Based Solutions for Restoring Rivers in the UK and Republic of Ireland*; CREW: Aberdeen, UK, 2016. Available online: www.crew.ac.uk/publication/river-restoration (accessed on 1 April 2022).

34. Spray, C.J. (Ed.) *Eddleston Water Summary Report 2016*; Tweed Forum: Old Melrose, UK. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 1 April 2022).
35. Spray, C.J.; Ball, T.; Rouillard, J. Bridging the water law, policy, science interface: Flood risk management in Scotland. *J. Water Law* **2009**, *20*, 165–174.
36. Harrison, J.G. The Eddleston Water Historical Change in Context. Report to Tweed Forum. 2012. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 1 April 2022).
37. Werritty, A.; Ball, T.; Spray, C.; Bonell, M.; Rouillard, J.; Archer, N. Restoration Strategy: Eddleston Water Scoping Study (p. 86). Melrose: Tweed Forum. 2010. Available online: https://tweedforum.org/download/172/general-eddleston-water-database/3962/restorationstrategy-eddleston-water-scoping-study.pdf (accessed on 25 May 2022).
38. Black, A.; Peskett, L.; MacDonald, A.; Young, A.; Spray, C.; Ball, T.; Thomas, H.; Werritty, A. Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study. *J. Flood Risk Manag.* **2021**, *14*, e12717. [CrossRef]
39. JBA. Eddleston Water Hydrological and Hydraulic Modelling of NFM: Phase 2. Report to Tweed Forum June 2020. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 25 May 2022).
40. Hankin, B.; Page, T.; McShane, G.; Chappell, N.; Spray, C.; Black, A.; Comins, L. How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? *Water Secur.* **2021**, *13*, 100091. [CrossRef]
41. Underwood, A.J. On Beyond BACI: Sampling Designs that Might Reliably Detect Environmental Disturbances. *Ecol. Appl.* **1994**, *4*, 3–15. [CrossRef]
42. Ball, T.; Hendry, S.; Werritty, A.; Spray, C. Flood risk management: (Scotland) Act/2009 (asp 6). Sweet & Maxwell, Edinburgh. 2010. Available online: http://library.dundee.ac.uk/F/?func=direct&local_base=DUN01&doc_number=000661496 (accessed on 25 May 2022).
43. Dochartaigh, B.Ó.; Archer, N.; Peskett, L.; MacDonald, A.; Black, A.; Auton, C.; Merritt, J.; Gooddy, D.; Bonell, M. Geological structure as a control on floodplain groundwater dynamics. *Hydrogeol. J.* **2019**, *27*, 703–716. [CrossRef]
44. Peskett, L.; Heal, K.; MacDonald, A.; Black, A.; McDonnell, J. Tracers reveal limited influence of plantation forests on surface runoff in a UK natural flood management catchment. *J. Hydrol. Reg. Stud.* **2021**, *36*, 100834. [CrossRef]
45. Peskett, L.; MacDonald, A.; Heal, K.; McDonnell, J.; Chambers, J.; Uhlemann, S.; Upton, K.; Black., A. The impact of across-slope forest strips on hillslope subsurface hydrological dynamics. *J. Hydrol.* **2020**, *581*, 124427. [CrossRef]
46. Archer, N.A.L.; Bonell, M.; Coles, N.; MacDonald, A.M.; Auton, C.; Stevenson, R. Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *J. Hydrol.* **2013**, *497*, 208–222. [CrossRef]
47. Spray, C.; Tharme, A.; Robeson, D. Scottish Borders Pilot Regional Land Use Framework. Scottish Borders Council, Melrose. 2016. Available online: https://www.scotborders.gov.uk/downloads/file/2216/lus_framework (accessed on 25 May 2022).
48. Parker, C.; Clifford, N.; Thorne, C. Automatic delineation of functional river reach boundaries for river research and applications. *River Res. Appl.* **2012**, *28*, 1708–1725. [CrossRef]
49. Martinez Romero, R. *SEPA Technical Note 2013. STREAM Model Applied to Scottish Baseline Rivers*; SEPA: Stirling, UK, 2013.
50. Williams, R.; Bangen, S.; Gillies, E.; Kramer, N.; Moir, H.; Wheaton, J. *Allt Lorgy River Restoration Scheme: Geomorphic Change Detection and Geomorphic Unit Mapping*; University of Glasgow: Glasgow, UK, 2020.
51. Ncube, S.; Spray, C.; Geddes, A. Assessment of changes in ecosystem service delivery–A historical perspective on catchment landscapes. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2018**, *14*, 145–163. [CrossRef]
52. Gyger, M. The Eddleston Water Project: Monitoring of the Ecological Benefits of Natural Flood Management Measures (Creation of Flood Storage Ponds). Master's Thesis, University of Applied Sciences, Delémont, Switzerland, 2022.
53. Rouillard, J.; Reeves, A.; Heal, K.; Ball, T. The role of public participation in encouraging changes in rural land use to reduce flood risk. *Land Use Policy* **2014**, *38*, 637–645. [CrossRef]
54. Spray, C.; Arthur, S.; Bergmann, A.; Bell, J.; Beevers, L.; Blanc, J. Land Management for Increased Flood Resilience. CREW. 2015. CRW2012/6. Available online: https://crew.ac.uk/publications (accessed on 25 May 2022).
