CENTRE OF EXPERTISE FOR WATERS

Environmentally effective and cost-efficient sediment management at impoundments

Richard Williams, Elizabeth Barre-Tabor, Lucy Daniels, Nick Hanley, Peter Downs

CENTRE OF EXPERTISE FOR WATERS

Environmentally effective and cost-efficient sediment management at impoundments

Richard Williams, Elizabeth Barre-Tabor, Lucy Daniels, Nick Hanley, Peter Downs

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes. The Centre is funded by the Scottish Government.

This document was produced by:
Richard Williams[1], Elizabeth Barre-Tabor[1,2], Lucy Daniels[1], Nick Hanley[3], Peter Downs[2,4]

[1]School of Geographical and Earth Sciences, University of Glasgow
[2]cbec eco-engineering UK Ltd, Inverness
[3]School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow
[4]School of Geography, Queen Mary University of London

CREW Project Manager: Maureen Whalen

Please reference this report as follows:
Williams, R.D., Barre-Tabor, E.M., Daniels, L.J., Hanley, N., Downs, P.W. (2024) *Environmentally effective and cost-efficient sediment management at impoundments.* CRW2023_01. Centre of Expertise for Waters (CREW).

Available online at: crew.ac.uk/publication/hydro-impoundments-sediment-management

ISBN: 978-1-911706-33-5

Dissemination status: Unrestricted

Acknowledgements: The research team would like to thank the members of the Project Steering Group: Chris Bromley, Alasdair Matheson, and Michael Wann (SEPA); Grace Gubbins (NatureScot); and Olivia Lassiere (Scottish Canals) and Koehler Renewable Energy UK Limited, Dee Fishery Trust, McGowan Environmental, Mallard Productions, Stormontfield Hydro, Allt Energy, and Glen Devon Energy.

Research was conducted under University of Glasgow ethical approval application number 300230213.

Cover photographs courtesy of: Richard Williams.

Contents

List of figures

List of figures in Appendices

List of tables

List of tables in Appendices

List of boxes

Executive Summary

River impoundments are critical infrastructure for hydropower operations and water supply. However, sediment accumulation behind impoundments can pose a risk to effective hydropower or water supply operations, and downstream river reaches that are depleted of sediment are likely to experience poor river health. An earlier CREW project (Williams *et al.*, 2022) assessed the impacts of sediment discontinuity at run-of-river (RoR) hydropower structures and found impacts which, in some instances, could have significant implications for hydro-project resilience under predicted future climate change. This previous project provided numerous suggestions for improving hydropower practices but it was not within the scope of the earlier project to engage with hydropower operators to share this knowledge. Moreover, an indication of the financial implications of sediment discontinuity issues was not included within the research. The current project was motivated to fill these knowledge gaps, by addressing the following aims:

1. To raise awareness in the hydropower sector about basic river geomorphological processes related to the impact of sediment (dis) continuity on river habitats and species.
2. To improve understanding and raise awareness of the net benefits or costs of different sediment management options available to address the environmental and commercial risks to hydropower and water supply impoundments.

As part of this project, three hydropower sites were visited to supplement findings from the earlier project and to provide information useful across several of the project objectives.

Project outputs included a cost benefit analysis, a video, an infographic, and a framework for planning the sediment management aspects of a hydropower scheme permit application or review intended to assist operators and regulators during hydropower permitting. A 'Theory of Change' approach was used to illustrate schematically how the long-term goals of the project can be achieved by the stakeholders. The video and infographic communicate (i) the importance of sediment continuity for good river health, (ii) potential implications for sediment management resulting from a changing climate and (iii) the importance of best-practice sediment management. They are available to view and download from crew.ac.uk/publication/hydro-impoundments-sediment-management

The cost-benefit analysis (CBA) was undertaken to evaluate different catchment sediment management options that could be applied by hydro scheme operators to address the environmental and commercial risks to hydropower and water supply impoundments. The CBA focused on hydropower impacts from the perspective of Scottish society rather than from the perspective of an individual operator. In line with HM Treasury's *Green Book* procedures, this social perspective is more relevant for a public policy analysis than an operator-level perspective, since it is assumed the government regulator (here, SEPA and Nature Scot) operates with the desire to maximise net social benefit rather than profits of an individual company. The net benefits of best practice sediment management were calculated for a representative catchment with a hydro scheme impoundment, considering scenarios including riparian corridor planting, catchment tree planting and peatland restoration. Benefits were considered for different scenarios of sediment management cost savings by the operator, different scenarios of damage caused to infrastructure by sediment accumulation, and seasonal variation in electricity generation losses during sediment removal from a headpond. For all sediment cost management savings scenarios, riparian planting and peatland restoration generated positive Net Present Values (NPVs). Catchment tree planting generated *mostly positive* NPVs.

Based on the various outcomes of this project, two sets of recommendations are proposed.

The first set focuses on raising awareness of the importance of sediment continuity through impoundments. To begin, the report from the earlier CREW project (Williams *et al.*, 2022) and outputs from this project should be widely shared (and periodically) to relevant teams in SEPA, NatureScot and Scottish Canals to raise awareness of sediment management within the regulatory hydropower and impoundment community. SEPA Water Permitting and Policy teams should modify hydropower application forms and associated guidance documents to facilitate the management framework guidance developed here.

SEPA and NatureScot should periodically update their joint hydropower guidance for the benefit of environmental protection, to improve the efficiency of the permitting process and to improve engagement between regulators and operators. Project outputs should be shared via SEPA and

NatureScot's websites, and suitable and regular email and media outreach by SEPA and NatureScot.

Operators should use project outputs to consider site specific sediment-related environmental and commercial risks both in the short and long-term, particularly in the context of expected climate change that is likely to increase sediment production. A forum should be established to enable key stakeholders within the hydropower community to communicate and collaborate for mutual benefit. Finally, monitoring and evaluation activities should be designed and implemented to evaluate the actual benefits of the project.

The second set of recommendations focus on improving the understanding and raising awareness of the benefits or costs associated with the sediment management options available to address the environmental and commercial risks to hydropower and water supply impoundments. These include investigating means of incentivising catchment improvement actions where the CBA shows positive values over a reasonable range of likely scenarios. Analyses indicate that catchment improvement actions generally generate a societal positive Net Present Value, but hydro operators will require the growth of 'nature markets' associated with biodiversity, carbon and water quality credits to capture these benefits as private revenues. At present, operators face issues including an inability to influence upslope land management and/or insufficient financial incentives to adopt improved catchment management practices.

Research here demonstrates that cost-benefit analyses would benefit from better data on the costs and benefits of catchment improvement actions; for example, integrating values associated with carbon sequestration may show the total benefit of catchment management changes to be higher than estimated here. Additional stated preference work could be undertaken to understand more about the relative benefits of different catchment management options (e.g., how tree planting is valued by citizens relative to peatland restoration).

Overall, a key finding from stakeholder engagement activities conducted during the project was that more communication and collaboration is required between different stakeholders (e.g., regulators, operators, consultants, hydromorphologists, ecologists, researchers) to improve understanding and knowledge sharing. Efforts should be made to develop a community of Scottish hydropower and water supply impoundment practitioners that openly exchange knowledge to enable the mitigation of impoundment impacts on river health and to improve commercial resilience in the context of climate change. Appropriate leadership will be necessary to achieve this.

1 Introduction

Centred on the Scottish Government's emission reduction targets of net zero by 2045, in part by transforming Scotland's energy system, this research project focused on raising awareness in the hydropower sector about the role and importance of maintaining the downstream transport of riverbed sediments through (or around) hydropower structures (i.e., sediment continuity) as the basis for sustaining hydropower operations, in both commercial and environmental terms. The project builds on a previous CREW project that provided a first-of-its-kind assessment of the impacts on sediment continuity of run-of-river (RoR) hydropower structures (Williams *et al.,* 2022). The earlier project determined that impacts were highly variable but, in some cases, had highly significant implications for hydro-project resilience and sustainability under current and especially future projected climate regimes. While numerous suggestions were provided for improving practices, their uptake is ultimately constrained to voluntary readership of the final report. Further, the research did not include an indication of the financial implications of sediment continuity problems – the matter was examined but was agreed by the Project Steering Group to require detailed analysis beyond the scope of the initial project. This project expanded on the earlier research by using various outreach activities to actively engage hydropower operators about sediment continuity, by developing a broad-based cost-benefit analysis to estimate the financial magnitude and consequences of sediment continuity issues, and by extending the scope from RoR structures to sediment continuity across all hydropower operations in Scotland. As such, the project very directly engaged hydropower operators in the policy agenda of transforming energy production to meet Scotland's 2045 net zero goal.

The aims of this project were:

1. To raise awareness in the hydropower sector of basic river geomorphological processes, in the context of the impact of sediment (dis) continuity on river habitats and species.
2. To improve understanding and raise awareness of the net benefits or costs of different sediment management options available to address the environmental and commercial risks to hydropower and water supply impoundments.

The first aim provided a platform for raising awareness of the environmental risks of not properly addressing sediment transport in permit applications, while the second focused on the commercial risks posed by climate change-related increases in the rate of sediment delivery to hydropower schemes and water supply impoundments. The improved understanding generated from this project should help make the process of applying for, issuing, and reviewing permits more efficient for hydropower scheme operators and the Scottish Environment Protection Agency (SEPA).

To deliver the aims, the following set of objectives were addressed during the project.

1. Co-produce a stakeholder map, communications and engagement plan, and impact plan.
2. Assess the extent to which hydropower scheme operators are aware of the geomorphological, ecological and climate change impacts, and sediment management options, on both hydropower scheme operation and the riverscape.
3. Characterise sediment management challenges and best practice at three hydropower schemes in Scotland.
4. Undertake a cost benefit analysis of the different sediment management options that could be applied by hydropower scheme operators to address the environmental and commercial risks to hydropower and water supply impoundments.
5. Produce a professional video on sediment management best practice at impoundments.
6. Produce an infographic on sediment management best practice at impoundments.
7. Design a framework for planning the sediment management aspects of a hydropower scheme permit application or review.

Ethics approval was obtained from the University of Glasgow's College of Science and Engineering (CoSE) Ethics Committee for all activities that involved stakeholder participation or participation from members of the public. Participant Information Sheets were provided to participants for each discreet activity and consent was gained before participants could take part in the discreet activity.

Whilst this project took place in a Scottish landscape, and within Scottish policy and practice, the impacts resulting from hydropower schemes in Scotland are not atypical of those accruing globally (Vörösmarty *et al.,* 2010; Williams *et al.,* 2022). Thus, whilst this project specifically targeted sediment continuity pressures in Scotland, the broad findings are applicable to other regions and nations with hydropower operations, especially those with relatively coarse river sediments.

In the subsequent sections of this report, we detail the steps undertaken to complete the project's objectives. Recommendations are provided in Section 8.

2 Stakeholder identification, mapping, communication, and engagement

The research team organised a facilitated stakeholder workshop (objective 1) to provide an opportunity for meaningful dialogue between key stakeholders in the hydropower community. The workshop facilitated discussion around awareness of the geomorphological, ecological and climate change impacts, and sediment management options, on both hydropower scheme operation and the riverscape (objective 2). The steps undertaken to identify stakeholders, organise a workshop and the findings from the engagement activity are detailed below.

2.1 Stakeholder identification and mapping

During a facilitated online meeting, the research team worked with the Project Steering Group to identify key stakeholders in the Scottish hydropower industry who could be impacted by changes to sediment management practices at impoundments. The meeting involved three exercises:

1. **Identify stakeholders**. Key questions were considered such as: Who is or will be impacted? Who can support/obstruct the change? How can non-humans be heard and who can advocate for them?
2. **Stakeholder grouping**. Stakeholders were categorised into five groups: policymakers, practitioners/businesses, third-sector organisations, other human, and non-human. These groupings were selected to ensure stakeholders from a diverse range of backgrounds were involved in the stakeholder workshop.
3. **Stakeholder influence mapping**. Stakeholders identified from the previous exercises were mapped by the Project Steering Group based on their professional opinion across a 'Power/Interest' grid (Mitchell *et al.,* 1997) to discuss appropriate communication strategies for each stakeholder group (Figure 2.1). This allowed the research team to focus their greatest communication efforts on those mapped within the 'manage closely' quadrant of the grid because of their combination of interest and power. However, other groups also needed tailored communication strategies, such as informing them of this final report and associated outputs. The Power/Interest grid in Figure 2.1 was also used to guide the choice of stakeholders invited to the stakeholder workshop.

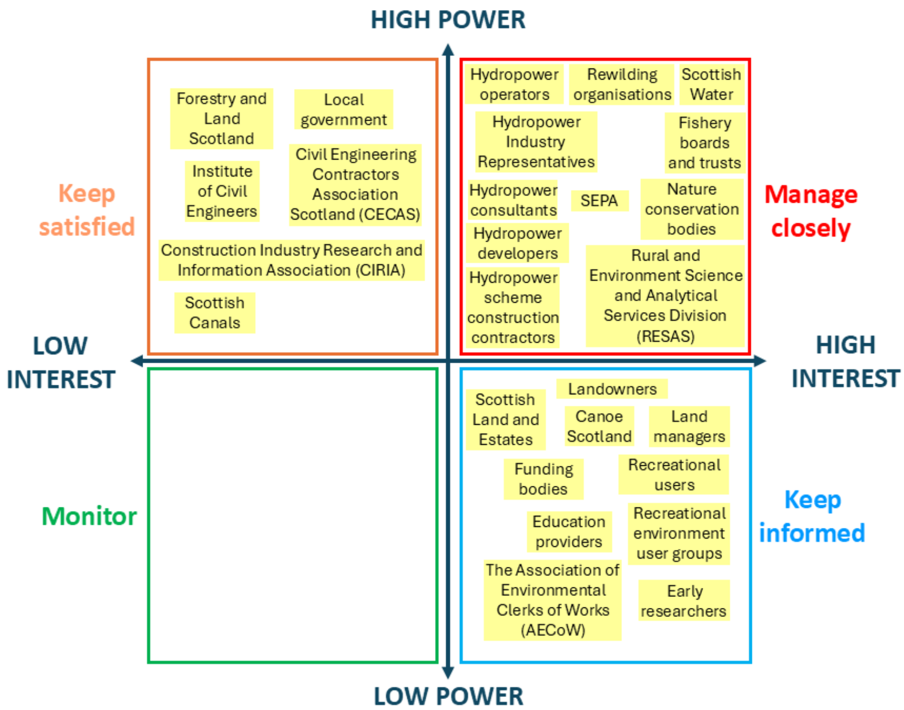


Figure 2.1. Stakeholder Mapping: result of mapping stakeholders across a 'Power/Interest' grid into four categories. Note that power does not equate importance; rather, mapping relative power ensures the project is conscious of power dynamics and subsequent activities can ensure space for different priorities to be heard. Power is based on the stakeholder's level of influence in the system and interest is the degree to which a stakeholder will be affected by the project.

2.2 Communication and engagement with the Scottish hydropower sector

An in-person, facilitated stakeholder workshop was organised to gather information required for the project as well as providing a 'benchmark' on stakeholder perspectives and to afford an opportunity for mutually beneficial dialogue between key stakeholders in hydropower and regulatory bodies. 434 organisations were identified as potential stakeholders for the workshop although contact information was not available for all the identified stakeholders. Subsequently, 226 organisations were invited to the workshop by email, 61 using online contact forms available on stakeholder websites, and 40 via telephone calls; in some cases, the same organisation was contacted through multiple communication channels. In total, 20 stakeholders accepted the invitation to the workshop which was held at the University of Glasgow on Tuesday 30th April 2024. In addition to the 20 stakeholders, there were five members of the Project Steering Group (who participated in the activities), and four members of the research team. The workshop was run by an independent professional facilitator (Dee Hennessy of Creative Exchange).

The workshop was organised around four core activities. Box 1 provides a summary of the activities and results. The first related to sediment management challenges in the hydropower sector and the second focused on the impacts and potential best practice sediment management. The third asked the stakeholders to problem solve sediment management challenges for various hypothetical case studies. Finally, stakeholders were asked about how hydropower sediment management challenges could be best communicated via a short video presentation, and what other communication formats might be effective. For the first and second activity, participants were placed into groups based on their organisation type, agreed upon during the workshop based on communication between the participants and the facilitator. The group types and number of people in each group were as follows:

- Hydropower industry: 10
- NGO/conservation: 9
- Environmental consultants: 3
- Public agency: 3

For the third and fourth activities, participants were placed into five groups of five with a mixture of members from each organisation category.

Information and insights from the workshop activities underpinned the research undertaken in the subsequent parts of the project, including developing the impact plan, the cost benefit analysis, and the production of a video, infographic and management framework. Critically, some key stakeholders volunteered to provide more information, or to facilitate site access, to enable these subsequent parts of the project to be undertaken.

Box 1: Results from the activities undertaken during the sediment management workshop

Group spokespersons provided feedback from each activity to all participants during discussions initiated by the professional facilitator. These outputs were noted during these discussion sessions by one of the project's research assistants. They are provided here as an accurate record of the points raised by workshop participants and their inclusion does not necessarily represent endorsement by other workshop attendees.

Activity 1: sediment management challenges

Question 1.1: ***What do you wish you had known about sediment management at impoundments before being involved with hydropower development, no matter what your job role is?***

- More about CAR (Water Environment (Controlled Activities) (Scotland) Regulations) licencing.
- More information about sediment management issues 10-15 years ago would have allowed operators to design structures better able to deal with sediment.
- Who is liable for sediment management.
- The volume of sediment in a headpond can change drastically overnight.
- The impacts of sediment discontinuity on fisheries and ecosystems.
- The magnitude of the sediment discontinuity issue.
- A better understanding from different perspectives (e.g., operators, NGOs and public agencies).
- The impacts of land use on sediment supply.

Question 1.2: ***How did/could you find out that information?***

- CAR licencing guidelines.
- Historically, there was a permitting group in SEPA.
- Experience within job role.
- Conversations between different organisations.

Question 1.3: ***How would you like to see sediment management structured in the future?***

- Clear and focused regulatory guidelines/framework and licence conditions (one comment was "Woolly licence conditions are unhelpful").
- Holistic collaboration between different stakeholders with interests across the catchment.
- A better commercial understanding from the regulator.
- Education, not enforcement from the regulator.
- Examples showing good and bad practice sediment management and the implications of both.
- Resource sharing, such as sharing sediment to catchments in need.
- NGOs/conservation bodies feel that their views on sediment management have been ignored and that there has been no meaningful regulation in this sector.
- Less reactive and more proactive identification of sediment sources and sediment management, with measures put in place to reduce sediment supply from upstream.
- More regulation of sediment. At the moment it seems like all the focus is on water and flows.
- Site-specific and outcome-based sediment management plans.
- Adopting a catchment approach similar to the approach used for Natural Flood Management.

Activity 2: sediment management impacts and best practice

Question 2.1: ***What are the costs of implementing different sediment management practices, or how would you calculate these costs?***

- Costs can range from zero on sites where sediment management is not required compared to some sites which cost tens of thousands of pounds annually.
- Financial costs to consider:
  - Access
  - Permission
  - Equipment
  - Permits (e.g., quoted £30,000 for a small hydropower scheme)
  - Environmental studies (e.g., quoted £150,000 on a small hydropower scheme)
  - Sediment removal/dredging (e.g., Costs for dredging can be considerable – a quote for removing c. 4000 t from a canal blocked by coarse sediment emanating from upslope commercial forestry after a storm event was £25,000)
  - Putting sediment back into the river ecosystem (e.g., quoted £100 per m^3 to remove an estimated 694,000 m^3 of deposited sediment from canals to restore them to their original navigable design profiles) (a total estimated cost c. £22–66m is stated in the Scottish Canals Corporate Plan 2023-2028).
  - Sediment disposal, for instance, when it is contaminated
  - Loss of power generation, such as when waiting for approval from SEPA
- Environmental costs, for example, the loss of renewable energy placing a greater reliance on fossil fuels.
- Reputational costs to operators and regulators, such as poor publicity if no or inadequate sediment management results in preventable damage to river habitats.

Question 2.2: ***What sediment management practices would you recommend?***

- Proactive measures:
  - Coanda screens
  - Sediment source control, such as woodland planting, peatland restoration, check dams, and large wood material
  - By-pass channels to route sediment downstream during higher flows
- Reactive measures:
  - Scour pipes and plates
  - Dredging

Activity 3: sediment management case study scenarios

Groups were each given a different hydropower scenario with details about the river, the hydropower scheme, and the sediment management practices carried out at the scheme. They were asked to write on sticky notes the environmental and operational impacts of sediment transport within the context of their hydropower scheme scenario. Groups then placed their sticky notes on a grid ranging from low to high operational impacts on the x-axis and low to high environmental impacts on the y-axis (Figure 2.2, see also Appendix A: Exercise identifying operational and environmental impacts of sediment discontinuity of hydropower schemes).

A more general discussion then addressed the issue of sediment impacts under climate change. Stakeholders were asked to consider how the schemes in their scenarios would be impacted if sediment yields were to increase by 20% and larger particles were transported to the scheme resulting from expected climate change. The responses included:

- Damage to structures, screens in particular, resulting from boulders as well as frequent transport of gravel and cobbles.
- Concern over peak/flood events.
- Sediment management would likely become more expensive.
- The scheme may no longer be financially viable.
- Exacerbation of impacts shown in Figure 2.2

Activity 4: best practice communication strategies for sediment management

This project required provision of a video and one alternative format output to illustrate sediment management challenges in hydropower to stakeholders. Participants were asked to provide ideas for the specification of these communications, such as the target audience and topics covered in the outputs, and to provide suggestions for the format of the alternative output. The target audience was suggested to include representatives from all the stakeholder entities in the room, as the consensus was that it would be good to provide a holistic overview. Suggested topics included: a basic explanation of river processes; the importance of sediment in a river; good sediment management practices with examples; and sediment management plan guidance. Suggestions for an alternative medium included an infographic, a flow diagram, an interactive animation, a GIS story map, the use of social media, a podcast, a Ladybird book, and a game.

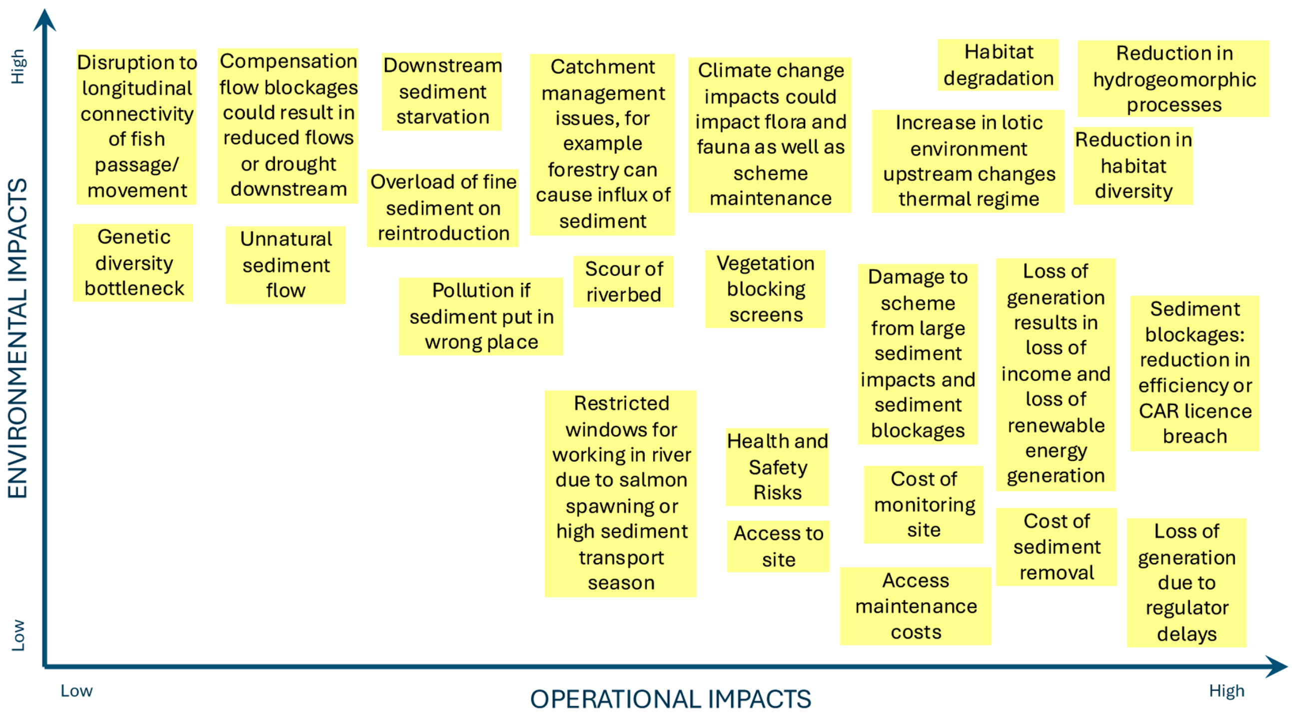


Figure 2.2. Operational impacts versus environmental impacts of sediment transport: grouped and consolidated answers provided by the workshop participant groups within the context of their hydropower scheme scenario. Very approximately, responses were grouped by quadrant as biology concerns (upper-left quadrant), engineering concerns (lower-right) and concerns for fluvial processes and habitats (upper right).

3 Impact plan

'Theory of Change' is an approach for describing and illustrating *how* and *why* a targeted change in behaviours is expected to happen following actions intended to encourage change (Institute for Methods Innovation (IMI), n.d.). CREW has utilised Theory of Change across a variety of projects. A Theory of Change diagram was developed to show how this project's activities can be used by the Project Steering Group to achieve their desired long-term goals (IMI, n.d.) and evaluate the success of the project (Blamey and Mackenzie, 2007). To create the diagram, the Project Steering Group were asked to describe (i) the specific benefits they envisaged from the project, and (ii) the route that they would expect to take from the end of the project to the realisation of these benefits. The contributions were then categorised and organised (see Figure 3.1) to illustrate the pathways from *input activities* (e.g., the development of the project) through the *enabling factors* (e.g., sharing of project outputs) leading to the *intermediate* outcomes (i.e., short to medium-term changes), and the *intended benefits* (i.e., long-term change) of the project (IMI, n.d.). Figure 3.1 also includes (top right) suggested next steps to monitor and evaluate the success of the project in terms of achieving its targeted changes. Overall, it is envisaged the development of a project specific Theory of Change should help the Project Steering Group to deliver targeted change from the project. It will also support CREW or the research team in evidencing change, if the next steps identified in the top right of Figure 3.1 are funded.

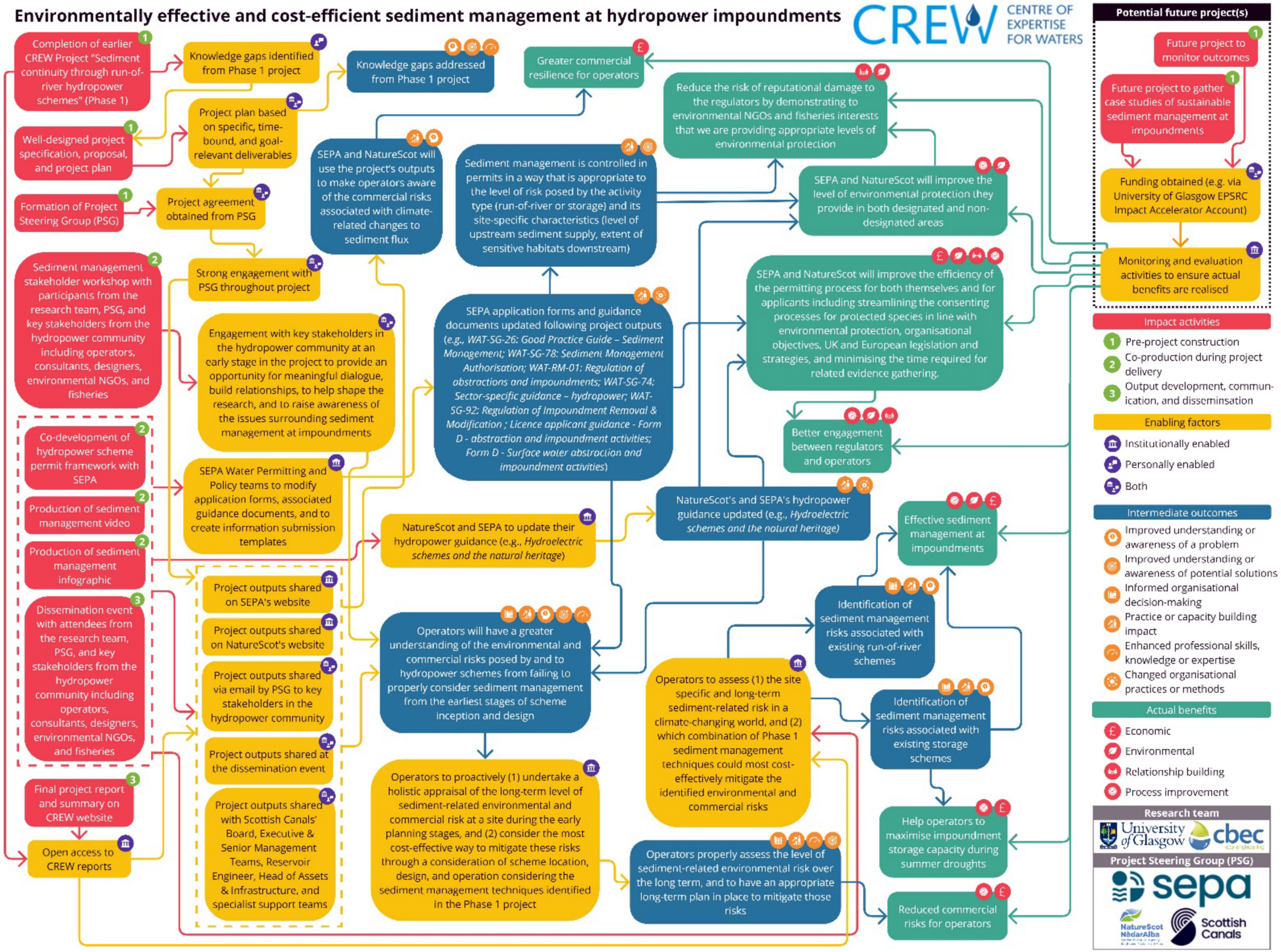


Figure 3.1. Theory of Change diagram showing how the project's activities can be supported by a variety of enabling factors to achieve real-world outcomes and benefits. Note: figure is made in the style of and using the categories developed by them in the CREW commissioned Strategic Impact Report (Jensen *et al.* 2022).

4 Case studies

Three hydropower sites were visited as part of this project: one storage hydropower and one RoR hydropower on the Keltie Water, and one RoR hydropower on the Allt an t-Sidhein. The purpose of the site visits were to: (i) further develop relationships established through the organisation and attendance of the stakeholder workshop; (ii) review sediment management practices and challenges within a real-world and catchment context; (iii) support data collection for the project's cost-benefit analysis; (iv) scope the development of the video and supporting infographic through the identification of filming locations, interviews regarding operator experiences, and narrative development; and (v) inform the sediment management framework produced as part of the project. During the stakeholder workshop, operators were asked to contact the research team if they would like their site to be considered as a case study for the project. Sites were subsequently selected based on the operator's willingness to engage with the various aspects of the project, site accessibility, and to ensure a representative sample of hydropower schemes to meet the project aims. Appendices B and C provide an overview of the case study catchments and current sediment management activities. All three sites were used for video production. Information supplied on the Allt an t-Sidhein hydropower scheme was used for the cost-benefit analysis. A further, undammed, site was visited that did not meet the required criteria to be a case study for this project, but did provide the opportunity to build positive relationships with a hydropower operator and to communicate the importance of sediment continuity.

5 Cost-benefit analysis

5.1 Introduction

Cost-Benefit Analysis (CBA) is an analytical tool regularly used for options appraisal in environmental contexts world-wide (Hanley and Barbier, 2009). The development of methods for estimating the monetary equivalents of environmental impacts, both positive and negative, has greatly helped in this regard, since now a sub-set of environmental impacts can be included with other, monetised costs and benefits of a project or policy. In the UK specifically, CBA has now become one of the main tools used within a public policy context (e.g., via the HM Treasury Green Book) to (i) assess the net benefits to society of different interventions (projects, policies); (ii) rank alternative options for achieving a specific target; and (iii) show how different groups within society win and lose to varying degrees from the implementation of a project. In this study, a CBA has been undertaken to evaluate different catchment sediment management options that could be applied by hydro scheme operators to address the environmental and commercial risks to hydropower and water supply impoundments of allowing sediment accumulation behind impoundments. There are various approaches to minimising sediment discontinuity at impoundments (see Figure 4.1 in Williams *et al.,* 2022). These include mechanical or hydraulic approaches for periodically excavating stored sediment, and by-pass measures that route sediments around or through storage impoundments. Scottish RoR hydropower sites appear to utilise mechanical excavation measures exclusively (Williams *et al.,* 2022), and this approach will be required more frequently under climate change, thus imparting additional costs to hydropower operators. In this CBA, we focus on a third approach, focused on the costs and benefits of catchment management alternatives to reduce sediment flux towards an impoundment. The approach taken views costs and benefits from the perspective of Scottish society as a whole, rather than from the perspective of an individual operator. This social perspective is more relevant for a public policy analysis than a firm-level perspective, since we assume the regulator operates on the basis of a desire to maximise net social benefits, rather than increasing firm profits. This is in line with *Green Book* procedures. We also note that despite contacting a very large number of industrial stakeholders through the project workshop and subsequent follow up emails, we only obtained case study cost data from one firm, and profits data from no firms. We thus do not have any data with which to undertake a CBA from the perspective of private firms. For such firms, benefits would be equal to the avoided loss in profits from electricity generation from undertaking any investment which reduced sediment load problems at a run of river site; and costs would be equal to either the difference between a business-as-usual sediment removal operation and an alternative, or simply the costs of each alternative investment. These costs and benefits would then be discounted using the firms' own risk-adjusted discount rate, or their weighted average cost of capital. However, we remind the reader that the research team do not have access to accurate (or indeed any) information on these private costs and benefits, despite a very considerable research effort.

The text below details the steps undertaken to perform a 'stated preference contingent-valuation survey', obtain estimated costs of sediment management, and use outputs from these to undertake the CBA. Survey questions and results are presented together in sequence, with survey questions shown in the blue boxes.

5.2 Stated Preference Contingent Valuation Survey

5.2.1 Survey Set up

A stated preference (SP) approach was used to quantify and value household preferences for implementing best practice catchment management approaches to reduce sediment yield into hydro schemes, thus increasing their environmental sustainability. SP methods are survey-based approaches that present respondents with simulated choices to measure their preferences and valuations for certain outcomes. The approach is highly flexible and can be used in many economic valuation contexts (Hanley and Czajkowski, 2019). This was preferred here as an SP approach is the only way to capture non-use values (Johnston *et al.,* 2017) and motivations (existence, altruism, and bequest), which are expected to be associated with environmental outcomes. SP methods are widely used in the UK as part of public policy analysis, for example in recent assessment of UK biodiversity policy (Browning *et al.,* 2024), in recent work by the University of Glasgow for the Forestry Commission on forest biodiversity values, and in on-going work (un-published as yet) for the Environment Agency on the benefits of water quality improvements.

Two SP approaches are typically used: choice modelling and contingent valuation (CV). In this project, a CV approach was chosen since we were mainly interested in the value of a bundle of environmental benefits associated with changes to catchment management practices, rather than wanting to understand the relative values of the benefits (using choice modelling). There are many approaches eliciting maximum Willingness to Pay (WTP) data (Hanley and Barbier, 2009), and here we use a payment ladder approach (as illustrated in Box 11) to capture potential uncertainty on the part of respondents in terms of the values they place on catchment management practices to sustain hydropower operations.

An important feature of any CV survey is the payment vehicle used, that is, how respondents are asked to pay towards obtaining the benefits presented to them in a hypothetical market. Most guidance (Johnston *et al.,* 2017) recommends a non-voluntary payment vehicle to make it less likely that people will behave strategically and mis-state their true maximum value. Here, we use increases in (council) taxes and other household expenditures, based on the approach in Browning *et al.,* 2024. We also take care to distinguish between those who are "in the market" – willing to pay even a small amount for the environmental benefits described – and those whose WTP is zero. For the latter, we also distinguish between genuine zero and protest bids.

The survey was designed by a research team at the University of Glasgow using the Qualtrics web-based software. Once designed, it was passed over to a project manager from Qualtrics LLC to obtain respondents and manage the survey. The quota for the survey was 1000 respondents, with the sample being representative of the Scottish general population. A soft launch pilot of the survey was undertaken with 50 participants, from this, question wording was refined and a 'speed check' of half the median completion time (5.7 minutes) was added to ensure that participants were properly completing the survey. Following issuance and completion of full (1018-respondent) survey, 86 responses were deemed not suitable for further analysis based on the way in which the WTP questions were answered. The following survey results are therefore from a sample size of 932 respondents.

5.2.2 Survey contents

On opening the survey, participants were shown a series of invitation paragraphs, these can be found in Appendix D: Stated Preference Contingent Valuation Survey Participant Information Sheet.

The second page introduced the research team and provided a list of consenting questions. If respondents did not consent, then the survey was ended automatically. Once the consenting questions were answered, those who consented were taken forward to a page explaining the nature of the survey questions. They were told that the survey was not a quiz or test and that they were to answer the questions based upon their own opinions, knowledge and the information shown throughout the survey.

The respondents were initially asked the demographics questions shown in Box 2, the answers to which can be seen in Figure 5.1.

Box 2: Demographics questions asked to survey population

a) How old are you?

b) How would you describe the type of area where you usually live?

c) What is the highest level of education you have completed?

d) What was your total household income before taxes during the past 12 months?

e) How do you describe yourself?

f) In the last 12 months, how often, on average, have you spent free time outside in green and natural spaces? This includes any visits to:

- Green spaces in towns and cities
- The countryside (for example farmland, woodland, hills and rivers)
- The coast (for example beaches, cliffs) and activities in the open sea

Please DO include visits of any duration (including short trips to the park, dog walks, etc). Please DO NOT include time in your garden, time spent outside as part of your job or time spent outside of the UK.

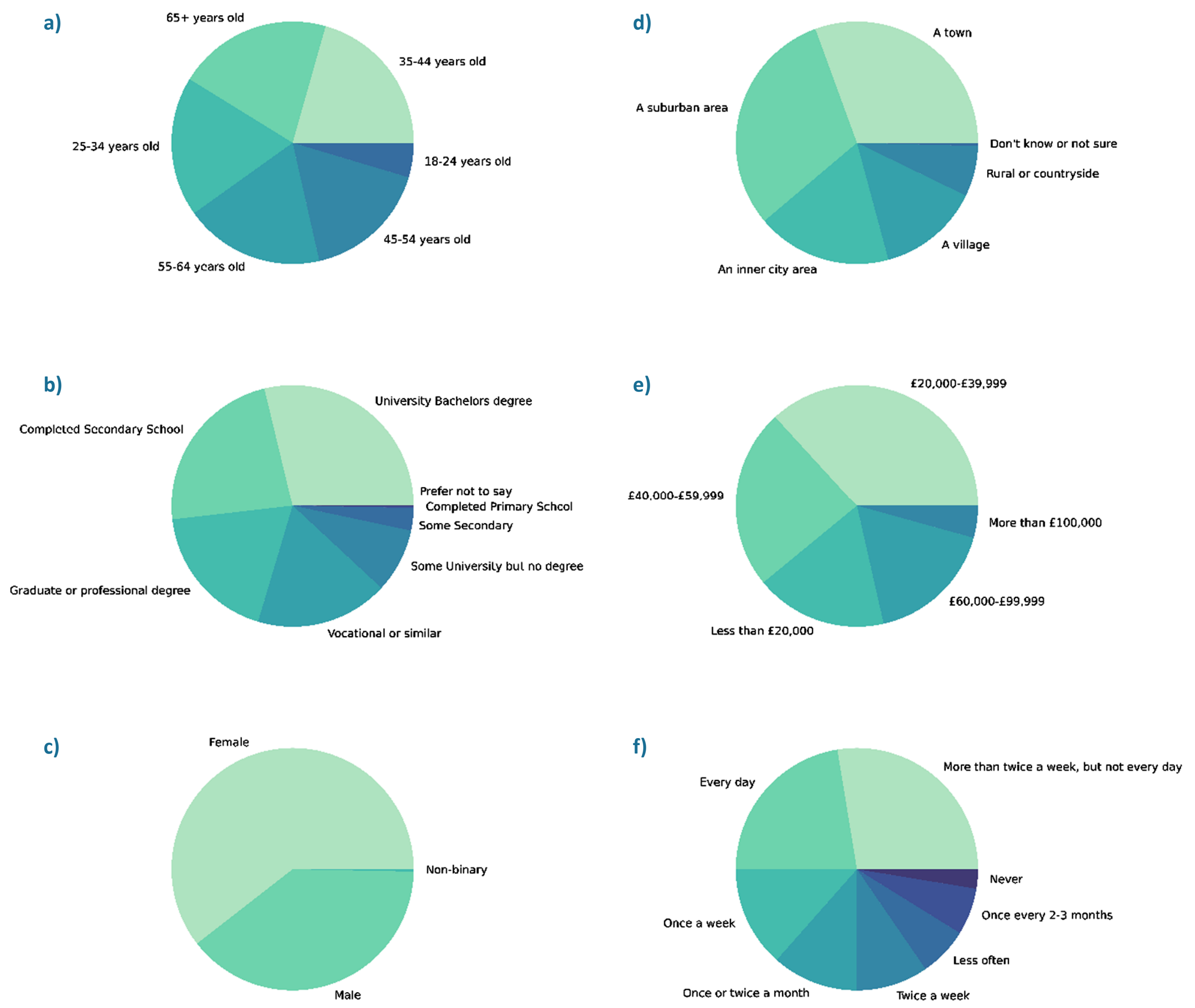


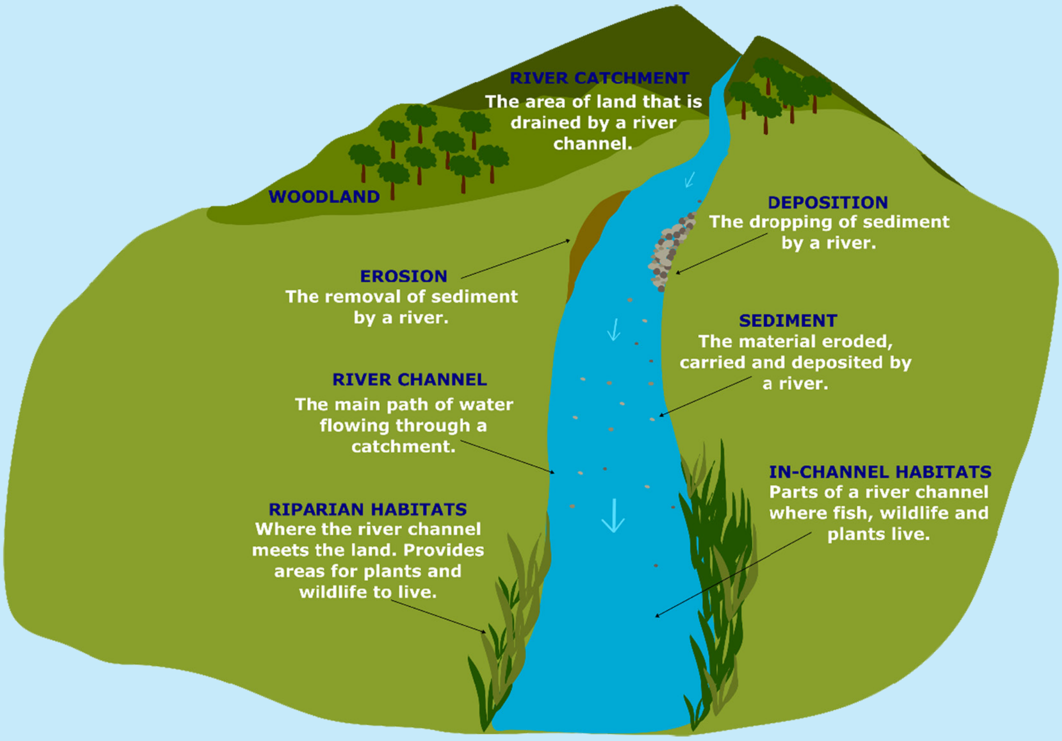
Figure 5.1. Survey population demographics. a) Age, b) Living area, c) Highest form of education, d) Annual total household income (before tax), e) Gender, f) Average weekly time outside in past 12 months.

5.2.2.1 Survey Technical Questions

Following demographics questions, Question 1 investigated respondents' familiarity with elements of a typical upland Scottish catchment and the terminology that was to be used throughout the duration of the survey (see Box 3). Respondents were asked to rank options in order of what they believed was most important for catchment health, providing us with a baseline idea of what respondents consider to be 'healthy' catchments, and how sediment continuity may factor into that.

Figure 5.2 shows the results from Question 1. Based upon respondents' own knowledge and the figure in Box 3, options that included habitats and woodland were most often selected by respondents as being most important for catchment health, rather than those related to catchment sediment dynamics. Most respondents ranked 'a variety of in-channel habitats' as the most important factor and 'some bank erosion' as the least important factor.

Box 3: Diagram shown to respondents when they open the survey to introduce river catchment terminology



Rivers flow from upstream towards downstream, following the natural slope of a river catchment.

Question 1. ***What do you think is important for river catchment health?***

Rank these in order from most important = 1, to least important = 8.

Please use the above diagram to help you understand some of the options listed below.