55. Cook, B.; Kesby, M.; Fazey, I.; Spray, C. The persistence of 'normal' catchment management despite the participatory turn: Exploring the power effects of competing frames of reference. *Soc. Stud. Sci.* **2013**, *43*, 754–779. [CrossRef]
56. Cook, B.; Forrester, J.; Bracken, L.; Spray, C.; Oughton, L. Competing Paradigms of Flood Management in the Scottish/English Borderlands. *J. Disaster Prev. Manag.* **2016**, *25*, 314–328. [CrossRef]
57. Bracken, L.; Oughton, E.; Donaldson, A.; Cook, B.; Forrester, J.; Spray, C.; Cinderby, S.; Passmore, D.; Bissett, N. Flood risk management; an approach to managing cross-border hazards. *Nat. Hazards* **2016**, *82*, 217–240. [CrossRef]
58. Mott Macdonald. Integrating Natural Capital into Flood Risk Management Appraisal. Report to Tweed Forum. September 2020. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 25 May 2022).
59. Spray, C.; Hickey, B. Integrating Natural Capital into Flood Risk Management Appraisal. Scottish Forum on Natural Capital. February 2021. Available online: https://naturalcapitalscotland.com/article/integrating-natural-capital-into-flood-risk-management-appraisal/ (accessed on 25 May 2022).
60. Ruman, S.; Ball, T.; Black, A.; Thompson, J. Influence of alternative representations of land use and geology on distributed hydrological modelling results: Eddleston, Scotland, Hydrological. *Sci. J.* **2021**, *66*, 488–502. [CrossRef]

61. Barnes, M. Assessing the Potential for Forest-Related Natural Flood Management to Mitigate Flooding. Ph.D. Thesis, University of Newcastle, Newcastle upon Tyne, UK, 2018. Available online: https://research.ncl.ac.uk/proactive/eddleston/ (accessed on 25 May 2022).
62. Costaz-Puyou, I. Assessing the Potential of Channel Remeandering for Flood Attenuation: A Detailed Case Study of the Restoration of the Eddleston Water, Scotland. Ph.D. Thesis, University of Dundee, Dundee, UK, 2022. Available online: https://discovery.dundee.ac.uk/en/studentTheses/assessing-the-potential-of-channel-re-meandering-for-flood-attenu (accessed on 25 May 2022).
63. Boon, P.J. River restoration in five dimensions. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **1998**, *8*, 257–264. [CrossRef]
64. Rouillard, J.; Spray, C.J. Working across scales in integrated catchment management: Lessons learned for adaptive water governance from regional experiences. *Reg. Environ. Chang.* **2017**, *17*, 1869–1880. [CrossRef]
65. Kondolf, G.M. Lessons learned from river restoration projects in California. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **1998**, *8*, 39–52. [CrossRef]
66. Anderson, D.H.; Dugger, B.D. A conceptual basis for evaluating restoration success. In Proceedings of the Transactions of the 63rd North American Wildlife and Natural Resources Conference, Orlando, FL, USA, 20–24 March 1998.
67. Kondolf, G.M.; Anderson, S.D.; Storesund, R.; Tompkins, M.; Atwood, P. Post-project appraisals of river restoration in advanced university instruction. *Restor. Ecol.* **2011**, *19*, 696–700. [CrossRef]
68. Leray, M.; Wilkins, L.G.E.; Apprill, A.; Bik, H.M.; Clever, F.; Connolly, S.R. Natural experiments and long-term monitoring are critical to understand and predict marine host–microbe ecology and evolution. *PLOS Biol.* **2021**, *19*, e3001322. [CrossRef]
69. Wilkes, M. *Future Rivers: Biological Monitoring and Assessment of English Waterways in the Twenty-First Century. A Report for the Environment Agency*; Environment Agency: Bristol, UK, 2021; p. 36.
70. England, J.; Skinner, K.S.; Carter, M.G. Monitoring, River restoration and the Water Framework Directive. *Water Environ. J.* **2008**, *22*, 227–234. [CrossRef]
71. Reid, H.; Bromley, C.; Dodd, J.; Martinez, R.; Spray, C.; Williams, R. Eddleston Water–Channel Sediment Analyses. Report to Tweed Forum May 2020. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 25 May 2022).
72. APEM. Eddleston Water Restoration Project Macroinvertebrate Responses 2012–2019. Report to Tweed Forum, June 2020. Available online: https://tweedforum.org/eddleston-project-database/ (accessed on 25 May 2022).
73. Perfect, C. Rates, Patterns and Mechanisms of Development in a Realigned River Channel. Ph.D. Thesis, University of Stirling, Stirling, UK, 2020. Available online: http://hdl.handle.net/1893/2431 (accessed on 25 May 2022).
74. Robertson, A.; Perkins, D.M.; England, J.; Johns, T. Invertebrate Responses to Restoration across Benthic and Hyporheic Stream Compartments. *Water* **2021**, *13*, 996. [CrossRef]
75. Stubbington, R.; Wood, P.; Reid, N.; Gunn, J. Benthic and hyporheic invertebrate community responses to seasonal flow recession in a groundwater-dominated stream. *Ecohydrology* **2011**, *4*, 500–511. [CrossRef]
76. Scottish Government. National Electrofishing Programme for Scotland. 2021. Available online: https://www.gov.scot/publications/national-electrofishing-programme-for-scotland/ (accessed on 25 May 2022).