- Woodland cover in the catchment
- Stable peatlands
- Cool water temperatures
- Some bank erosion
- Some deposition of sediment
- Slow sediment movement
- A variety of in-channel habitats
- A variety of riparian habitats

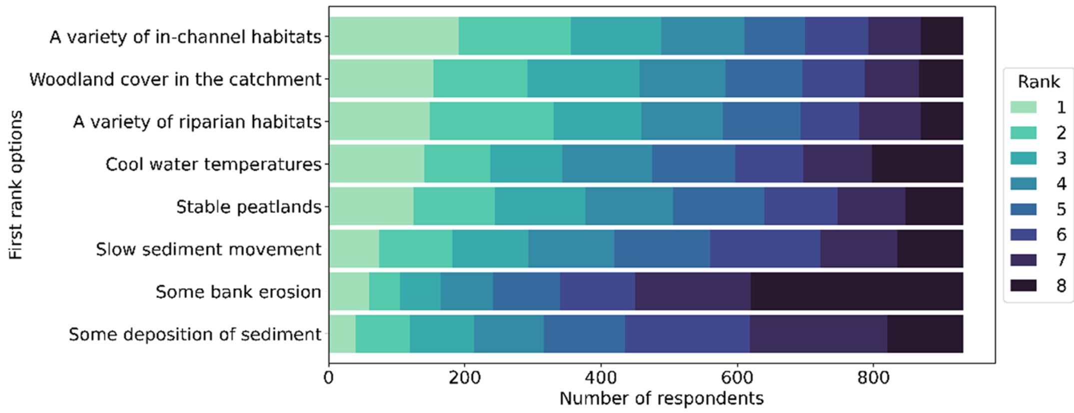
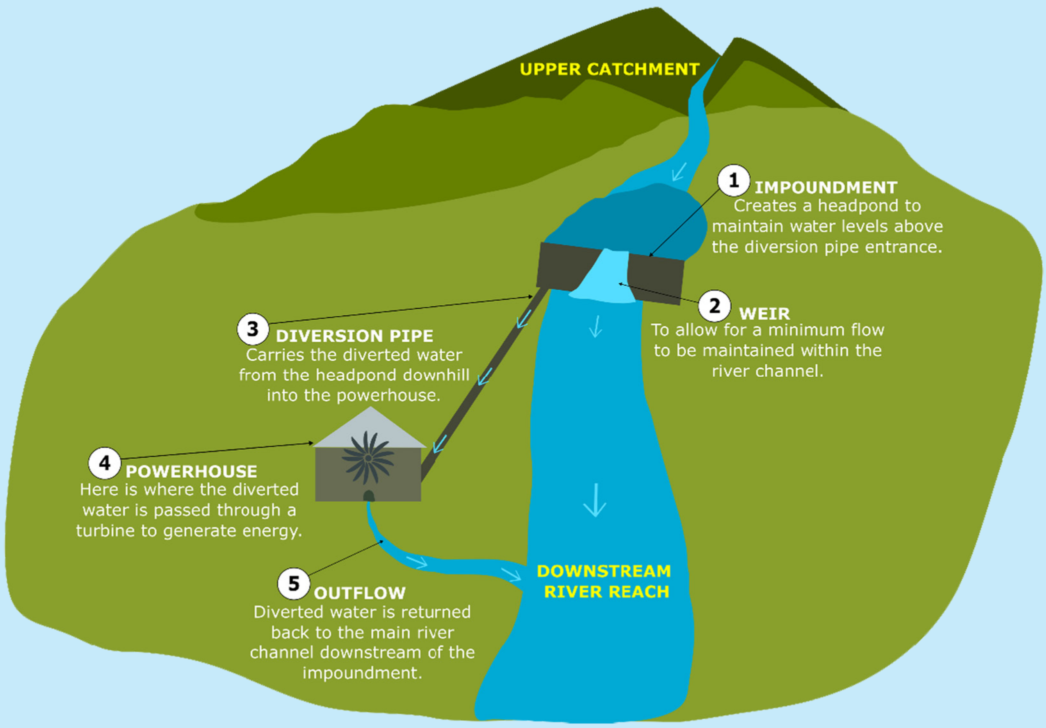


Figure 5.2. Respondents' rankings of factors affecting river catchment health. Lighter colours indicate options that were most often ranked as more important for river catchment health, darker colours indicate options that were most often ranked as less important for river catchment health.

After being shown the diagram in Box 4 as the basis for Question 2, most respondents (336) did not think that hydropower had any negative impacts on river catchments. This majority was, however, not statistically significantly different from those who answered 'yes' (302) or 'don't know' (294).

Box 4: Diagram shown to respondents to introduce Run-of-River hydropower

The graphic below shows an example of a Run-of-River hydropower scheme. There are over 530 of these schemes across Scotland. This type of hydropower generates energy by building an impoundment (e.g weir/dam) across a steep river channel, taking water out of the river, passing it through a turbine and returning it downstream to the channel.



Question 2. ***Do you think that hydropower has any negative impacts on river catchments?***

- Yes
- No
- Don't know

Following the second question, respondents were split into two randomly selected quotas, with each group being shown a different treatment.

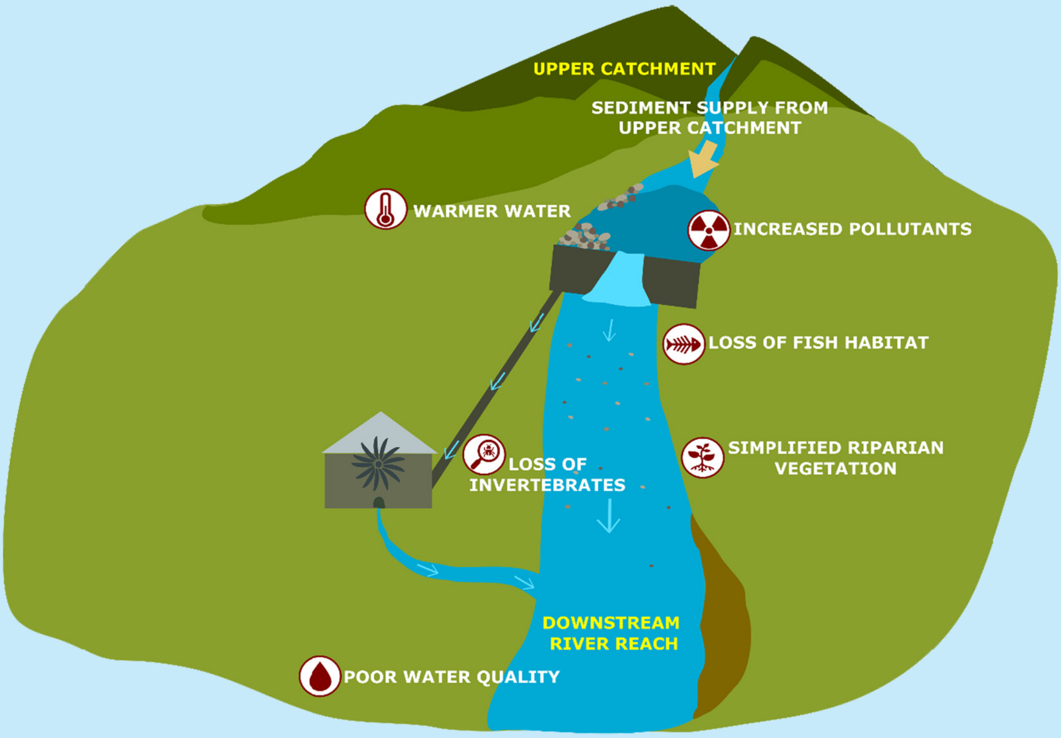
Treatment 1 shows more generalised information about negative environmental impacts of hydropower on river catchments (Box 5) and Treatment 2 shows more detailed information on the negative impacts of hydropower on sediment dynamics within river catchments (Box 6).

TREATMENT 1 (environmental): 468 respondents

Respondents within Treatment 1 were only shown the negative environmental impacts that hydropower schemes can have on river catchments, with no information about how sediment continuity links to them. Negative impacts for use in the survey were selected based upon a review of relevant literature (Kuriqi *et al.*, 2021) and simplified for the general public audience.

Box 5: Diagram shown to Treatment 1 respondents to introduce negative environmental impacts of hydropower on river catchments

Negative impacts on river catchments can affect fish, wildlife and plants in (in-channel) and near the river channel (riparian). The graphic below shows a range of negative impacts that hydropower schemes can have on river catchment health in Scotland.



Question 3a. ***Which factor do you think is the most important to maintain healthier rivers?***

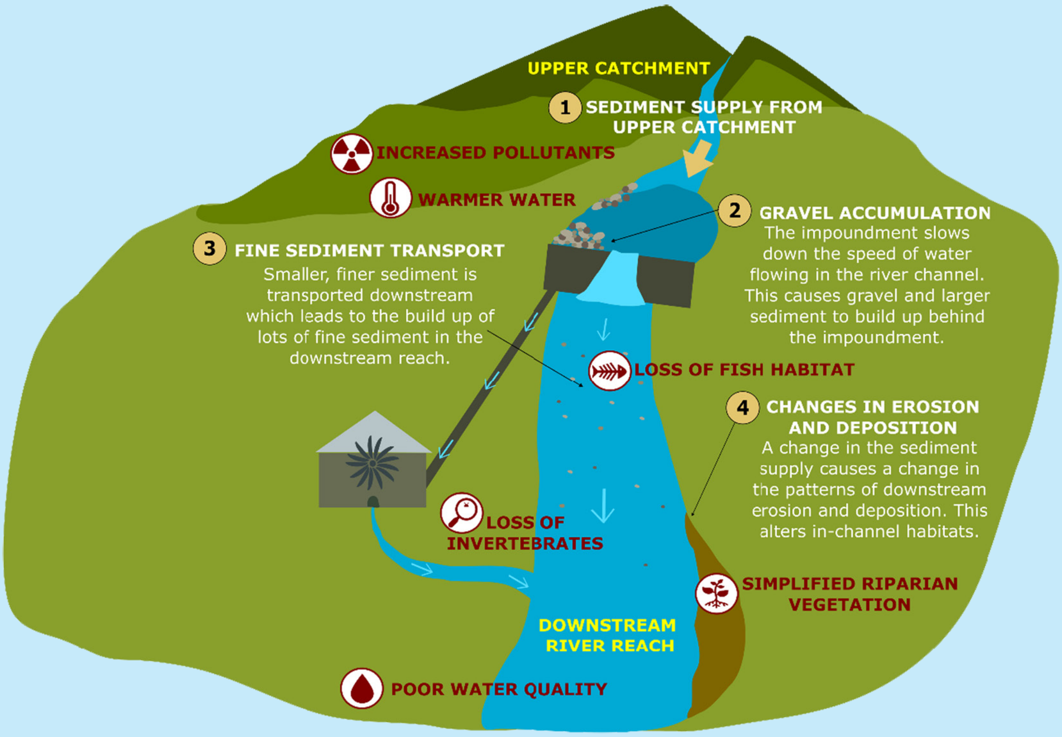
- Sediment moving freely down the river
- Water moving freely down the river
- Difficult to decide
- Don't know

TREATMENT 2 (sediment): 464 respondents

Respondents within Treatment 2 were shown the negative environmental impacts that hydropower schemes can have on river catchments, along with information on how sediment continuity links into them. Negative impacts on sediment continuity for use in the survey were selected based upon a review of relevant literature (Petts and Gurnell, 2005) and simplified for the general public audience.

Box 6: Diagram shown to Treatment 2 respondents to introduce negative environmental and sediment continuity impacts of hydropower on river catchments

Negative impacts on river catchments can affect fish and wildlife, plants in (in-channel) and near (riparian) the river channel. The graphic below shows a range of negative impacts that hydropower schemes can have on river catchment health and sediment dynamics in Scotland.



Question 3b. ***Which factor do you think is the most important to maintain healthier rivers?***

- Sediment moving freely down the river
- Water moving freely down the river
- Difficult to decide
- Don't know

Most respondents believed that water moving freely down the river was most important to maintain healthier rivers. Of those, 315 respondents were in Treatment 1 and 304 were in Treatment 2. Of those who selected sediment moving freely down the river, 68 were in Treatment 1 and 88 were in Treatment 2. This indicates that the inclusion of negative sediment impacts as part of Treatment 2 had some influence on the opinion of the importance of sediment continuity, despite more people within Treatment 2 selecting the sediment option.

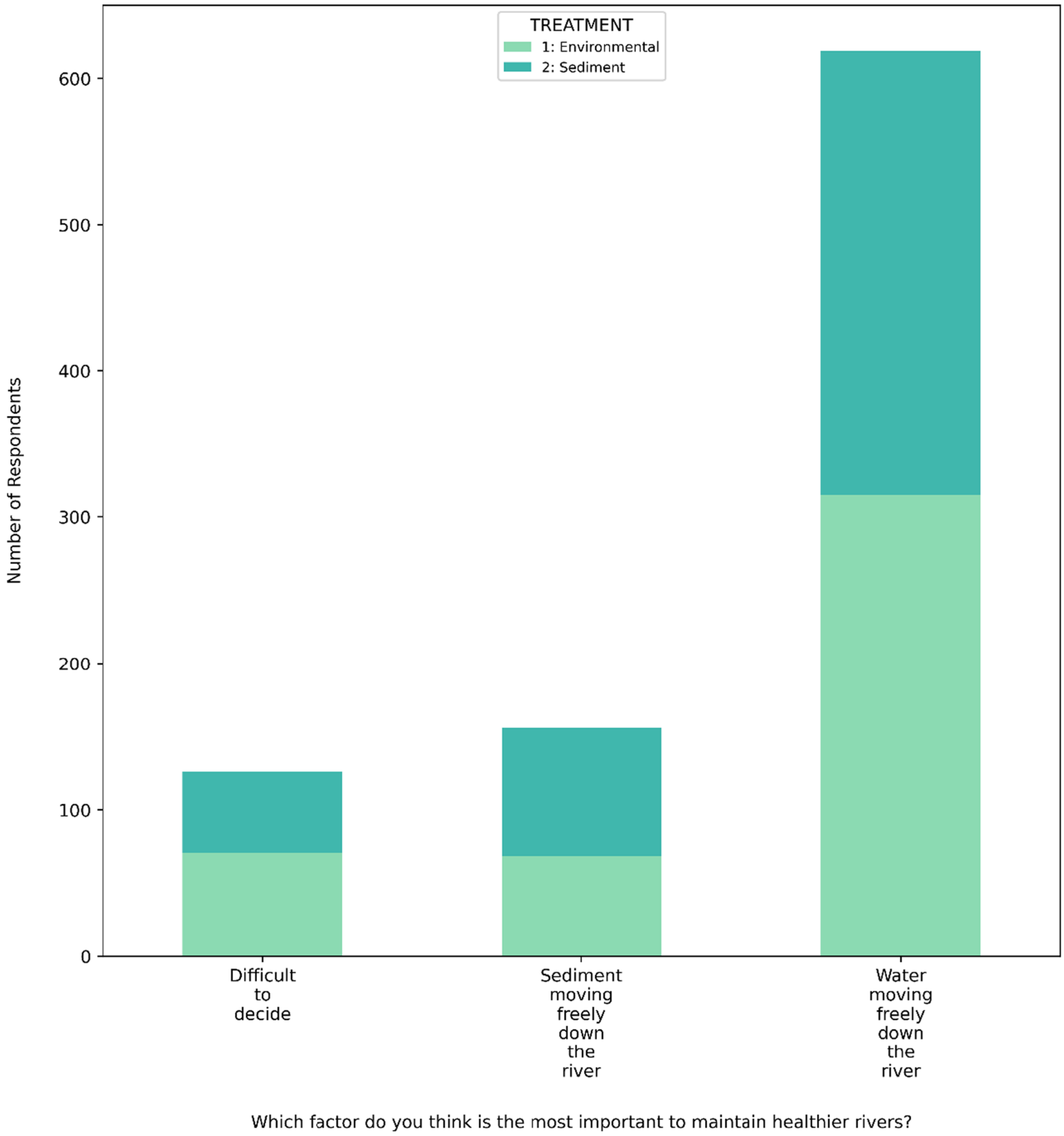


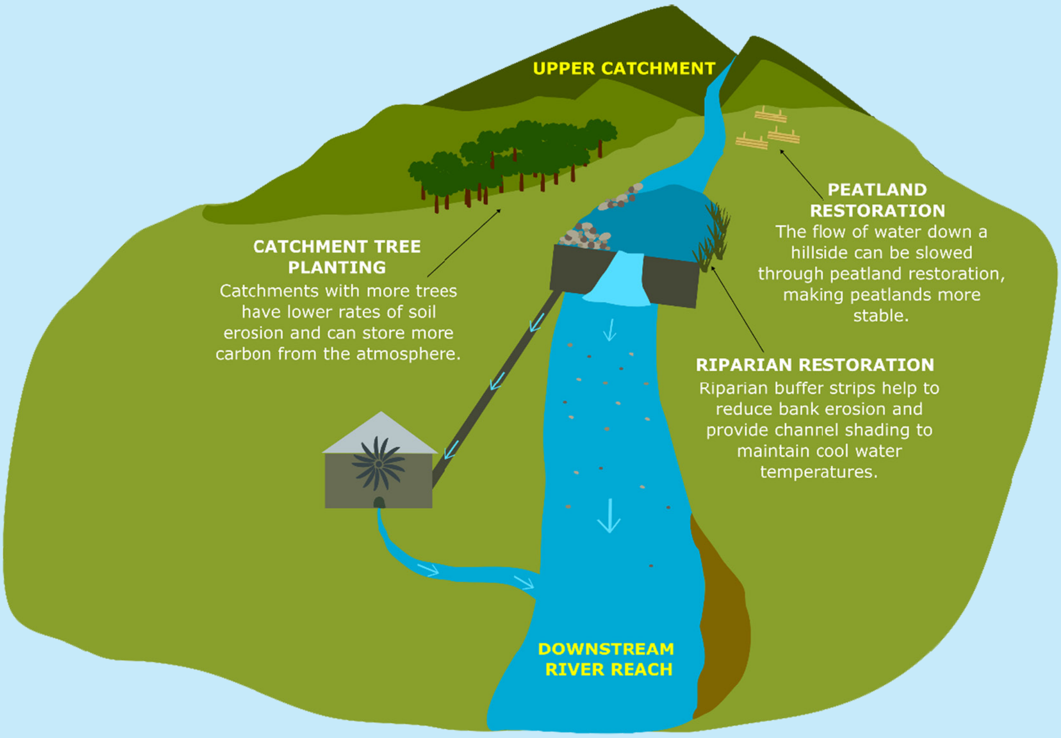
Figure 5.3. Respondents' selections when asked which factor is the most important to maintain healthier rivers, split by treatment 1 (environmental) and 2 (sediment).

Respondents were then introduced to three types of catchment improvement actions that could be used to reduce the degree of sediment accumulation resulting from hydropower schemes by reducing the volume of sediment delivered into hydropower impoundments (Box 7). Catchment tree planting, peatland restoration (Dadson *et al.*, 2017) and riparian restoration (Broadmeadow and Nisbet, 2004) were selected as they are popular techniques across upland Scotland to address catchment sediment continuity issues and can provide a range of other environmental benefits.

Respondents were most aware of catchment tree planting as a catchment improvement action, followed by peatland restoration and then riparian restoration. 364 respondents were not aware of any of the catchment improvement actions presented to them.

Box 7: Diagram shown to respondents to introduce catchment improvement actions

The graphic below shows the types of actions that could be carried out in the upper catchment (upstream of impoundments) to improve river health in Scotland.



Question 4. ***Before this survey, which of these actions to improve river catchment health were you already aware of? Please select all that apply.***

Please use the above to help you understand the options listed below.

- Catchment tree planting
- Peatland restoration
- Riparian restoration
- None

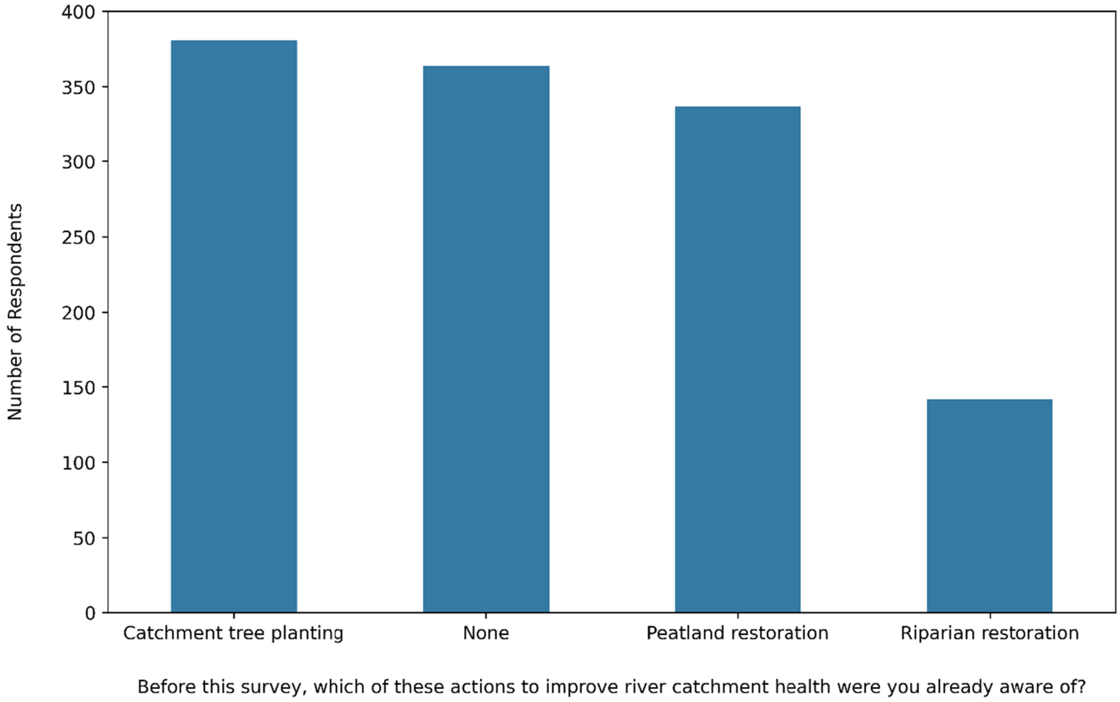


Figure 5.4. Catchment improvement actions introduced within the survey and number of respondents that were already aware of each method.

Figure 5.5 shows the results from question 5 (Box 8). Based upon respondents' own knowledge and the more detailed information presented to them in the survey, stable peatlands were more often ranked as most important for improving river catchment health, followed by increased catchment woodland cover. Options relating to catchment sediment dynamics were more often ranked as less important.

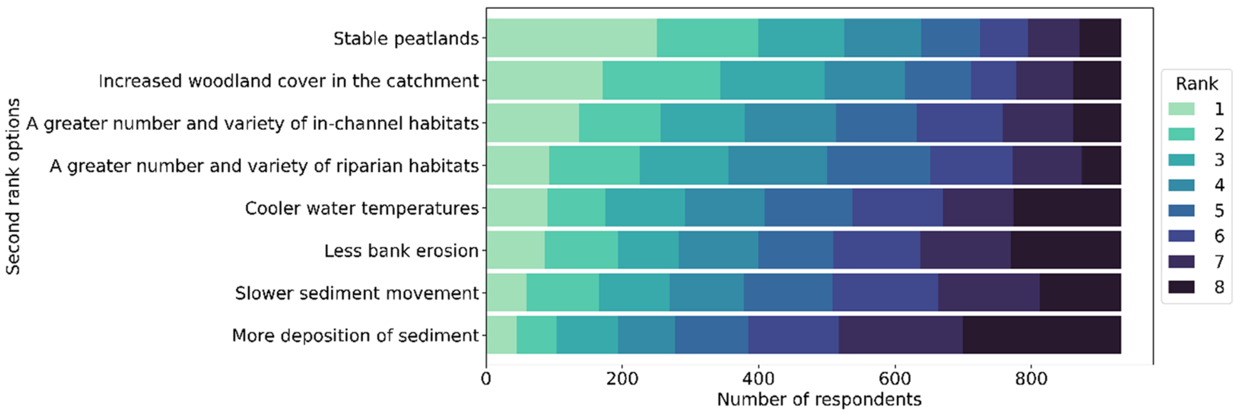
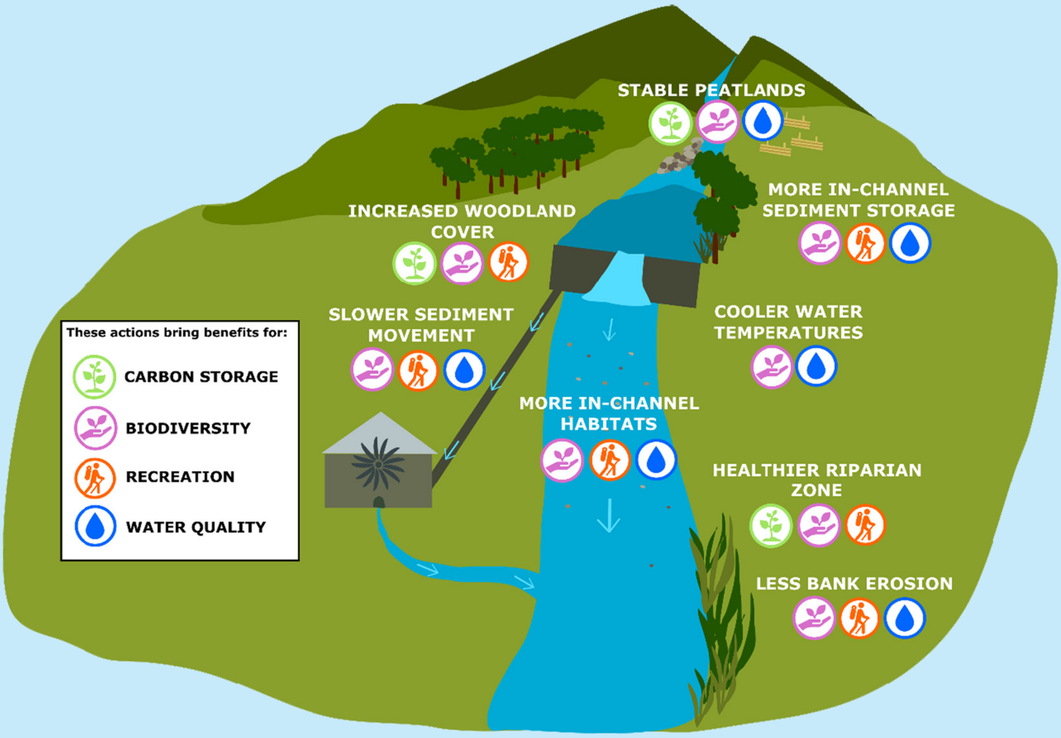


Figure 5.5. Respondents' rankings of factors affecting river catchment health after being shown more technical information in the survey. Lighter colours indicate options that were most often ranked as more important for river catchment health, darker colours indicate options that were most often ranked as less important.

Box 8: Diagram shown to respondents to highlight the benefits of river catchment improvements

The graphic below shows the river catchment benefits that could be seen in Scotland by 2040 if the improvements described in the previous question were carried out in 2025.



Question 5. ***Now that you have been given more information, what do you think is important for improving river catchment health? Rank these in order from most important = 1, to least important = 8.***

- Increased woodland cover in the catchment
- A greater number and variety of riparian habitats
- Less bank erosion
- More deposition of sediment
- Cooler water temperatures
- A greater number and variety of in-channel habitats
- Stable peatlands
- Slower sediment movement

5.2.2.2 Willingness-to-Pay Questions

After introducing participants to possible catchment improvement actions, household preferences for implementing these changes across relevant catchments in Scotland were valued. Firstly, respondents were shown the information in Box 9 to determine whether in principle they would be willing to pay anything towards catchment improvement actions to achieve the catchment-wide benefits shown to them.

If respondents answer no, they were taken to Question 7a (Box 10). If respondents answer yes, they were taken forward to Question 7b (Box 11). Of the 932 respondents, 462 stated that they would be willing to pay (WTP) towards catchment improvements (Figure 5.6). This means that 470 respondents were not willing to pay (Figure 5.7), which likely signals zero perceived benefit and/or an inability to pay for the changes (indeed, as we see below, this inability to pay characterises most zero bids). Both count as "genuine zeros" in cost-benefit analysis. Of those not WTP, 224 respondents were shown treatment 1 (environmental) and 246 were shown treatment 2 (sediment).

Box 9: WTP screening question shown to respondents

To achieve these benefits across all Scottish catchments containing a hydropower scheme (at least 530 catchments), there is a cost. One way of meeting this cost is by increasing household taxes and expenditure across Scotland over the period 2025-2040. If the improvements were carried out next year in 2025, we would start to see these benefits in 2040.

Question 6. ***In principle, would you be willing to pay anything towards these improvements through an increase in your household taxes and expenditure over the period 2025-2040?***

- Yes
- No

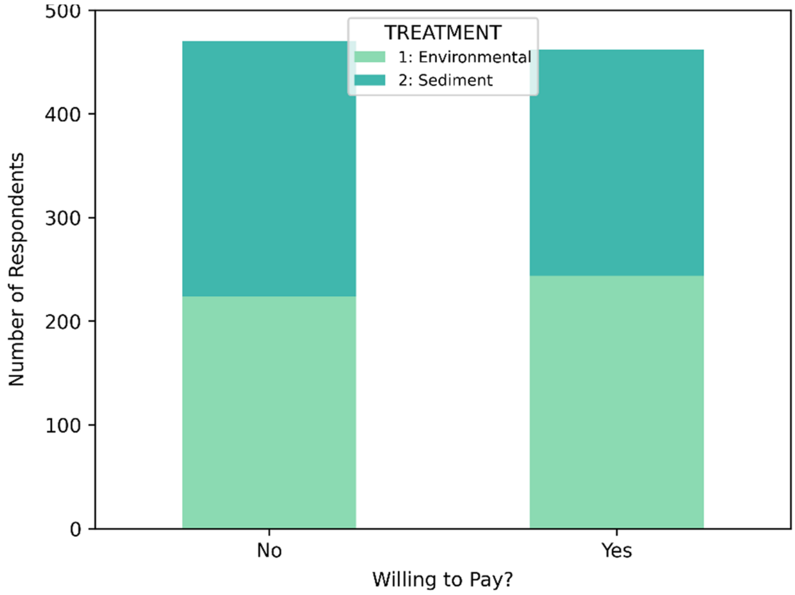


Figure 5.6. Number of respondents willing to and not willing to pay for catchment improvement actions, split by treatment 1 (environmental) and treatment 2 (sediment).

Box 10: Question shown to respondents who were not WTP to determine reasoning

Question 7a. ***Why would you not be willing to pay anything towards these improvements through an increase in your household taxes and expenditure over the period 2025-2040?***

- I can't afford it
- I am not interested in improving Scottish river catchment health
- Other (please explain why)

73 respondents selected the 'Other' category and were provided with a text entry box to explain their choice. Themes commented on by respondents included:

- Catchment improvement action costs should be covered by taxes as they are already high
- Catchment improvement action costs should be covered by hydropower operators
- Catchment improvement action costs should be covered by Government
- Other services should take financial priority (e.g NHS)
- Not convinced that money would be spent on catchment improvement actions

People who responded in the ways listed above were classified as protest bids.

The data used to estimate mean WTP is the highest maximum amount that people were sure that they would be willing to pay towards catchment improvement actions. Responses ranged across all the payment ladder levels in Box 11. The average maximum value that respondents were willing to pay for catchment improvements was £52 per year (Figure 5.8). Respondents that were shown Treatment 2, which includes information on how hydropower negatively impacts sediment dynamics were willing to pay more than those who were shown Treatment 1, which only includes information on negative environmental impacts. This was a statistically significant difference at a 95% confidence interval (Table 5.1).

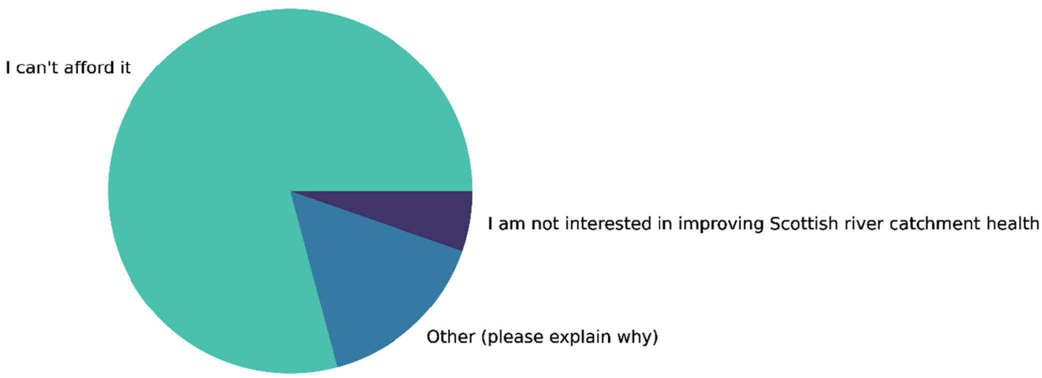


Figure 5.7. Reasons why respondents were not willing to pay for catchment improvement actions.

Box 11: Payment ladder question shown to respondents who were WTP, to determine the annual amount

Question 7b. ***To see these catchment benefits in 2040 across Scotland, over the period of 2025-2040, how much would you be willing to increase your household taxes and expenditure by? Tick yes for all amounts that you are SURE you would be willing to pay, and tick no for all amounts that you are SURE you would not be willing to pay. Remember, if you say that you would be willing to pay an extra £100 per year, for example, you would have to reduce your spending on other things by this amount. Think hard about whether you'd be willing to do this.***

Amount	Yes	Not sure	No
£5 per year			
£10 per year			
£25 per year			
£50 per year			
£75 per year			
£100 per year			
£150 per year			
£250 per year			
£500 per year			

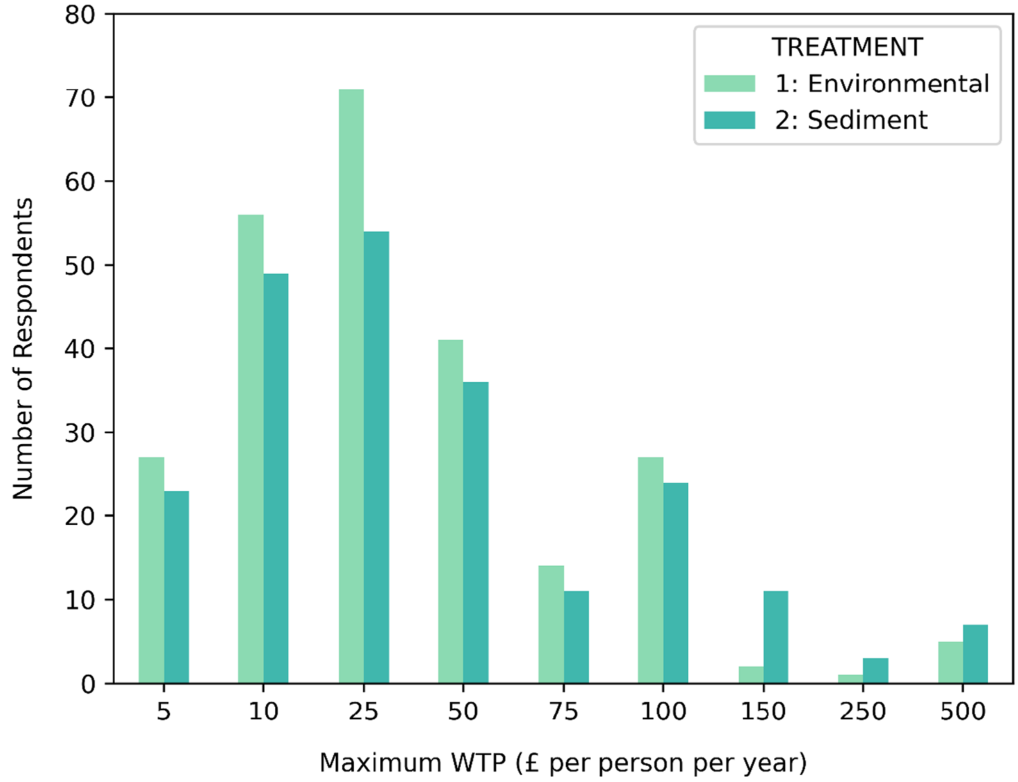


Figure 5.8. Maximum amount that respondents were willing to pay per person per year for catchment improvement actions, split by treatment 1 (environmental) and 2 (sediment).

Table 5.1 WTP values with upper and lower 95% confidence value intervals for full WTP group, and each treatment.

	Full WTP group	Environmental (Treatment 1)	Sediment (Treatment 2)
Average maximum yes	£52.00	£46.00	£59.00
Lower 95% confidence	£44.40	£36.72	£46.73
Upper 95% confidence	£59.60	£55.28	£71.27

On completion of the survey, respondents were given the opportunity to add comments. Comments suggested that, while respondents found that the survey was technical, they could understand and follow it. Overall, respondents found the survey content interesting and the project worthwhile but were concerned about potential increases in household expenditures amidst the cost-of-living crisis, believing that catchment improvement actions should be covered by operators and Government.

5.3 Analysis

The CBA in this study has been undertaken over a 50-year period as the Treasury Green Book recommends staying below a 60-year appraisal period in most cases. The costs of catchment improvement actions only occur within the first year, and the environmental benefits occur from year 15, as this is estimated to be when catchment improvement actions are expected to have an impact on sediment delivery rates. To adjust net benefit values for the effects of time preference (the phenomenon whereby people value benefits more highly the sooner they are received) (Hanley *et al.*, 2009, 2013), the recommended Treasury Green Book discount factors of 3.5 % for the first 30 years and 3.0 % for the following 20 years of the CBA has been applied to convert all benefit and cost flows into consistent present value terms. We assume that the effects of the catchment improvement options eventually reduce the need for operators to continue to engage in sediment removal, and that there is thus no loss in power outputs due to sedimentation. Note that we lack estimates of the private net benefits (profits) of each unit of electricity produced, since no operator would disclose these values to us.

We held a workshop with hydropower owners and operators at the start of this project (Section 2.2) and developed opportunities for the hydropower community to contribute to the cost-benefit analysis by sharing information on their schemes. We are very grateful to Koehler Renewable

Energy UK Limited for their willingness to share information and enable us to undertake this component of the project. For this report, we have used a hypothetical catchment similar to the Allt an t-Sidhean hydro catchment (area of 2.005 km^2) as a representative catchment for the CBA, as operator sediment management costs were estimated based upon information provided to the research team by Koehler Renewable Energy UK Limited.

5.3.1 Stated Preference Contingent Valuation Survey Result

The stated preference contingent valuation survey obtained an average annual maximum WTP value of £52 per year for the survey sample population. This value was scaled up across all Scottish households (2.55 million according to the 2022 census) to provide an average annual maximum WTP value if every household in Scotland was willing to contribute £52 per year towards catchment improvement actions. Note that this accommodates a scaled frequency of households who were not willing to pay, since the mean sample WTP is weighted for WTP zero bids. The WTP total was subsequently scaled across all 'relevant' (see below) catchments in Scotland to obtain an average annual maximum WTP value per km^2 of relevant catchments. This value can then be used for CBA calculations for specific catchments.

'Relevant' Scottish catchments were defined using a SEPA dataset containing the locations of licenced hydropower impoundments up to June 2020. Data included as part of licensing includes the size of impoundments (e.g., small RoR and large storage reservoirs) and operator types (e.g., private and commercial) but does not include catchment area, which was needed for our calculations. We therefore manually sampled 20% of this dataset (545 impoundments) and derived catchment areas using the Flood Estimation Handbook (FEH) Web Service. It is important to note that the FEH is less effective at detecting smaller catchments, due to the coarse nature of the topographic data used to derive the hydrological network, therefore any catchment with an area <0.5 km^2 was assigned a value of 0.25 km^2. The median area of sampled catchments was taken (1.99 km^2) and then scaled to estimate the total area of catchment upstream of impoundments in Scotland, this was estimated to be 5406 km^2.

5.3.2 Operator Sediment Management Costs

Sediment management costs were provided by Koehler Renewable Energy UK Limited and relate to a one-off sediment management event at their site Allt an t-Sidhein Hydro which occurred early in 2024. Note that these costs are generalised and only for use in indicative estimates. The costs are broken down as:

- Sediment dredging (i.e., excavating received sediment from the impoundment): £11,350
- Pipeline pigging (i.e., mechanically removing sediment build-up from pipes): £2,000
- Energy generation loss due to shut-down: £22,500 (note: this is a gross revenue figure, and so is of limited use in indicating the net benefits foregone, which are equal to profit foregone – not revenue foregone)
- Spare parts: £35,000

John Cuthbert, Asset Manager at Koehler Renewable Energy UK Limited noted that dredging is expected to occur annually, so the CBA incorporates these figures as an annual amount (the present value of which declines over time). For this analysis, we assume that such operator annual sediment management costs are reduced by three different scenarios (25%, 50% and 75%) when sediment is managed on a catchment scale; this benefit occurs from year 15 of the CBA. Separate calculations were estimated for Summer and Winter management, with the latter including the energy generation loss due to shut-down (£22,500). It was assumed that this would not occur in the Summer months due to low flows, hence negating the need for shut-down. Separate calculations were also undertaken to include and exclude the cost of spare parts.

5.3.3 Catchment Improvement Action Costs

The selected catchment improvement options (catchment tree planting, riparian corridor woodland planting and peatland restoration) were chosen as they are applicable to Scottish catchments (Scottish Forestry, 2022; Peatland Action, 2024; Scottish Forestry, no date). Catchment tree planting and peatland restoration both reduce sediment yield in a similar way, through slowing the flow of water through a catchment, reducing erosion (Allot, *et al*., 2019) and hence the volume of sediment entering river channels. Riparian tree corridor woodlands stabilise riverbanks and reduce more localised fluvial erosion (The Riverwoods Science Group, 2022). Estimated costs for catchment improvement actions were provided by the Dee Fishery Trust and McGowan Environmental. It is acknowledged that costs may vary depending on techniques used but information from other organisations were not available for this study. The upper limits of these estimates, including VAT have been scaled for use within the CBA in this study and are outlined below:

Dee Fishery Trust (costs exclude pre-planting administration e.g. peat depth survey, woodland design etc)

- Catchment tree planting: £1,920,000 per km^2
- Riparian corridor woodland: £2,440,000 per km^2

McGowan Environmental

- Peatland restoration: £100,500 per km^2

To utilise the riparian corridor woodland planting cost, the viable area of the Allt an t-Sidhein catchment was estimated using SEPA's Recommended Riparian Corridor Layer for using in Land Use Planning (SEPA, 2024). For Allt an t-Sidhein, a 15 m buffer has been recommended for riparian planting, generating a target area of 0.3 km^2 which represents 15% of the FEH derived catchment area. This value was used as the target riparian planting area for our hypothetical catchment.

5.3.4 Cost-Benefit Analysis Scenarios

To calculate the net benefits of catchment improvements for each year for the hypothetically 'average' catchment (area of 2 km^2), we used the provided catchment improvement action costs and calculated benefits (i.e., the WTP value for social benefits and reduction in operating costs). These were corrected using discounting to generate present values for each year of the CBA and the sum of annual present values (i.e., Net Present Values, NPVs) were then calculated. Positive NPVs indicate that the benefits associated with catchment improvement actions outweigh the costs associated with managing sediment on a catchment scale from the viewpoint of Scotland as a whole. Negative NPVs indicate that the costs associated with managing sediment on a catchment scale outweigh the benefits associated with catchment improvement actions from the viewpoint of Scotland as a whole. We have evaluated a range of catchment improvement action scenarios for the hypothetical catchment within this study, as well as seasonal management cost saving scenarios. These are shown in Table 5.2 for Winter management and Table 5.3 for Summer management. It is important to note that as these restoration scenarios are based upon a hypothetically 'average' catchment, we assume that the area available for restoration is suitable for the outlined improvements. For example, we assume that 50% of the catchment area is covered by degraded peatland.

For all sediment cost management savings scenarios, riparian planting and peatland restoration generated positive NPVs. Catchment tree planting generated *mostly* positive NPVs apart from when management cost savings are below 75%, including spare parts in Summer and Winter, and below 50% excluding spare parts in the Winter. The sensitivity of these NPVs to individual WTP was also tested using the lower (£44.40) and upper bounds (£59.60) of the 95% confidence interval of average maximum WTP per person per year. When using the lower bound of the 95% confidence interval, changes from positive to negative NPVs were only observed within catchment tree planting scenarios (four occurrences). When using the upper bound, changes from negative to positive NPVs were also only observed within catchment tree planting scenarios (three occurrences). Despite catchment tree planting being cheaper per km^2 than riparian planting, it generates negative NPVs due to the area over which catchment planting is applied. For example, if catchment planting only occurred over 30% of the catchment area, positive NPVs are generated across all scenarios. Details regarding these results can be found in Appendix E: Cost-benefit analysis scenarios. These NPVs demonstrate that in most scenarios, catchment scale improvements are a cost-effective way for society to reduce sediment yield from the hypothetically 'average' catchment used in this cost-benefit analysis.

Table 5.2. Cost-benefit analysis scenarios run as part of this study for Winter management, assuming electricity generation loss. Figures in green represent positive NPVs, those in red represent negative NPVs.

	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	+£1,089,500	+£1,211,400	+£1,333,300	+£732,500	+£973,400	+£1,214,300
Catchment tree planting covering 50% catchment	−£56,000	+£65,900	+£187,800	−£413,000	−£172,000	+£68,800
Peatland restoration covering 50% catchment	+£1,706,300	+£1,828,200	+£1,950,100	+£1,349,300	+£1,590,200	+£1,831,100

Table 5.3. Cost-benefit analysis scenarios run as part of this study for Summer management, assuming no electricity generation loss. Figures in green represent positive NPVs, those in red represent negative NPVs.

	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	+£1,319,100	+£1,364,500	+£1,409,800	+£962,000	+£1,126,400	+£1,290,800
Catchment tree planting covering 50% catchment	+£173,500	+£218,900	+£264,300	−£183,500	−£19,100	+£145,300
Peatland restoration covering 50% catchment	+£1,935,900	+£1,981,200	+£2,026,600	+£1,578,800	+£1,743,200	+£1,907,600

6 Video and infographic

A video (objective 5) and infographic (objective 6) were produced to share knowledge from both the previous CREW project (Williams *et al.*, 2022) and this project.

6.1 Video

Videos are effective educational tools that can enhance engagement with a topic when they are brief, targeted, signal important ideas, and when a conversational and enthusiastic style is used to convey information (Brame, 2016). During the stakeholder workshop, participants were asked to provide input regarding the best target audience for the video and what topics they would like to be covered (see Box 1). Participants felt that the video should be suitable for a wide range of viewers, for example, the variety of participants who attended the workshop which included representatives from regulators, hydropower operators and designers, and environmental consultants and NGOs. Recommended topics included an explanation of natural river processes and particularly the importance of sediment in these processes, examples of good sediment management practices, and guidance for creating sediment management plans. Following a PSG meeting to discuss this participant feedback, the suggested key messages for the video were determined to be:

1. Allowing sediment to travel naturally down a river underpins good river health

    1.1. Include a simple narrative on how a river works including sediment transport.

    1.2. Stress the importance of sediment for river habitats complexity and diversity.

    1.3. Highlight sediment discontinuity problems, for instance at impoundments.

2. Climate change will increase sediment management challenges in many rivers

    2.1. Provide a description on projected climate changes for Scotland.

    2.2. Outline the sediment transport consequences of this change.

    2.3. Outline the implications for management of river impoundments.

3. Good sediment management practices should improve the resilience of river infrastructure and ecosystems

    3.1. Describe what constitutes good sediment management.

    3.2. Provide a case study example of good sediment management.

    3.3. Win-Win-Win! Argue for river resiliency through good sediment management.

Subsequent to the agreement of these key messages, a video brief was produced which was sent to a shortlist of four video production companies, as part of the University of Glasgow procurement process. Mallard Productions were selected to film and produce the video. Through the relationships developed with hydropower operators during and following the stakeholder workshop, representatives from two hydropower operator companies participated in filmed interviews and three companies allowed filming of their hydropower sites. We recommend that the video is made widely available, through CREW, SEPA, and NatureScot's websites, and that it is shared during the project dissemination event.

The video can be found at: crew.ac.uk/publication/hydro-impoundments-sediment-management

6.2 Infographic

Stakeholder workshop participants suggested a variety of alternative formats to communicate information on sediment management best practice at impoundments (see Box 1). Following discussions with the PSG, an infographic was selected as the most suitable medium to communicate the same key messages to the same target audience as the video. Infographics are a useful tool for increasing research outreach as well as improving information retention and topic understanding (Murray *et al.*, 2017). The infographic is available at: crew.ac.uk/publication/hydro-impoundments-sediment-management

7 Framework for planning the sediment management aspects of a hydropower scheme permit application or review

A framework was developed (objective 7) to guide applicants and SEPA staff towards an environmentally-progressive, cost-beneficial and consistent approach to hydropower scheme Permit Authorisations or Renewals (Figure 7.1). This section provides the rationale for this framework. The framework is intended to be suitable for inclusion in CAR guidance documentation following review for suitability by SEPA's Water Permitting and Water Policy Teams. With the addition of supporting text, we recommend that the framework is integrated as an Annex into one of SEPA's Guidance Documents to guide applicants and SEPA staff through the process of conceiving, designing, authorising and implementing a sediment management strategy. As SEPA is in the process of updating its guidance documents to support implementation of the Environmental Authorisations (Scotland) Regulations 2018 (EASR), (C. Bromley, *pers. comm.*), the framework has been developed without a specific Authorisation or Guidance Document in mind.

The guidance framework is based on the recommendations resulting from the earlier phase of this study (Williams *et al.,* 2022), and new knowledge and guidance stemming from the tasks performed in this project. The task list also accommodates the potential implications of climate change on Scottish hydropower as a consequence of predicted increases in future storm frequency (Adaptation Scotland, 2021), and subsequent anticipated increases in the volume and size of transported sediment (see Appendix F). The framework should suit both RoR and permanent water storage hydropower and water supply schemes as the sediment management implications for each are not particularly different. The short-term expectation is for permit applications designed to turn many RoR hydropower schemes into permanent impoundments (C. Bromley, *pers. comm.*). The framework has been styled after several related frameworks including those that provide guidance for sediment management during dam removal (Downs *et al.,* 2009; USBR, 2017) and planning for sustainable river restoration (Skidmore *et al.,* 2011).

The guidance framework was initiated by categorising all 29 recommendations made in the previous project phase (Williams *et al.,* 2022) according to their role in the licensing process for operators or SEPA. Following discussions with SEPA about the overarching scope of the framework, recommendations were grafted into the overall process of hydropower development (or renewal/modification) from project inception through to final monitoring and evaluation of the implemented scheme (Figure 7.1). To break the various tasks into manageable pieces, the framework was subdivided into three elements covering planning, design, and implementation and monitoring, with each element containing two or three processes. The scheme emphasises the need to consult with a SEPA coordinating officer both during project initialisation (or renewal) and prior to the licence application (tasks 1 and 7, respectively), to better ensure licensing efficiency and success. The framework also emphasises the need to assess geomorphological setting of the project (tasks 2 and 3), and environmental and commercial operational viability of the project (tasks 4 and 5), prior to selecting and justifying the preferred option (task 6). These steps form the basis for the second discussion with a SEPA coordinating officer (task 7) at which various mitigation actions and climate change adaptation plans can be formulated (task 8) and a suitable monitoring and evaluation plan developed (task 9). Project implementation would follow a successful licence application (task 10) after which monitoring of various simple sediment measurements (task 11) provide the basis for an annual submission to SEPA. The submission would allow SEPA to develop documentary evidence for site-specific and proportionate regulation as well as generalised best practices for future applicants (task 12).

Each of the 12 tasks requires actions which range from discussions through to field or model-based assessments, and these actions are symbolised in Figure 7.1. Some of the actions are straightforward and commonplace, while others are novel and represent the development of existing applications towards an environmentally-progressive, cost-beneficial and consistent approach to hydropower development as the basis for sustainable hydropower generation in Scotland. The novel items are those that will eventually require further guidance. These items are listed in Table 7.1, with an indication of the necessary guidance or actions.

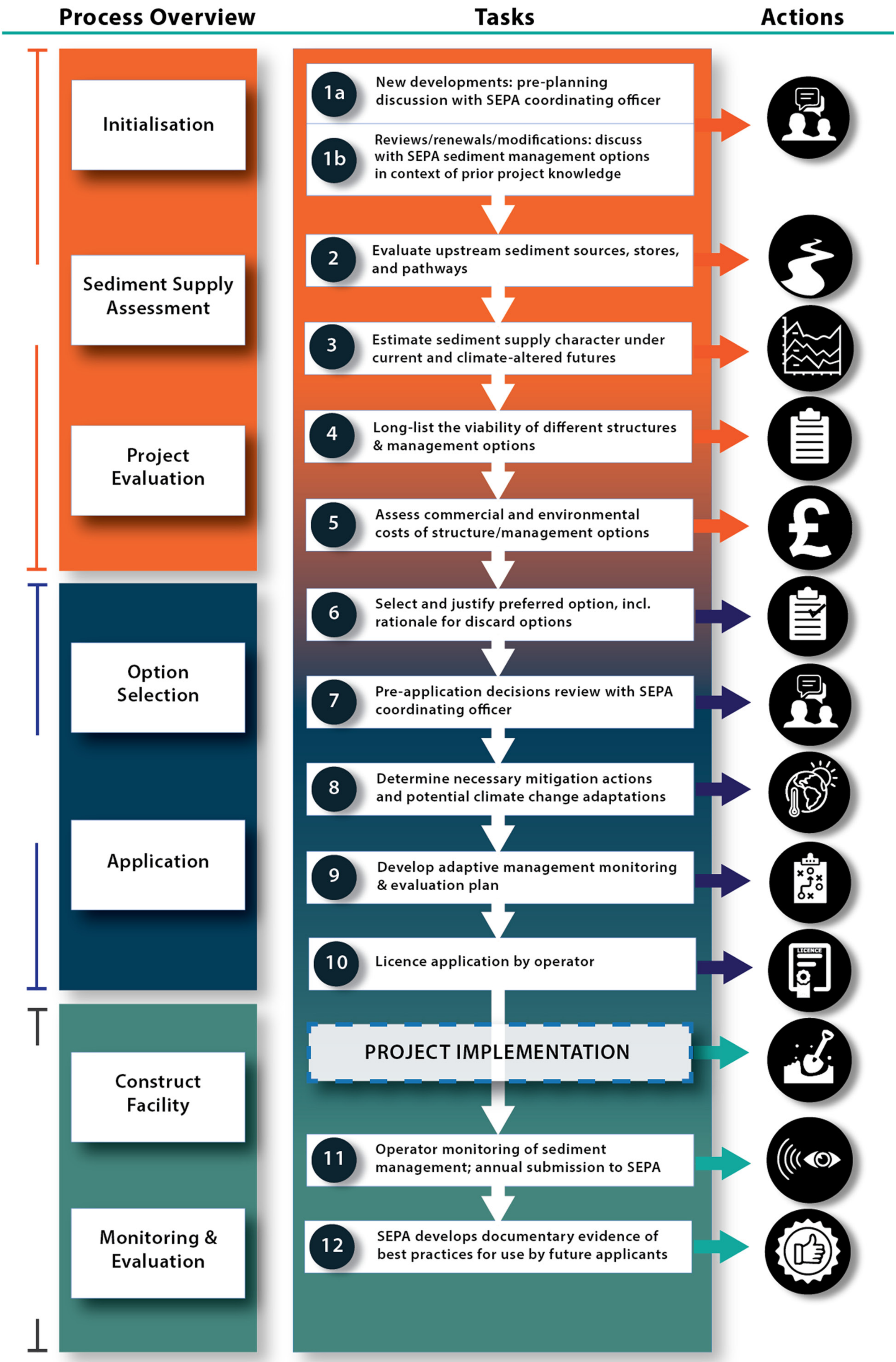


Figure 7.1. Guidance framework for sediment best practice during hydropower licence applications.

Table 7 1. Recommendations for additional guidance need for several of the tasks outlined in Figure 7.1.		
Task Number	**Task action**	**Guidance required, and status**
2	Evaluate upstream sediment sources, stores and pathways	Field and/or desk-based geomorphology assessment by competent party. It is likely that a simple GIS-based computer model can be developed for this purpose.
3	Estimate sediment supply character under current and climate-altered futures	Simple computations of potential sediment volumes and sizes under current and future conditions, guided by climate change forecasts. Such capacity is being developed, see Appendix F.
4	Long-list the viability of different structures and management optionss	Based around the list of options developed by Morris and others (Kondolf, *et al.*, 2014, Morris, 2016, 2020).
5	Assess commercial and environmental costs of structural/management options	Potentially based on the development of a model for cost-benefit evaluation similar to that illustrated in section 5.
8	Determine necessary mitigation actions and potential climate change adaptations	Developing various options for sustaining the project's viability thought best sediment management practices at instream, riparian and/or catchment scales, developed in discussion with a SEPA coordinating officer (see also Williams *et al.,* 2022).
9	Develop an adaptive management and monitoring plan	Plan developed using guidance and examples from a SEPA coordinating officer, to include monitoring requirements (see also Williams *et al.,* 2022).
11	Operator monitoring of sediment management; annual submission to SEPA	Using simple guidelines provided by SEPA (guidance in Williams *et al.,* 2022), and refined as the documentary evidence base (task 12) is developed.

8 Recommendations

The theory of change flow chart (Figure 3.1) illustrates how the long-term goals of this project can be achieved. Below, we supplement the detail presented in Figure 3.1 with recommendations related to raising awareness of the importance of sediment management within the hydropower community, better understanding of the costs associated with different sediment management options and developing a community of hydropower practitioners.

8.1 Raising awareness of the importance of sediment management within the hydropower community

- SEPA, NatureScot, and Scottish Canals Project Steering Group representatives should share the report from the earlier CREW project (Williams *et al.,* 2022) alongside the outputs from this project (report, theory of change, cost benefit analysis, video, infographic and management framework) to relevant colleagues to raise awareness of sediment management within the regulatory hydropower and impoundment community. Such sharing should be repeated at a regular (e.g. annual) frequency to maintain awareness.
- SEPA Water Permitting and Water Policy teams should modify new hydropower application forms and associated guidance documents to facilitate the process outlined in Figure 7.1, and create suitable information submission templates.
- SEPA and NatureScot should update their joint hydropower guidance to improve environmental protection, reduce the risk of reputational damage, and improve the efficiency of the permitting process whilst also improving engagement between regulators and operators.
- Project outputs should be shared via SEPA and NatureScot's websites, supported by any associated media outreach by SEPA and NatureScot's media teams, which could coincide with the project's proposed dissemination event (see below).
- Operators should use project outputs to consider site specific sediment-related environmental and commercial risks both in the short and long-term, particularly considering the context of expected climate change in Scotland. This will improve river health and commercial resilience.
- Monitoring and evaluation activities should be designed and implemented to evaluate the actual benefits of the project.

8.2 Improving understanding and raising awareness of the benefits and costs associated with the sediment management options available to address the environmental and commercial risks to hydropower and water supply impoundments

- Investigate means of incentivising catchment improvement actions where the cost-benefit analysis shows positive values over a reasonable range of likely scenarios. Our analysis shows that, in most cases, catchment improvement measures generate a positive Net Present Value from society's viewpoint, but neither hydro operators nor landowners will typically be able to capture these benefits as private revenues. This problem may be eased by the growth of 'nature markets' associated with biodiversity, carbon and water quality credits. Private landowners would need the ability to capture at least some of these as incentives for undertaking catchment improvement actions.
- Collect more data on the costs and benefits of catchment improvement actions; at present, we only have estimates for a subset of these values. We estimate the overall benefit for the effects of catchment management improvements for a limited set of environmental outcomes; but total benefit could be higher. For example, net carbon sequestration values could be included.
- Undertake additional stated preference work to understand more about the relative benefits of the management options outlined in Table 5.1 and Table 5.2. It would be valuable to learn how, for example, tree planting is valued by citizens relative to peatland restoration. Right now, we value these as a package.

8.3 Developing a practitioner community

Overall, a key finding from stakeholder engagement activities conducted during this project was that more communication and collaboration is required between different stakeholders (e.g. regulators, operators, consultants, hydromorphologists, ecologists, researchers) to improve understanding and knowledge sharing. We recommend that efforts are made to facilitate a Scottish community of hydropower and water supply impoundment practitioners that openly exchange knowledge to enable the mitigation of impoundment impacts on river health and to improve commercial resilience of hydro operations in the context of climate change. Appropriate leadership will be necessary to achieve this. This could be facilitated by CREW, or by the University of Glasgow, but would require further funding.

9 References

Adaptation Scotland, 2021. *Climate projections for Scotland – summary*, report compiled by Sniffer for the Scottish Government, Edinburgh, 14pp.

Allott, T., Auñón, J., Dunn, C., Evans, M., Labadz, J., Lunt, P., MacDonald, M., Nisbet, T., Owen, R., Pilkington, M., Proctor, S., Shuttleworth, E., & Walker, J, 2019. *Peatland Catchments and Natural Flood Management*. Available at: https://research.bangor.ac.uk/portal/files/27930383/Allott_et_al_2019_IUCN_COI_Peatlands_and_NFM_FULL_REPORT.pdf

Blamey, A. & Mackenzie, M., 2007. T*heories of Change and Realistic Evaluation: Peas in a Pod or Apples and Oranges*. Sage Publications, 13(4): 439-499. DOI: 10.1177/1356389007082129

Brame C.J., 2016. *Effective Educational Videos: Principles and Guidelines for Maximizing Student Learning from Video Content*. CBE Life Sciences Education, Winter 2016; 15(4):es6, 1-6. DOI: 10.1187/cbe.16-03-0125. PMID: 27789532; PMCID: PMC5132380.

Broadmeadow, S. & Nisbet, T.R., 2004. *The effects of riparian forest management on the freshwater environment: a literature review of best management practice*. Hydrology and Earth System Sciences, 8(3): 286–305. Available at: https://doi.org/10.5194/hess-8-286-2004

Browning, E., Christie, M., Czajkowski, M., Chalak, A., Drummond, R., Hanley, N., Jones, K.E., Kuyer, J., & Provins, A., 2024. *Valuing the economic benefits of species recovery programmes*. People and Nature, 6(2):894–905. Available at: https://doi.org/10.1002/pan3.10626

Dadson, S.J., Hall, J.W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I.P., Lane, S.N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C., & Wilby, R., 2017. *A restatement of the natural science evidence concerning catchment-based "natural" flood management in the UK*. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 473(2199). Available at: https://doi.org/10.1098/rspa.2016.0706

Downs, P.W., Cui, Y., Wooster, J.K., Dusterhoff, S.R., Booth, D.B., Dietrich, W.E. & Sklar, L., 2009. *Managing reservoir sediment release in dam removal projects: an approach informed by physical and numerical modelling of non-cohesive sediment*. International Journal of River Basin Management, 7:433-452. DOI: 10.1080/15715124.2009.9635401

Hanley, N. & Barbier, E., B., 2009. *Pricing Nature: Cost-benefit Analysis and Environmental Policy.* Cheltenham: Edward Elgar Publishing Limited.

Hanley, N. & Czajkowski, M., 2019. *The Role of Stated Preference Valuation Methods in Understanding Choices and Informing Policy.* Review of Environmental Economics and Policy, 13(2):248–266. Available at: https://doi.org/10.1093/reep/rez005

Hanley, N., Shogren, J. and White, B., 2013. *Introduction to Environmental Economics*. Oxford University Press, Oxford.

IMI (Institute for Methods Innovation), n.d. *Guide: How to Translate Survey Responses into a Theory of Change Diagram Format*. IMI (Institute for Methods Innovation).

Jensen, E., Reed, M., Noles, S. (2022) CREW Strategic Impact Report (Internal report) by the Institute for Methods and Innovation and Fast Track Impact.

Johnston, R.J., Boyle, K.J., Adamowicz, W., Bennett, J., Brouwer, R., Cameron, T.A., Hanemann, W.M., Hanley, N., Ryan, M., Scarpa, R., Tourangeau, R., & Vossler, C.A, 2017. *Contemporary Guidance for Stated Preference Studies*. Journal of the Association of Environmental and Resource Economists, 4(2):319–405. Available at: https://doi.org/10.1086/691697

Kondolf, G. M., Gao, Y., Annandale, G. W., Morris, G. L., Jiang, E., Zhang, J., & Yang, C. T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future, 2, 256-280.

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., & Garrote, L., 2021. *Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition*. Renewable and Sustainable Energy Reviews, 142:110833. Available at: https://doi.org/10.1016/j.rser.2021.110833

Mitchell, R.K., Agle, B.R., & Wood, D.J., 1997. *Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts*. The Academy of Management Review, 22(4), 853–886. https://doi.org/10.2307/259247

Morris, G.L., 2016. *Sediment management techniques*, in Annandale, G. W., Morris, G. L., and Karki, P. (eds). Extending the life of reservoirs: sustainable sediment management for dams and run-of-river hydropower. Washington DC, World Bank Group, 99-126.

Morris, G.L., 2020. *Classification of management alternatives to combat reservoir sedimentation*. Water, 12:861.

Murray, I.R., Murray, A.D., Wordie, S.J., Oliver, C.W., Murray, A.W., & Simpson, A.H.R.W., 2017. *Maximising the impact of your work using infographics*. Bone & Joint Research 6(11):619-620. DOI: 10.1302/2046-3758.611.BJR-2017-0313

NatureScot, 2024. *Peatland action annual review 2023-24: Scottish Government edition*. Available at: https://www.nature.scot/sites/default/files/2024-09/peatland-action-annual-review-2023-24-scottish-government-edition-accessible.pdf

Petts, G.E. & Gurnell, A.M., 2005. *Dams and geomorphology: Research progress and future directions*. Geomorphology, 71(1–2):27–47. Available at: https://doi.org/10.1016/j.geomorph.2004.02.015

Scottish Environment Protection Agency (SEPA), 2024. *Recommended Riparian Corridor Layer for use in Land Use Planning*. Available at: https://www.sepa.org.uk/environment/water/river-basin-management-planning/publications/

Scottish Forestry, 2022. *Scotland's Forestry Strategy: Progress report 2019-2022*. Available at: https://www.forestry.gov.scot/publications/1443-scotlands-forestry-strategy-progress-report-2019-2022/download

Scottish Forestry, no date. *Scottish Forestry Map Viewer, Scottish Forestry*. Available at: https://forestry.gov.scot/support-regulations/scottish-forestry-map-viewer

Skidmore, P.B., Thorne, C.R., Cluer, B.L., Pess, G.R., Castro, J.M., Beechie, T.J., & Shea, C.C., 2011. *Science base and tools for evaluating stream engineering, management, and restoration proposals*. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-112, Springfield, VA, 255pp.

The Riverwoods Science Group, 2022. *Riverwoods for Scotland Report on Scientific Evidence, Riverwoods*. Available at: https://www.riverwoods.org.uk/resource/riverwoods-evidence-review/

United States Bureau of Reclamation (USBR), 2017. *Dam Removal Analysis Guidelines for Sediment*, report produced by the Advisory Committee on Water Information, Subcommittee on Sedimentation, December 2017, USBR Technical Service Center, Denver, CO, 179pp.

Williams, R.D., Downs, P.W., Moir, H.J. & Lavarini, C., 2022. *Sediment continuity through run-of-river hydropower schemes.* CRW2019_02. Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/publication/sediment-continuity-through-run-river-hydropower-schemes

Appendix A: Exercise identifying operational and environmental impacts of sediment discontinuity of hydropower schemes

Figure A.1. Photograph of sticky notes added by the groups to the operational impacts versus the environmental impacts of sediment transport within the context of their hydropower scheme scenario during Activity 3.

Appendix B: Case studies 1 and 2 – Keltie Water

The Keltie Water has a catchment area of ≈53.4 km^2 (UKCEH, 2024a). It flows from its source between the peaks of Meall na Caora and Beinn Bhreac in a southeasterly direction towards the town of Callander where it joins the River Teith, and lies in the eastern boundary of the Loch Lomond and the Trossachs National Park (NatureScot, 2024). Two hydropower sites on tributaries of the Keltie Water were visited on 18th June 2024 as part of this project: a water storage scheme on the Allt a'Chroin, subsequently referred to as 'Intake 1' (Table A.2: Photo 1D), and a RoR scheme on the Allt Breac-nic, subsequently referred to as 'Intake 2' (Table A.3: Photo 2A).

Intake 1 has a catchment area of ≈9.65 km^2 and Intake 2 has a catchment area of ≈10.05 km^2 (UKCEH, 2024a); together these catchments comprise more than a third of the Keltie Water's total catchment area (Figure A.4, Figure A.5). Both catchments are dominated by very low permeability bedrock (UKCEH, 2024b) and have an elevation range of 60 to 900 m AOD (metres above ordnance datum; Figure A.4); Intake 1 is located at approximately 300 m AOD and Intake 2 is located at approximately 310 m AOD (Figure A.4). The Allt a'Chroin is dominated by steep headwater sections with topographically confined channels until approximately 2.5 km upstream of the impoundment at Intake 1 where the valley widens allowing more lateral movement of the channel (Figure A.4). The Allt Breac-nic is also dominated by steep headwater sections with topographically confined channels, the valley remains relatively confined except for a ca. 560 m section located 1.5 km upstream of the weir at Intake 2 and a ca. 250 m section located directly upstream of the weir at Intake 2 (Figure A.4). The average annual rainfall (calculated between 1961-1990) of the catchment at Intake 1 is 2201 mm and Intake 2 is 2021 mm (UKCEH, 2024a). Both sites are encompassed by the Loch Lomond and Trossachs National Park, and downstream of both sites lies a Geological Conservation Review site due to the presence of Dalradian rocks (NatureScot, 2024; Figure A.4). The Keltie catchment is dominated by grassland cover with the same being true for the catchments of Intake 1 and Intake 2 (Marston *et al.,* 2022; Figure A.5); there are also the presence of inland rock patches at the upstream extent of Intake 1's catchment, and a relatively large area of coniferous woodland (likely forestry) surrounding much of the Allt Breac-nic in the mid-catchment area of Intake 2's catchment (Marston *et al.,* 2022; Figure A.5).

Intake 1

The impoundment was completed in 1932 as a water supply reservoir and was converted to storage hydropower in 2015. A large reservoir (Table A.2 : Photo 1C) has formed, stretching ca.240 m upstream, and a 50 m point bar (Table A.2: Photos 1A and 1B) has formed approximately 390 m upstream of the impoundment (Figure A.6). A Wolman Pebble Count (Wolman, 1954) was carried out on two point bar formations; one upstream and one downstream of the impoundment (Figure A.6). The grain size distribution of the surface of the upstream point bar ranges from coarse pebbles to coarse cobbles[1] (i.e., 20-140 mm, Table A.1, Figure A.2). The D_{16}, D_{50}, and D_{84}[2] of the surface were 40, 62.5, and 90.8 mm, respectively, (Table A.1) and the low flow wet channel width immediately upstream of the point bar was 4.3 m. The grain size distribution of the surface of the downstream point bar formed ca. 280 m downstream of the impoundment (Figure A.6, Table A.2: Photos 1F and 1G) ranges from medium pebbles to fine boulders (15-270 mm, Table A.1, Figure A.2). The D_{16}, D_{50}, and D_{84} of the surface were 29.2, 50, and 90 mm, respectively (Table A.1), and the low flow wet channel width at the point bar apex was 3.8 m. The sediment on the point bar upstream of the impoundment was available for active transport (i.e., available to be picked up and carried downstream by the river), whereas the presence of vegetation on the point bar downstream of the impoundment (Table A.2: Photos 1F and 1G) indicates that this bar has likely stabilised and would only provide sediment for transport under fast-flowing conditions capable of stripping the bar surface vegetation. Whilst there is not a huge variation in the sediment distribution between the upstream and downstream point bars according to the Wolman pebble count (Figure A.2), observationally the channel bed downstream of the impoundment is coarser compared to the upstream extent with the presence of bedrock outcrops and dominated by boulders (e.g., Table A.2: Photo 1H). This observed difference in sediment coarseness is likely a result of the presence of the impoundment

[1] Modified Udden-Wentworth grain-size scale from Blair and McPherson (1999)

[2] Sediment mixtures of different particle sizes can be distinguished by comparing the percentile values of the distributions. The notation used is Dx where D represents the particle size (mm) and x represents the sediment size for which a percentage is finer. Specifically, D_{16}, D_{50}, and D_{84} refer, respectively, to the particle size for which 16, 50 and 84% of sample is finer. D50 is the median grain size.

causing downstream sediment starvation and channel incision. The channel morphology upstream of the impoundment is typified by pool-riffle bedforms, whereas downstream of the impoundment, the channel has predominantly a plane bed/step-pool morphology.

The current sediment management plan at this site is to remove accumulated sediment using a mechanical excavator and place the material back into the channel immediately downstream of the impoundment, specifically the minimum volume of sediment removal necessary to maintain efficient operation of the scheme. The operator advised that sediment was dredged in 2015 from the reservoir and was used to create the maintenance tracks from Braeleny Farm to the two hydropower impoundments. These works are the only record of sediment excavation since the impoundment's construction in 1932 and were completed as part of the hydropower scheme construction. The operator expects that it could be at least 20 years before excavation is required from an operational perspective; however, they have been in communication with SEPA to improve sediment management at this site.

Intake 2

Intake 2 is a low-level RoR hydropower structure with Coanda screen and was constructed in 2016. The channel upstream of the impoundment is characterised by plane bed and pool-riffle bedforms, whereas immediately downstream of the impoundment, the channel has a cascade morphology initially, followed by a lower gradient section with a small floodplain before returning to a cascade. A small headpond (Table A.3: Photos 2A, 2D, and 2E) has formed, stretching ca. 20 m upstream of the impoundment, and a 20 m side bar (Table A.3: Photos 2A, 2D, and 2E) has formed immediately upstream of the headpond (Figure A.6). A Wolman Pebble Count (Wolman, 1954) was carried out on two point bar formations; one upstream and one downstream of the impoundment (Figure A.6). The grain size distribution of the surface of the point bar formed ca. 100 m upstream of the impoundment (Figure A.6; Table A.3: Photo 2B) ranged from medium pebble gravels to coarse cobbles (15-160 mm, Table A.1, Figure A.3). The D_{16}, D_{50}, and D_{84} of the surface were 30, 47.5, and 75.8 mm, respectively (Table A.1), and the low flow wet channel width immediately upstream of the confluence located on the river left approximately 17.5 m upstream of the point bar was 6 m. The grain size distribution of the surface of the downstream point bar (Figure A.6; Table A.3: Photos 2F and 2G), located within the lower gradient channel section ca. 169 m downstream of the impoundment ranged from very coarse sand to medium boulders (≤2-710 mm, Table A.1, Figure A.3). The D_{16}, D_{50}, and D_{84} of the surface were 10, 110, and 350 mm, respectively (Table A.1), and the low flow wet channel width immediately upstream of the point bar was 3.8 m. There is a notable difference between the sediment distribution between the bars upstream and downstream of the impoundment (Figure A.3), however, this shift in geomorphic processes between the reaches upstream and downstream of the impoundment was present before its construction as observed on historic aerial maps.

The current sediment management practice at this site is to remove accumulated sediment using a mechanical excavator and to deposit the excavated sediment back in the river channel immediately downstream of the intake, but only in the event that sediment starts to block the compensation flow or the abstraction ability of the intake. Excavation occurred in June 2018 and June 2020 but it did not result in increased energy generation. Without excavation, sediment appears to wash over the crest of the weir following its accumulation immediately behind the impoundment structure. Thus, excavation has not been undertaken since 2020. Sediment deposited behind the impoundment structure was observed during the site visit (Table A.3: Photos 2A, 2D, and 2E), and appears to result in a bar forming immediately upstream of the impoundment structure and extending further downstream towards the compensation flow intake on the river right (Table A.3: Photo 2D).

Table A.1. Grain size distribution for point bars upstream (US) and downstream (DS) of Intakes 1 and 2. Sizes in mm.

	US of Intake 1	DS of Intake 1	US of Intake 2	DS of Intake 2
Minimum	20	15	15	2
D_{16}	40	29.2	30	10
D_{50}	62.5	50	47.5	110
D_{84}	90.8	90	75.8	350
Maximum	140	270	160	710

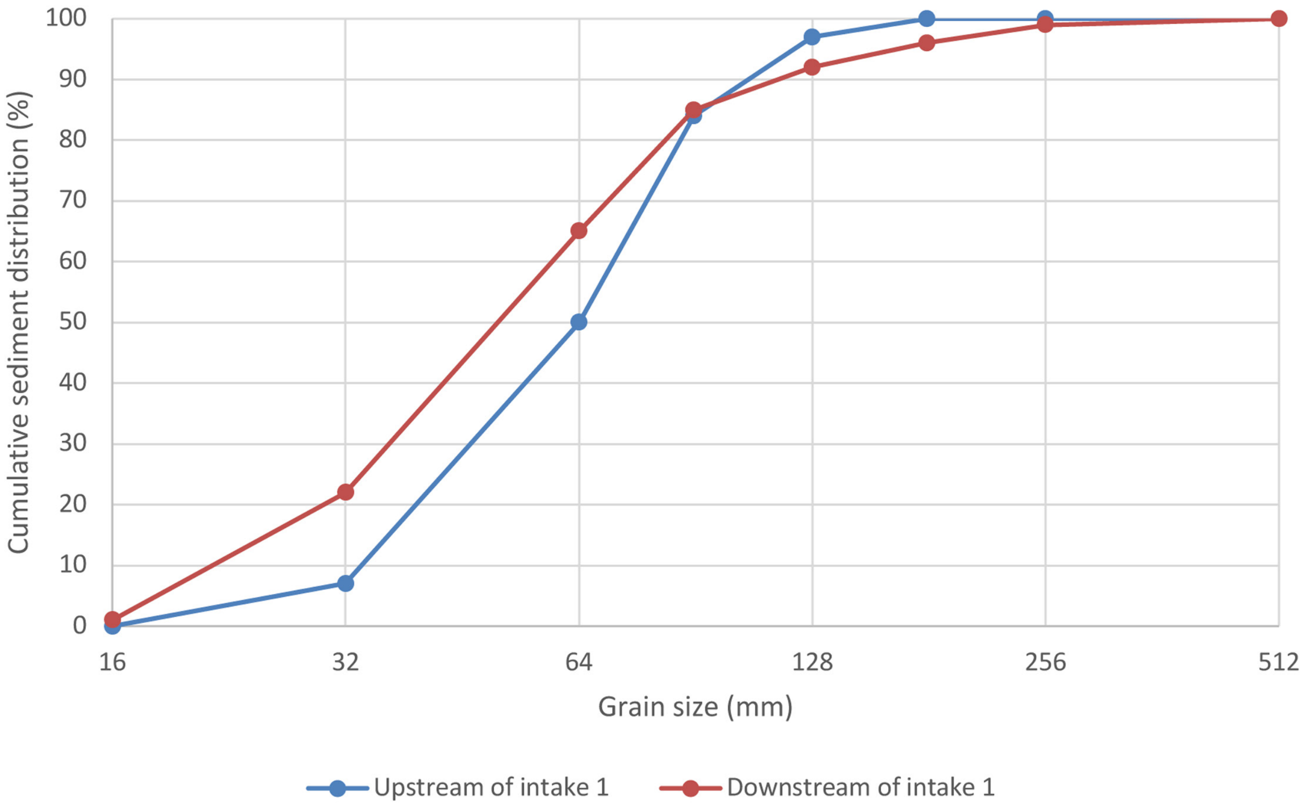


Figure A.2. Cumulative sediment distribution curve for point bars upstream and downstream of Intake 1.

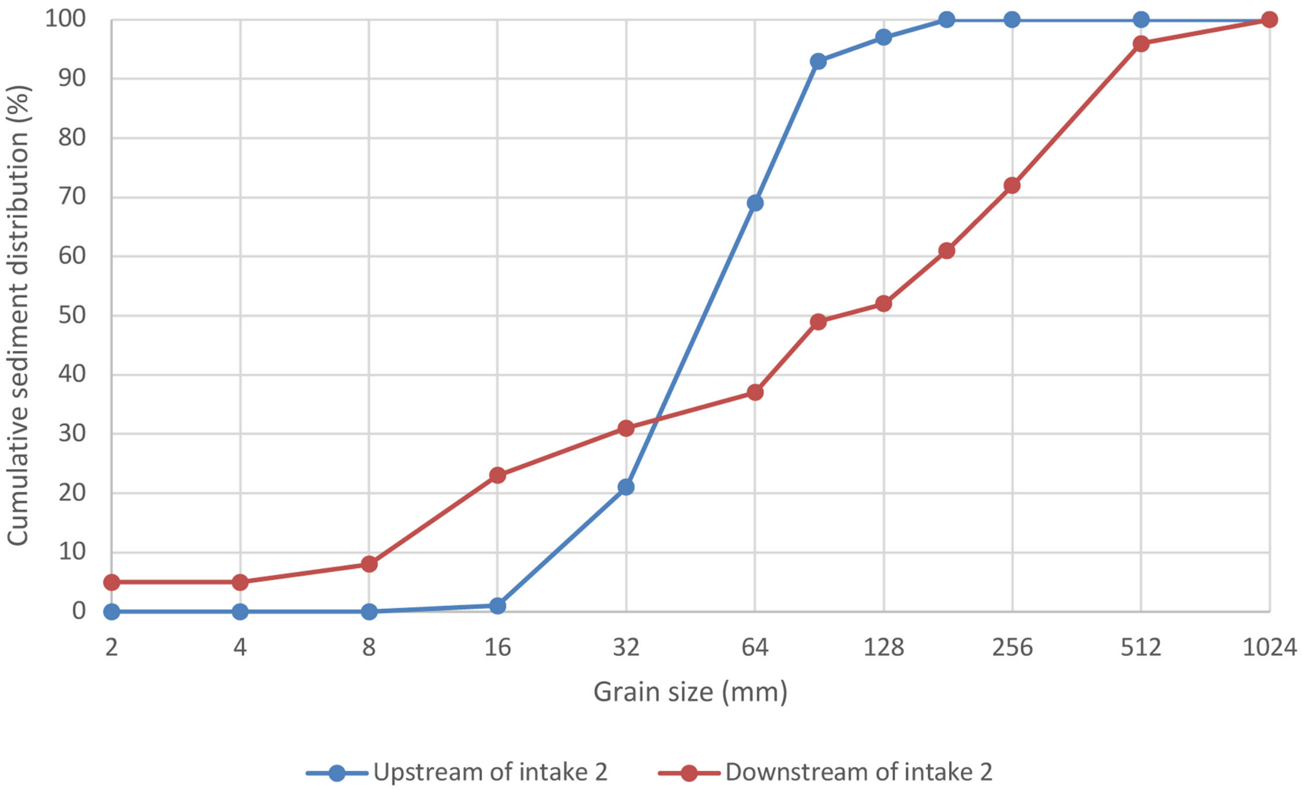


Figure A.3. Cumulative sediment distribution curve for point bars upstream and downstream of Intake 2.

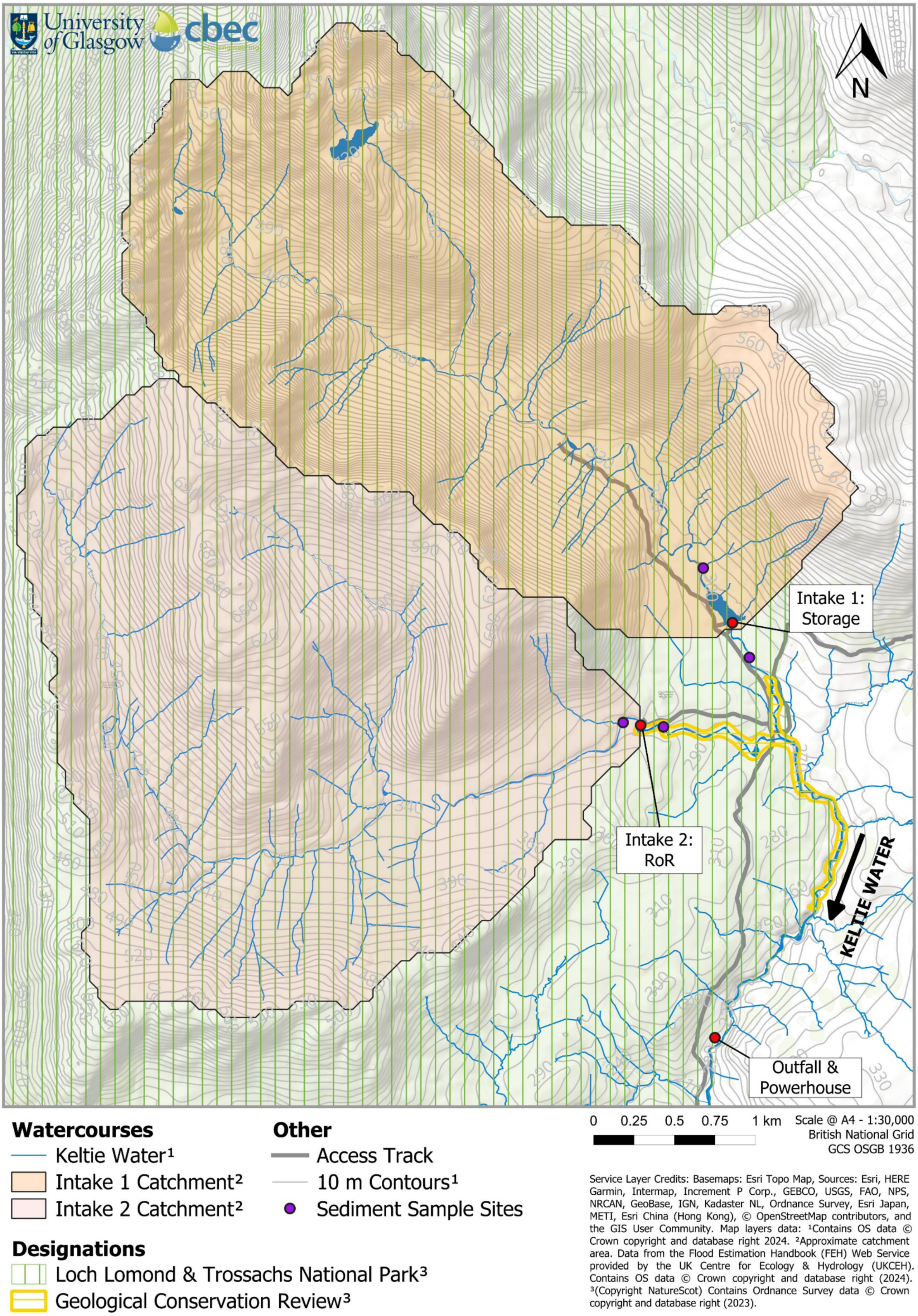
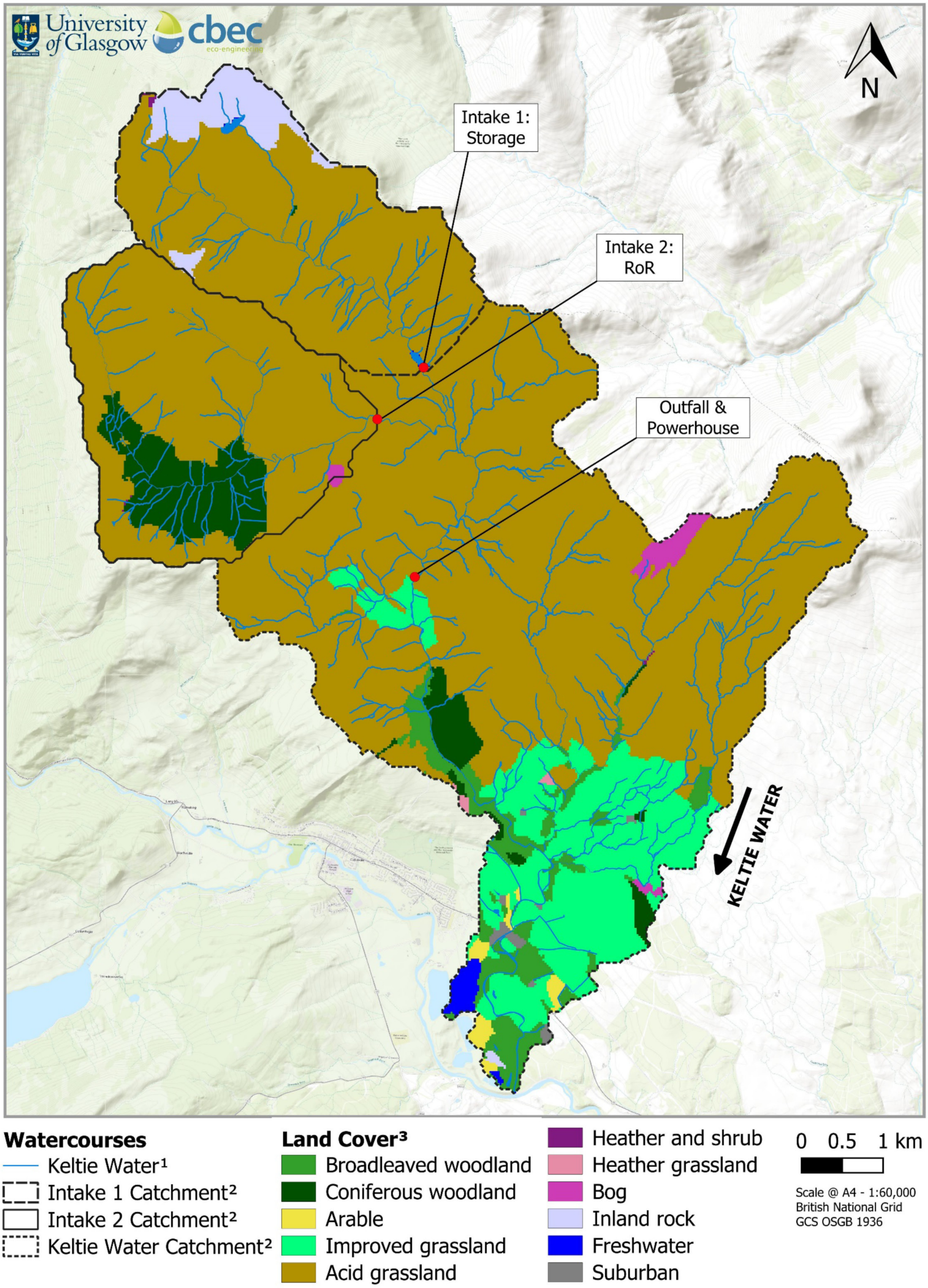


Figure A.4. Map showing the catchment extents of each intake as well as the locations of each intake, the outfall, powerhouse, sediment sampling sites, and access tracks to the site, together with the 10 m contours and the ecological designations present within the Keltie Water catchment.



Service Layer Credits: Basemaps: Esri Topo Map, Sources: Esri, HERE Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community. Map layers data: [1]Layers contain OS data © Crown copyright and database right 2024. [2]Approximate catchment area. Data from the Flood Estimation Handbook (FEH) Web Service provided by the UK Centre for Ecology & Hydrology (UKCEH). Contains OS data © Crown copyright and database right (2024). [3]Land Cover map of Great Britain (2021) [TIFF geospatial data], Scale 1:250000, Tiles: nn40,nn60, Updated: 10 August 2022, CEH, Using: EDINA Environment Digimap Service, <https://digimap.edina.ac.uk>, Downloaded: 2024-07-04 10:40:31.084. Catchment shapefiles: © Database Right/Copyright NERC – Centre for Ecology & Hydrology. Contains Ordnance Survey data © Crown Copyright and database right 2024. All rights reserved.

Figure A.5. Land cover map within the extent of the Keltie Water catchment together with the location of both intakes and their catchment boundaries.

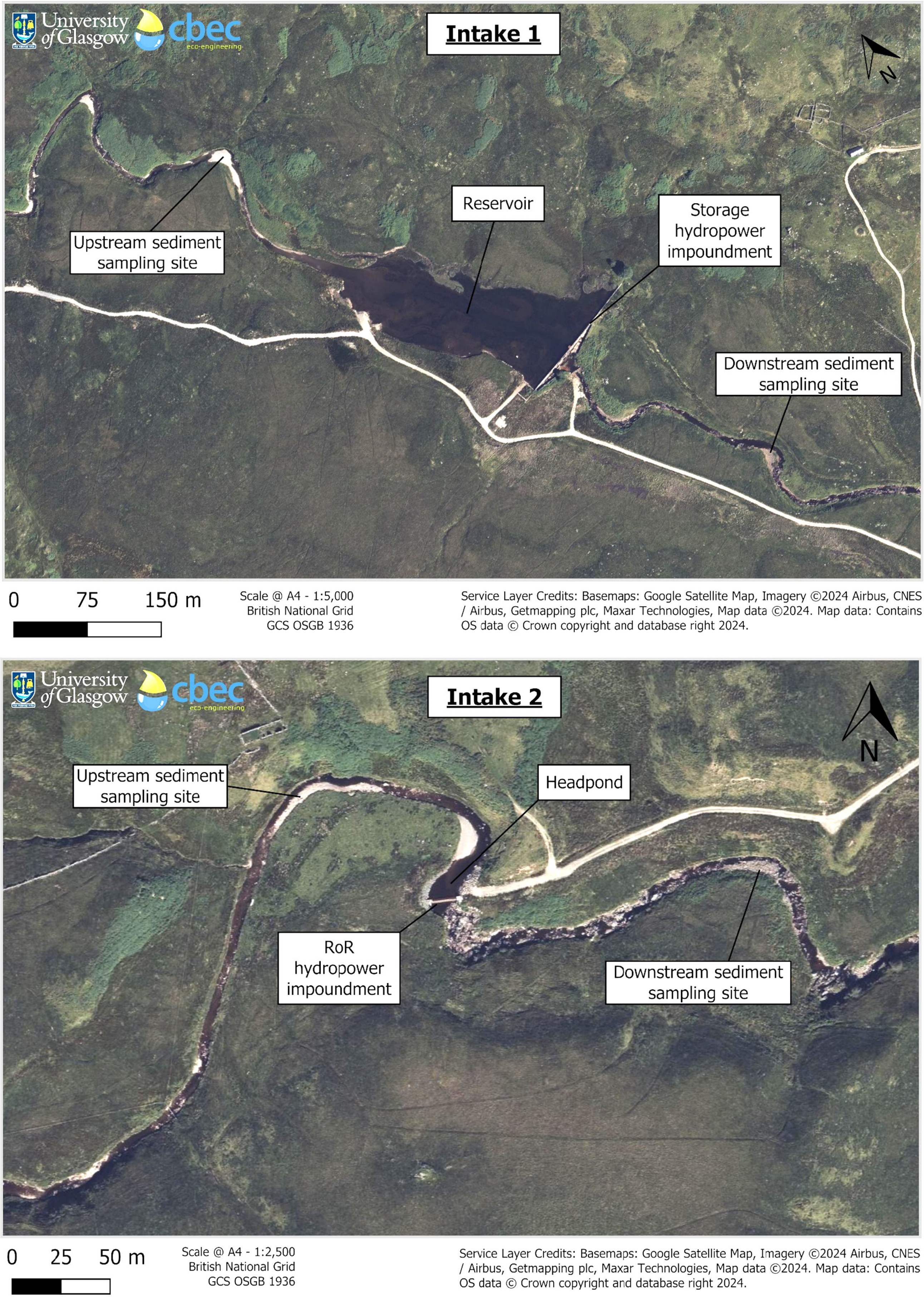


Figure A.6. Satellite images of each site showing the intakes, the reservoir at Intake 1, the headpond at Intake 2, and the sediment sampling sites.

Table A.2. Photographs captured during the site visit of Intake 1 on 18th June 2024.

Photo 1A Point bar located on river right upstream of impoundment. Taken from river left.

Photo 1B Point bar located on river right upstream of impoundment. Taken from river left.

Photo 1C Reservoir upstream of impoundment. Looking downstream. Taken from river right.

Photo 1D Impoundment. Looking upstream. Taken from river right.

Photo 1E Impoundment. Looking downstream. Taken from impoundment.

Photo 1F Vegetated point bar located on river right downstream of impoundment. Looking upstream. Taken from river left.

Photo 1G Vegetated point bar located on river right downstream of impoundment. Looking downstream. Taken from river left.

Photo 1H Section of channel downstream of impoundment. Looking upstream. Taken from bridge located downstream of impoundment.

Table A.3. Photographs captured during the site visit of Intake 2 on 18th June 2024.

Photo 2A RoR impoundment. Looking upstream. Taken from river right.

Photo 2B Point bar located on river right upstream of impoundment. Taken from river left.

Photo 2C Section of channel upstream of impoundment. Looking upstream. Taken from river left.

Photo 2D Headpond behind intake and side bar located on river right upstream of impoundment. Looking downstream. Taken from river left.

Photo 2E RoR impoundment. Looking upstream. Taken from river right.

Photo 2F Point bar located on river right downstream of impoundment. Taken from river left.

Photo 2G Point bar located on river right downstream of impoundment. Looking downstream. Taken from river left.

Appendix B References

Blair, T.C., & McPherson, J.G., 1999. *Grain-size and textural classification of coarse sedimentary particles*. Journal of Sedimentary Research, 69 (1): 6–19. https://doi-org.ezproxy2.lib.gla.ac.uk/10.2110/jsr.69.6

Marston, C., Rowland, C.S., O'Neil, A.W., & Morton, R.D., 2022. *Land Cover Map 2021 (25m rasterised land parcels, GB)*. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/a1f85307-cad7-4e32-a445- 84410efdfa70

NatureScot, 2024. *SiteLink Web Map Search*. Available at: https://sitelink.nature.scot/map [Accessed: 25 July 2024]

UKCEH, 2024a. *The Flood Estimation Handbook (FEH) Online Service*. UK Centre for Ecology & Hydrology, Wallingford, Oxon, UK. Available at: https://fehweb.ceh.ac.uk/ [Accessed: 25 July 2024]

UKCEH, 2024b. *National River Flow Archive (NRFA) Online Service*. UK Centre for Ecology & Hydrology, Wallingford, Oxon, UK. Available at: https://nrfa.ceh.ac.uk/data/search [Accessed: 25 July 2024]

Wolman, M. G., 1954. *A method of sampling coarse river-bed material, Eos Transactions American Geophysical Union*, 35(6): 951–956. DOI: 10.1029/TR035i006p00951.

Appendix C: Case study 3 – Allt an t-Sidhein

The Allt an t-Sidhein has a catchment area of approximately 3.42 km^2 (UKCEH, 2024a). It flows from its source in the peak of Coire an t-Sidhein in a northwesterly direction through the South Laggan Forest towards its mouth at Loch Lochy. A RoR hydropower scheme on the Allt an t-Sidhein (Table A.5: Photo 3A) was visited on 6th August 2024 as part of this project.

The upper and lower extents of the catchment are dominated by very low permeability bedrock and the mid-catchment is dominated by moderate permeability (fissured) geology (UKCEH, 2024b). The elevation range of the catchment ranges from ca. 40 to 670 m AOD and the RoR intake is located at ca. 310 m AOD (Figure A.9). The Allt an t-Sidhein has a very steep gradient (estimated at 0.2200) and is topographically confined until about the last 1 km before the river mouth, which is relatively flat (Figure A.9). The average annual rainfall (calculated between 1961-1990) of the RoR catchment is 2061 mm (UKCEH, 2024a). The catchment is located within land managed by Forestry and Land Scotland and is dominated by coniferous woodland (forestry) and grassland (Marston *et al*., 2022; Figure A.10).

The RoR hydropower has a catchment of ca. 2 km^2 (UKCEH, 2024a) and thus comprises more than half of the Allt an t-Sidhein's total catchment area (Figure A.9). The intake is a low-level RoR hydropower structure with Coanda screen which was constructed in 2020. Access to the channel was difficult due to the steep valley sides and so channel morphology was difficult to observe between the impoundment and powerhouse; however, the river's steep gradient and observable reaches suggest a cascade morphology (Table A.5: Photo 3B). A Wolman Pebble Count (Wolman, 1954) was carried out on two side bar formations upstream of the impoundment; access was not possible downstream of the impoundment. The grain size distribution of the surface of the river left side bar formed ca. 80 m upstream of the impoundment on the main channel (Figure A.9, Figure A.11, Table A.5: Photos 3E and 3F) was 10-320 mm (Table A.4, Figure A.7) indicating a range from medium pebbles to fine boulders. The D_{16}, D_{50}, and D_{84} of the surface were 25, 60, and 131.6 mm, respectively (Table A.4), and the low flow wet channel width at the downstream extent of the bar was 4.2 m. The grain size distribution of the surface of the river left side bar located on the tributary which enters the main channel ca. 27 m upstream of the impoundment (Figure A.9, Figure A.11, Table A.5: Photos 3G and 3H) consisted of very coarse sand to coarse cobbles (≤2-200 mm, Table A.4, Figure A.8). The D_{16}, D_{50}, and D_{84} of the surface were 10, 37.5, and 80 mm, respectively (Table A.4), and the low flow wet channel width at the downstream extent of the bar was 2.5 m.

The current sediment management practice at this site is to remove accumulated sediment using a mechanical excavator and to place the excavated sediment on the bank top immediately downstream of the intake, if sediment starts to block the compensation flow or the abstraction ability of the intake. It was not possible to observe the connectivity between the excavated sediment on the bank top and the river during high flows but it is likely that sediment may need to be deposited closer to the wet channel in order for it to be re-entrained during high flows, to enable sediment continuity. No excavation was required for the first 2.5 years of operation as sediment washed over the crest of the weir following its accumulation immediately behind the impoundment structure. However, a summer flooding event in July 2023 caused a high volume of sediment to accumulate behind the weir which required excavation. This sediment was excavated in January 2024, however, a heavy winter rainfall in February 2024 resulted in another large flux of sediment to travel downstream and accumulate behind the weir; this accumulated sediment is evident in Table A.5: Photos 3C and 3D. The longer-term frequency of sediment management at the site is currently unknown due to the sporadic nature of flooding events but it appears that management may be required after every large storm event.

Table A.4. Grain size distribution for side bars upstream of the impoundment located on the main channel and on a tributary. Sizes in mm.

	Main channel	Tributary
Minimum	10	2
D_{16}	25	10
D_{50}	60	37.5
D_{84}	131.6	80
Maximum	320	200

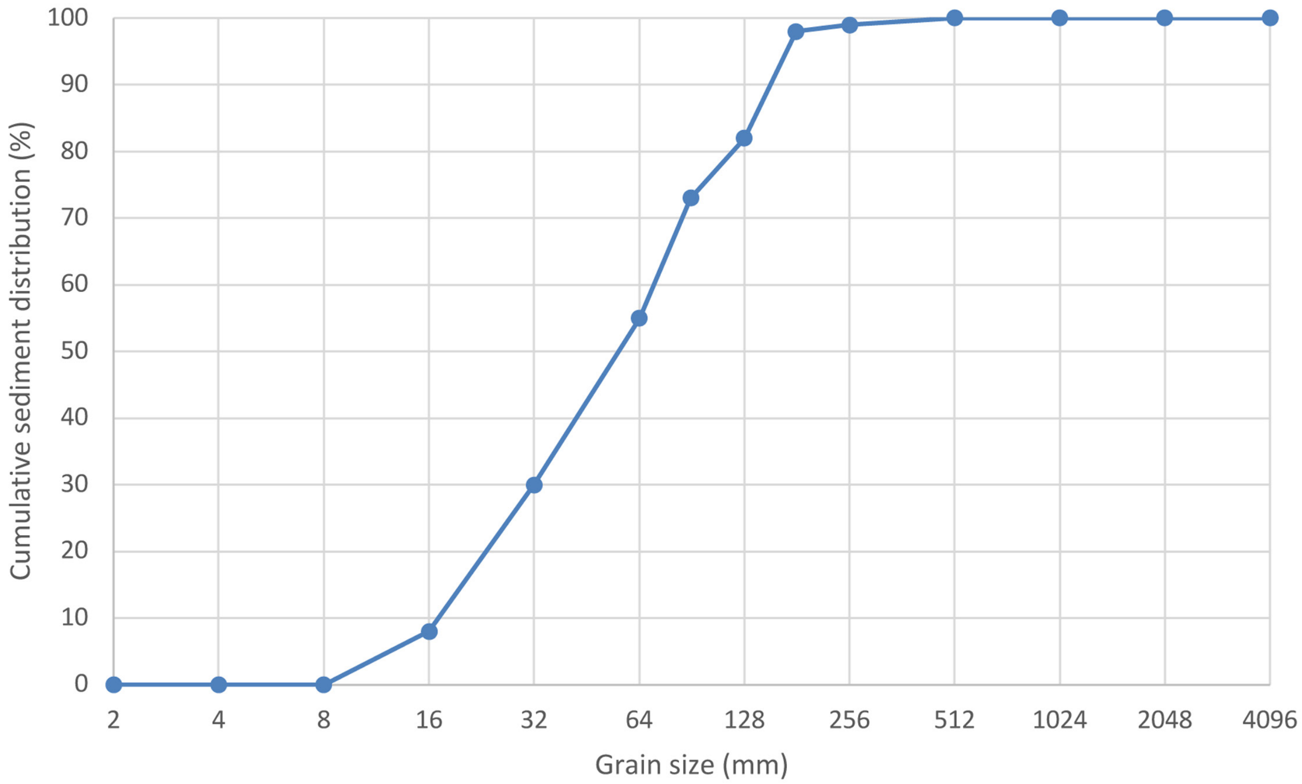


Figure A.7. Cumulative sediment distribution curve for river left side bar located upstream of the impoundment on the main channel.

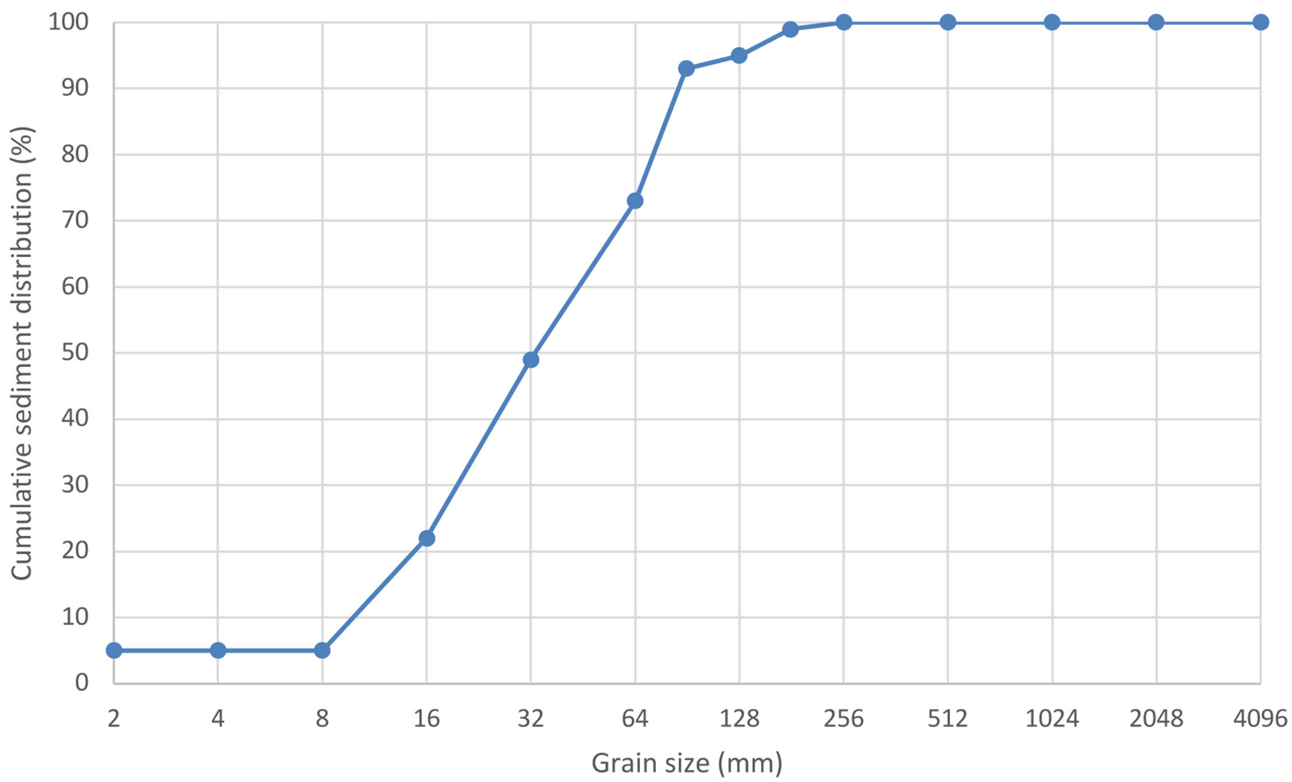


Figure A.8. Cumulative sediment distribution curve for river left side bar located upstream of the impoundment on a tributary to the main channel.

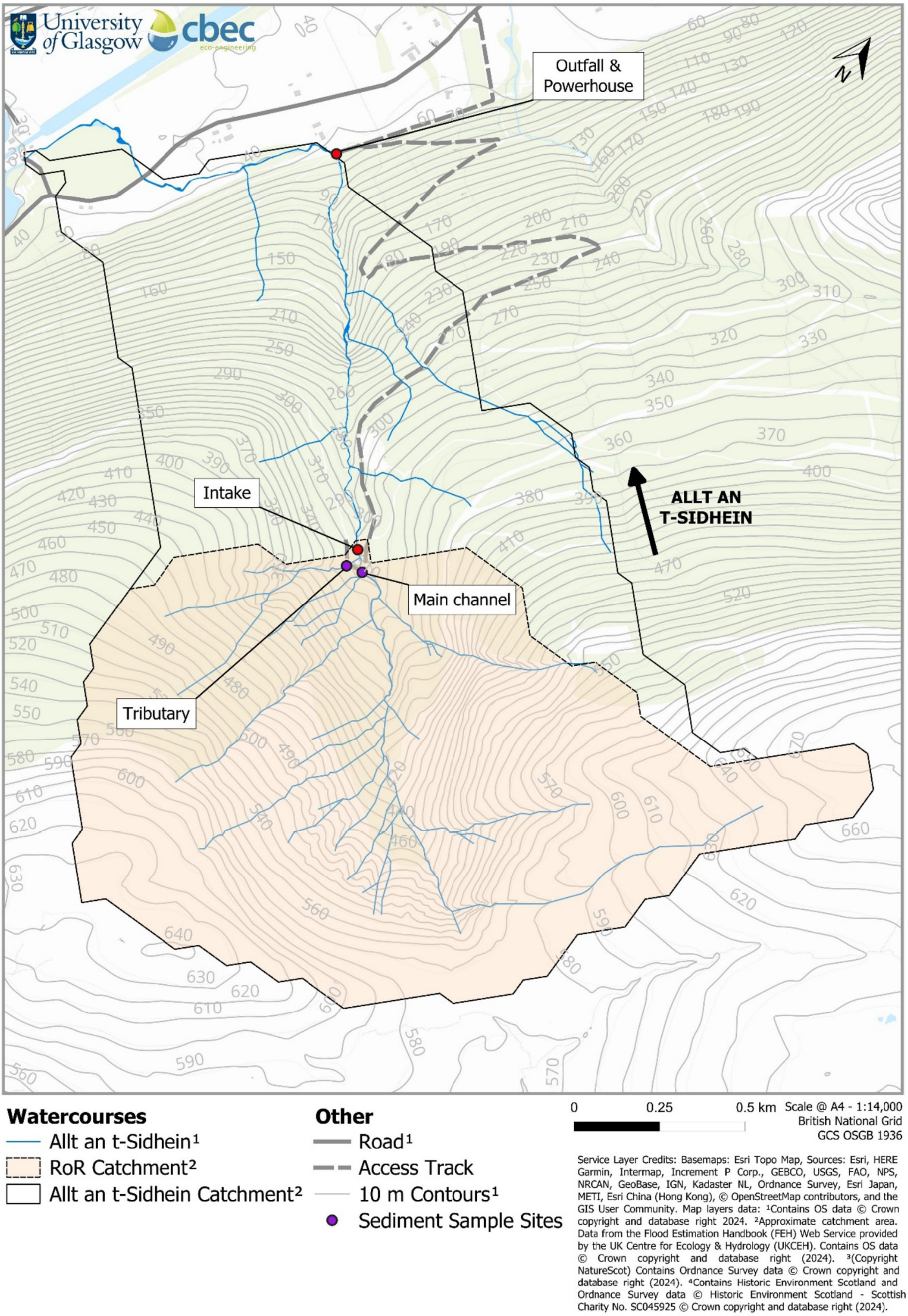


Figure A.9. Map showing the catchment extents of the Allt an t-Sidhein and the RoR intake as well as the locations of the intake, outfall, powerhouse, sediment sampling sites, main road and access tracks to the site, together with the 10 m contours.

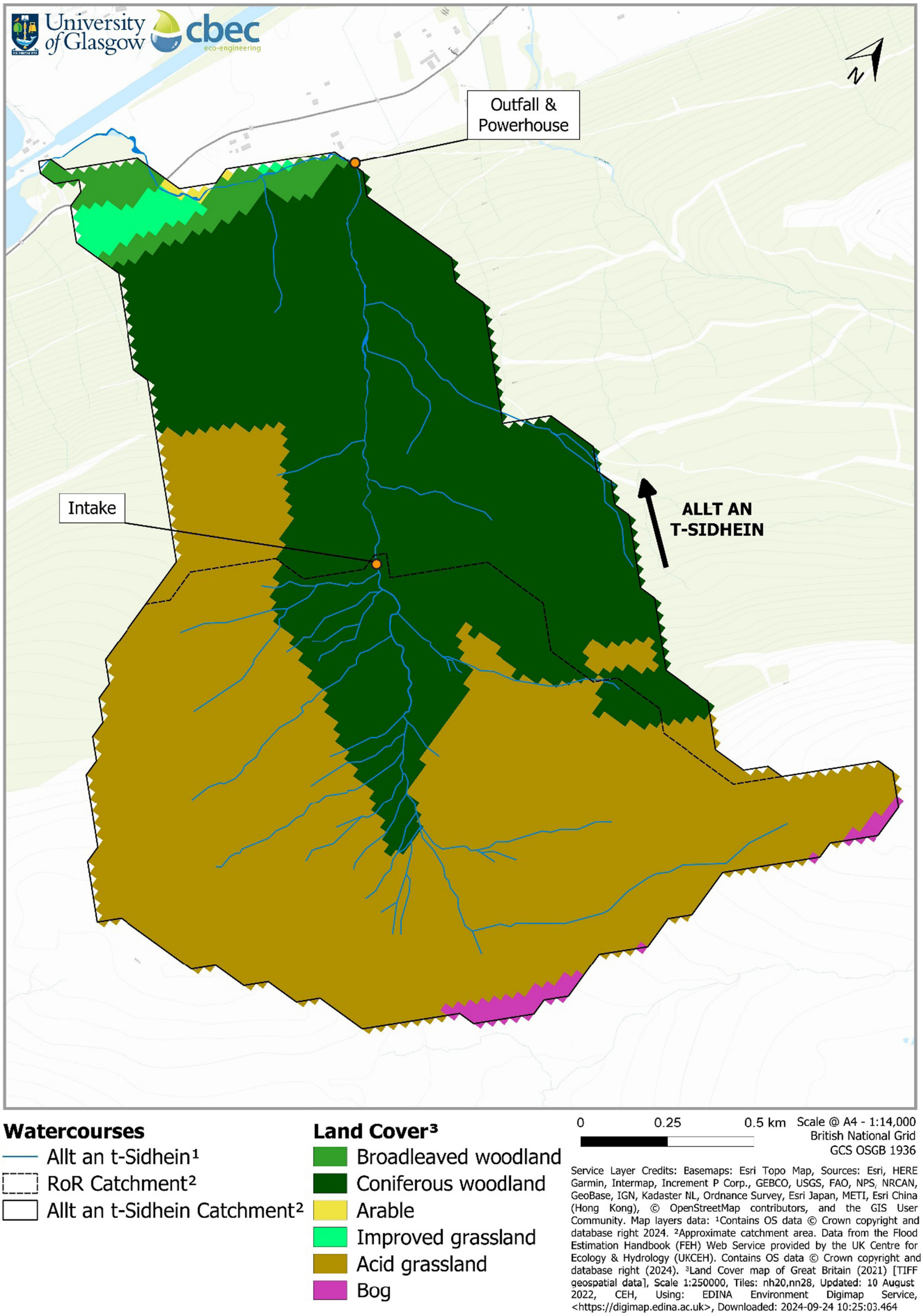


Figure A.10. Land cover map within the extent of the Allt an t-Sidhein catchment together with the location of the RoR intake and its catchment boundary.

Figure A.11. Satellite image of the site showing the impoundment, headpond, and sediment sampling sites.

Table A.5. Photographs captured during the site visit on 6th August 2024.

Photo 3A RoR impoundment. Looking upstream. Taken from river right.

Photo 3B Channel downstream of impoundment. Looking downstream. Taken from river right.

Photo 3C Headpond and sediment accumulation behind impoundment. Looking downstream. Taken from river left.

Photo 3D Sediment accumulation behind impoundment. Looking upstream. Taken from river left.

Photo 3E Sediment sample site on bar on river left upstream of impoundment. Looking upstream. Taken from river left.

Photo 3F Culvert on the main channel upstream of impoundment. Looking downstream. Taken from river left.

Photo 3G Tributary where it enters the main channel on river left upstream of impoundment. Looking upstream.

Photo 3H Sediment sample site on tributary entering the main channel on river left upstream of impoundment. Looking upstream.

Appendix C References

Marston, C., Rowland, C.S., O'Neil, A.W., & Morton, R.D., 2022. *Land Cover Map 2021 (25m rasterised land parcels, GB)*. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/a1f85307-cad7-4e32-a445- 84410efdfa70

UKCEH, 2024a. *The Flood Estimation Handbook (FEH) Online Service*. UK Centre for Ecology & Hydrology, Wallingford, Oxon, UK. Available at: https://fehweb.ceh.ac.uk/ [Accessed: 25 July 2024]

UKCEH, 2024b. *National River Flow Archive (NRFA) Online Service*. UK Centre for Ecology & Hydrology, Wallingford, Oxon, UK. Available at: https://nrfa.ceh.ac.uk/data/search [Accessed: 25 July 2024]

Wolman, M. G., 1954. *A method of sampling coarse river-bed material, Eos Transactions American Geophysical Union*, 35(6): 951–956. DOI: 10.1029/TR035i006p00951

Appendix D: Stated Preference Contingent Valuation Survey Participant Information Sheet

Study title

Improving river health at hydropower impoundments

Invitation paragraph

You are being invited to take part in a research study on hydropower impoundments (commonly known as weirs or dams) and how they impact river health. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. If you have any questions you can contact us using the contact details at the end of this information sheet. **All information will be anonymous**.

What is the purpose of the study?

The purpose of the survey is to understand your views about river environments and actions that could be taken to improve them. Your answers will help inform decisions by the Scottish Government, Local Authorities, and other organisations on how they can protect and improve river health.

Why have I been invited to participate?

You are invited to participate in this study because you are a member of the Scottish public.

Do I have to take part?

No, you do not have to take part. Participation is completely voluntary. You will be asked to consent to the study before it begins. Please contact us if there is anything that is not clear, or if you have any questions, or need more information.

What will happen to me if I take part?

If you decide to take part, you will be asked to electronically sign a consent form to confirm your agreement to participate. Around 1000 people from Scotland will take part in the survey. You are free to withdraw during the survey at any time, without giving a reason. Please note that after completing the survey withdrawing will not be possible.

What do I have to do?

You will be asked a series of questions. Questions will include demographic information (such as your age), how you interact with nature, and how you value the benefits of improved management techniques at hydropower impoundments. This should take around 20 minutes.

What are the possible disadvantages and risks of taking part?

We don’t foresee any risks involved in participating in this study.

What are the possible benefits of taking part?

You will receive no direct benefit from taking part in this study. The information that is collected during this study will give us a better understanding of how to improve the management of hydropower impoundments.

Will my taking part in this study be kept confidential?

We are responsible for making sure your participation is kept confidential and any data is kept secure and used only in the way described in this information sheet. Your information may be reviewed for monitoring and audit purposes by the University of Glasgow and/or regulators who will treat your data in confidence. **All information will be anonymous**.

What will happen to my data?

All study data will be held in accordance with The General Data Protection Regulation (2018). Anonymised data may be shared with other researchers and the data processor, Qualtrics LLC. The data will be stored in archiving facilities in line with the University of Glasgow retention policy of up to 10 years. After this period, further retention may be agreed, or your data will be securely destroyed in accordance with the relevant standard procedures.

What will happen to the results of the research study?

The results will be used in a Scotland's Centre of Expertise for Waters (CREW) report. We will also produce manuscripts from the data collected that will be submitted to appropriate academic peer-reviewed journals. The results of the study will also be communicated at academic conferences, lectures and other presentations. You may contact the study team to find out the main findings of the research.

Who is organising and funding the research?

The research is organised by the University of Glasgow and funded through CREW.

The project has been reviewed by Glasgow University's College of Science and Engineering Ethics Committee.

Contact for Further Information

If you have any questions or require more information about this study, please contact the research team using the following contact details:

Name: [redacted]

Role: Research Assistant

Email: [redacted]

Thank you for reading this information sheet.

Appendix E: Cost-benefit analysis scenarios

Values in red indicate a change from a positive Net Present Value when using the average maximum WTP per person per year, to a negative Net Present Value when using an alternative 95% confidence interval. Values in green indicate a change from a negative Net Present Value to a positive net present value.

Table A.6. Scenario using the lower 95% confidence interval of average maximum WTP per person per year (£44.40) (Winter management, assuming generation loss).

	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	+£913,300	+£1,035,200	+£1,157,100	+£556,300	+£797,200	+£1,038,100
Catchment tree planting covering 50% catchment	−£232,300	−£110,400	+£11,500	−£589,300	−£348,400	−£107,500
Peatland restoration covering 50% catchment	+£1,530,100	+£1,652,000	+£1,773,900	+£1,173,100	+£1,414,000	+£1,654,900

Table A.7. Scenario using the upper 95% confidence interval average maximum WTP per person per year (£59.60) (Winter management, assuming generation loss).

	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	+£1,265,800	+£1,387,700	+£1,509,600	+£908,800	+£1,149,700	+£1,390,600
Catchment tree planting covering 50% catchment	+£120,200	+£242,100	+£364,000	−£236,800	+£4,100	+£245,000
Peatland restoration covering 50% catchment	+£1,882,600	+£2,004,500	+£2,126,400	+£1,525,500	+£1,766,400	+£2,007,400

Table A.8. Scenario using the lower 95% confidence interval average maximum WTP per person per year (£44.40) (Summer management, assuming no generation loss).

	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	+£1,142,800	+£1,188,200	+£1,233,600	+£785,800	+£950,200	+£1,114,600
Catchment tree planting covering 50% catchment	−£2,700	+£42,700	+£88,000	−£359,800	−£195,400	−£31,000
Peatland restoration covering 50% catchment	+£1,759,600	+£1,805,000	+£1,850,400	+£1,402,600	+£1,567,000	+£1,731,400

Table A.9. Scenario using the upper 95% confidence interval average maximum WTP per person per year (£59.60) (Summer management, assuming no generation loss).						
	Net Present Values (excluding spare part costs)			Net Present Values (including spare part costs)		
Improvement Scenario	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**	**25% sediment management cost savings**	**50% sediment management cost savings**	**75% sediment management cost savings**
SEPA Recommended Riparian Corridor planting (15 m buffer)	**+£1,495,300**	**+£1,540,700**	**+£1,586,100**	**+£1,138,300**	**+£1,302,700**	**+£1,467,100**
Catchment tree planting covering 50% catchment	**+£349,700**	**+£395,100**	**+£440,500**	**−£7,300**	**+£157,100**	**+£321,500**
Peatland restoration covering 50% catchment	**+£2,112,100**	**+£2,157,500**	**+£2,202,900**	**+£1,755,100**	**+£1,919,500**	**+£2,083,900**

Appendix F: Climate change impacts on sediment transport – a pilot test

Climate change predictions for Scotland envisage wetter winters with higher flow peaks (Sniffer, 2021, after Hannaford, 2015; Kay *et al*., 2021). Logically, the effect of these changes will be to increase the volume of coarse sediment transported in rivers, and to permit the transport of larger grain sizes. However, at least some of the increase in the volume of transported coarse sediment will be offset by the somewhat shorter duration of the 'flashier' flow events. Increasing the volume and maximum grain sizes transported during flood events is potentially problematic for the hydropower industry. Impoundments could fill with sediment more rapidly (and thus need costly clearing more frequently), while larger grain sizes increase the operational risk to impoundments using Coanda screens if large particles lodge against the screen and reduce its effective operational area. There are, as yet, no established methods for estimating the relative changes in fluvial sediment transport caused by such climate changes, but a pilot approach was developed from existing research as part of this project.

The estimation approach uses multi-year hydrological records from gauging stations tied to channel morphology data and sediment grain size information to simulate the potential annual volume of coarse sediment transported (see, e.g., Soar and Thorne, 2011). The hydrological records provide an indication of the magnitude and frequency of flows theoretically large enough to transport river bed sediments hence the method is known as magnitude-frequency analysis (MFA). The actual amount of coarse sediment transport is generally far below the estimated potential because coarse sediment in most rivers is 'supply limited' (i.e., there is not enough supply to meet the potential for transport), and because the larger sediment grains on a river bed shield smaller ones from the full force of flowing water so that fewer smaller particles are transported than estimated (Gomez, 2006). Recent advances in approaches to MFA include calculations by individual grain sizes, the use of annualised flow duration curves, and macro-driven software that greatly reduces computational time (Soar and Downs, 2017; Soar *et al*., 2023). For this application, a fundamental addition was the ability to re-distribute the proportion of received flows between summer and winter, and the ability to scale flow peaks (P. Soar, University of Portsmouth, pers. comm.).

To pilot test the potential impact of climate change on coarse sediment transport, three gauged river sites were chosen relatively near to hydropower installations and spanning a range of typical catchment sizes to test whether the impact of climate change on fluvial sediment transport is scale dependent. Flow records were downloaded from the National River Flow Archive (https://nrfa.ceh.ac.uk/) for the Dargall Lane at Loch Dee (station ID 80005, catchment area 2.1 km^2), the Abhainn a' Bhealaich at Braevallich (station ID 80007, catchment area 24.1 km^2), and Ettrick Water at Brockhoperig (station ID 21017, catchment area 37.5 km^2). Gauge records spanned approximately 40-45 years, from 1981 (Abhainn) or 1987 to July 2024 when records were downloaded. The catchments span various ranges of elevation but all are underlain by relatively impermeable bedrock and have similar 'upland' land covers consisting of rough grassland, heathland and bog, and some woodland. Average annual rainfall (1961-1990) ranges from 1740 mm (Ettrick Water) to 2489 mm (Abhainn a' Bhealaich). Bankfull channel widths, channel gradients and floodplain cross slopes were estimated using Google Earth imagery, and channel depths were estimated from the channel widths for the appropriate channel type using a database of channel geometry data (Buffington, 2012). 'Typical' Manning's roughness coefficients were applied to the channel bed and floodplain according to the channel type and floodplain land cover. Channel cross-sections were assumed to be rectangular, which is a reasonable assumption in gravel and cobble-bedded streams. River bed grain size distributions (1 – 256 mm) were derived from sampling undertaken during the previous phase of this project (Williams *et al*., 2022), with distributions being matched to the closest type of river morphology to those sampled previously. Assumed median grain sizes ranged from 40 – 70 mm.

For the pilot tests, sediment transport potential was estimated according to several assumptions about river flows under climate change. In each case, an initial model run generated a 'baseline' estimate of coarse sediment transport based on existing flow records. Scenarios were then run whereby the flow volumes and flood peaks were multiplied by factors indicative of assumed climate change in 6-monthly 'summer' and 'winter' periods. Winter flow volumes were increased by 20% to 30%, and summer flow volumes decreased to 80% of present, acknowledging that climate change predictions suggest a more significant change in the *distribution* of rainfall rather than the *total*. Summer peak flow magnitudes were increased by 20% (simulating the likelihood of more peaky convective rainfall) and winter peak flow magnitudes by 40 to 50%, in line with predictions. Example graphical outputs from each station is provided in Figure A.12.

The results indicate that changing the volume of winter rainfall is more important to the amount of sediment transported than increasing peak flow magnitudes. This is logical because winter flows are more likely to exceed the threshold for sediment transport, so greater volumes of winter flow make it more likely that greater volumes of fluvial sediment transport will result. Conversely, greater peak flow magnitudes allows larger particles to be transported but also implies greater peakedness of flow. This reduces the duration of the event thus reducing the potential period over which sediment is transported. Increasing winter peakedness by 40 to 50% over baseline conditions makes a negligible change in the potential volume of sediment transport, but increasing the volume of winter rainfall by 20% over baseline increases potential yields by 9-15% across the stations, and when increased by 30%, potential yields increase by 26-27%. Change is greatest at the Ettrick station which has the largest catchment area but has also the coarsest sediment grain size distribution and we are as yet unable to separate out the relative contribution of each factor. However, increasing flow peakedness does increase the potential maximum grain size transported, with the impact apparently scaled inversely to catchment area: maximum grains sizes increase by 15%, 12% and 6% with catchment area (respectively) when winter flow peak magnitudes are increased by 50%.

In conclusion, the potential impact of climate change on hydropower operations could be very significant, with 15-27% increases in sediment volume (assuming sufficient supply exists) and with 6-15% increases in grain size (assuming such grain sizes are available) for simulations related to 'reasonable' estimates of climate change. Such results emphasize the importance of looking towards catchment management improvements that decrease coarse sediment input to rivers as a way of minimizing the impact of climate change on hydropower operations. Note that the results here are part of a pilot test, and a significant volume of sensitivity testing related to the mechanisms 'internal' to the sediment transport calculations (e.g., Manning's n values, Shields parameters and grain size distributions) is planned for research outside of the scope of this project.

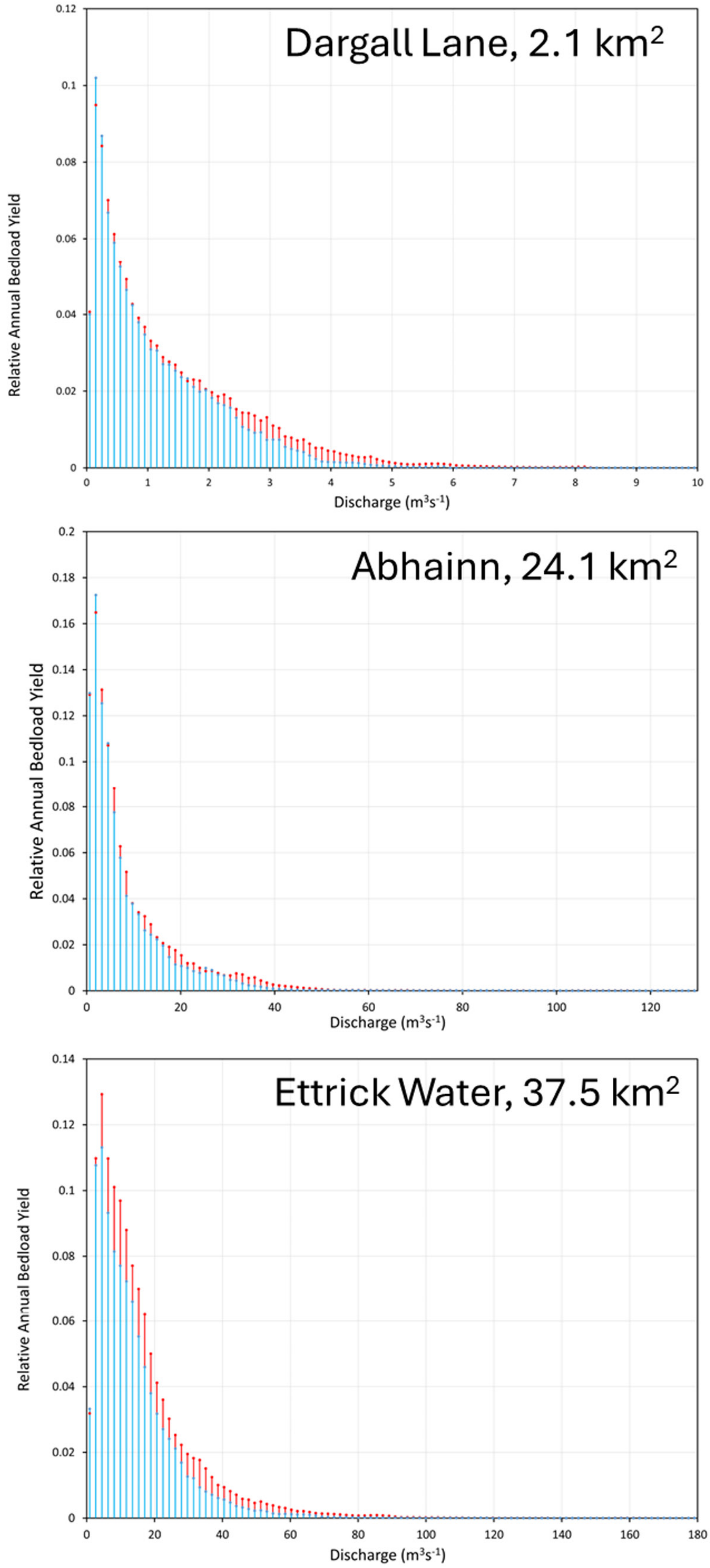


Figure A.12: Representative outputs from simulating the effect of predicted climate change on coarse sediment transport. Blue bars represent transport potential based on long-term flow records to present; red bars indicate changes in sediment transport potential at each increment of discharge.

Appendix F References

Buffington, J.M. 2012. Changes in Channel Morphology over Human Time Scales. In Gravel-Bed Rivers: Processes, Tools, Environments, edited by M. Church, P.M. Biron, and A.G. Roy, pp.435–63. Chichester: Wiley. https:// doi.org/10.1002/9781119952497.ch32

Gomez, B. 2006. The potential rate of bed-load transport. Proceedings of the National Academy of Sciences, 103: 17170–17173. https://doi.org/10.1073/pnas.0608487103

Hannaford, J. 2015. Climate-driven changes in UK river flows: A review of the evidence. Progress in Physical Geography, 39: 29-48, https://doi.org/10.1177/0309133314536755

Kay, A.L., Rudd, A.C., Fry, M., Nash, G. and Allen, S. 2021. Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections, Climate Risk Management, 31:100263, https://doi.org/10.1016/j.crm.2020.100263

Sniffer, 2021 Climate Projections for Scotland, summary. Adaptation Scotland: supporting climate change resilience, Edinburgh, Scottish Government, 14pp.

Soar, P.J. and Downs, P.W. 2017. Estimating bedload transport rates in a gravel-bed river using seismic impact plates: model development and application, Environmental Modelling and Software, 90:182-200, https://doi.org/10.1016/j.envsoft.2017.01.012

Soar, P. J., & Thorne, C. R. 2011. Design discharge for river restoration. In A. Simon, S. J. Bennett, & J. Castro (Eds.), Stream restoration in dynamic fluvial systems: scientific approaches, analyses, and tools, AGU geophysical monograph (Vol. 194; pp. 123–149). Washington, DC: American Geophysical Union

Soar, P.J., Cox, A., Biedenharn, D.S., Dahl, T.A., Thorne, C.R., Haring, C.P., Little, C. and Downs, P.W. (2023) Future River Analysis & Management Evaluation (FRAME): A new approach to forecasting long-term morphological evolution and response in rivers, Proceedings of SEDHYD 2023 – Fifth Joint Federal Interagency Sedimentation Conference, St. Louis MO, May 2023. https://www.sedhyd.org/2023Program/s98.html

Williams, R.D., Downs, P.W., Moir, H.J. & Lavarini, C., 2022. Sediment continuity through run-of-river hydropower schemes. CRW2019_02. Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/publication/sediment-continuity-through-run-river-hydropower-schemes

CREW
CENTRE OF EXPERTISE FOR WATERS

Centre of Expertise for Waters

James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK

www.crew.ac.uk

CREW publications can be accessed here:
www.crew.ac.uk/publications

@crew_waters

CREW-scotland

CREW is a partnership between the James Hutton Institute
and all Scottish Higher Education Institutes and Research Institutes.
The Centre is funded by the Scottish Government.

Scottish Government
Riaghaltas na h-Alba
gov.scot