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Richard Williams, Peter Downs, Hamish Moir, Chrystiann Lavarini

Hydro Nation International Centre

The James Hutton Institute

Scottish Government
Riaghaltas na h-Alba
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**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 and Research Institutes supported by MASTS. The Centre is funded by the Scottish Government.

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**Please reference this report as follows:** Williams, R.D., Downs, P.W., Moir, H.J. and Lavarini, C. (2022), Sediment continuity through run-of-river hydropower schemes. CRW2019_02. Centre of Expertise for Waters (CREW). Available online with appendices at: crew.ac.uk/publications

**ISBN number:** 978-0-902701-04-5

**Dissemination status:** Unrestricted



**Cover photographs courtesy of:** cbec

# Contents

# Foreword

The Scottish Government's ambition to decarbonise its electricity generation means that run-of-river hydroelectric power schemes are now a feature of many Scottish catchments. The essential requirements of these schemes (adequate hydraulic head and flow) mean that their locations often coincide with important freshwater habitat. A scheme can have various effects on the quality and extent of this habitat, in and downstream of the depleted reach (between the intake and tailrace), and upstream of the impoundment.

The interruption of natural sediment movement is one such effect and, if measures to ensure that conveyance is maintained are not included in the design of a scheme, it can have significant and far reaching consequences for habitats, species, channel evolution, and adjacent land. It can also, significantly for the operator, affect the efficiency and profitability of a scheme.

The realisation that the need to maintain sediment continuity has not been adequately taken into account for many schemes was the impetus for this project. The research has led to recommendations for dealing with accumulations of sediment at operational schemes, and for the incorporation of sediment management measures in proposed schemes. The effects of climate change and the biodiversity crisis have increased the imperative for remedial action and to ensure that measures for maintaining sediment movement and other natural processes are incorporated in the design of existing and new schemes.

# Executive summary

There are currently over 530 feed-in-tariff (<5 MW) scale hydropower schemes installed across Scotland, with a further 30 in planning, consented (awaiting construction), or under construction in 2021. Small scale hydropower schemes are explicitly identified in the Scottish Government's Energy Strategy (2017) to play an "*important role in our* [Scotland's] *economy and our* [Scotland's] *energy mix*". The majority of installed small scale schemes are Run-of-River (RoR) designs consisting of an impoundment and screened offtake.

This report presents the findings and recommendations of a project that investigated sediment continuity in RoR hydropower schemes in Scotland through a set of six objectives. These objectives are grouped to answer the following questions:

- What preventative and mitigation measures could be used to counter the impacts of sediment accumulation behind the weir of run-of river hydro schemes on fluvial dynamics, habitats and species?
- Are there measures that could address both the impacts of single developments and the cumulative impacts of multiple developments within catchments?

We found that sediment management plans are rarely developed for Scottish RoR hydropower schemes. In addition, SEPA staff guidance for issuing Water Environment (Controlled Activities) (Scotland) Regulations 2011 (CAR) licenses is not clear enough to allow staff to identify the need for a sediment management plan. The severity of changes in sediment dynamics vary from case to case. In addition, we found a research gap on the cumulative effects of multiple RoR hydropower schemes in a single catchment and there is a paucity of investigations that focus upon RoR hydropower schemes on Scottish rivers. A literature review on sediment management techniques showed several approaches that can be grouped into those intended to 'reduce sediment yield', 'minimise sediment deposition through sediment routing', and 'increase or recover impoundment volume through mechanical, and hydraulic excavation'. It also showed that some techniques cannot be transferred to Scottish rivers due to a scaling issue (i.e. the techniques were originally developed for wider channels), but others could be more widely applied. . A selection of five RoR hydropower schemes (named Case Studies One to Five) in Scotland were assessed to determine the magnitude and the extend of their geomorphological impacts. These were chosen to  to illustrate a range of situations encountered in Scotland, such as: individual and cumulative impacts; different degrees of upstream/downstream impact; different river types/sediment loads; structures more or less difficult to retrofit; and more or less difficult to get heavy plant on site and to points of sediment removal and reallocation. In Case study One, the accumulation of sediment in the headpond is likely to be the cause of an impact downstream as minimal flows may not be maintained. The Case Study Two hydropower scheme had the largest volume of sediment retained due to the impoundment. This impoundment has been mechanically excavated and sediments have been stockpiled on both riverbanks downstream. A lack of connectivity to the stockpiled sediments has starved the downstream corridor of sediment and resulted in large-scale morphological change. The impoundment of Case Study Three was not a RoR hydropower structure, but it demonstrates typical dam impact issues such as extensive deposition upstream and sediment starvation downstream. Case Study Four RoR scheme has no visible depositional bars either upstream or downstream of the impoundment and may have a naturally limited sediment supply or low effect of impoundment in longitudinal connectivity.

Based on the findings of this project, recommendations for new and existing RoR hydropower schemes in Scotland are suggested. For the former, these suggestions include, but are not limited to: creating clear guidance on what information developers are required to submit in their application about sediment management; establishing clear guidance for SEPA staff granting CAR Licences, including best practice for sediment reallocation in the standard sediment management conditions; and updating the Morphological Impact Assessment System (MImAS) formula. We also propose that new licences should be encouraged to establish, restore and maintain a natural riparian corridor that (i) buffers sediment supply to the channel and (ii) encourages the full expression of in-channel fluvial sediment processes. Applicants should be strongly encouraged to incorporate sediment sluices, bypasses, or similar structures to enable the hydraulic transfer of sediment during high flows. New schemes should also be strongly encouraged to apply operating rules that enhance connectivity of water and sediment throughout the catchment, hence, reducing cumulative impacts of multiple individual impoundments, especially for catchments with schemes run by different operators. Lastly, new licences or compliance verification of existing schemes could encourage monitoring and managing sediment accumulation in headponds to improve the understanding of hydropower scheme impacts in Scotland.

The second set of recommendations are for existing schemes; we propose that plans should be developed for the restoration of degraded riparian corridors upstream of intakes to reduce sediment yield from upstream areas. Operators should also be encouraged to develop operating rules that ensure longitudinal connectivity and therefore enable sediment transport through the scheme affected reach (and where appropriate, through multiple structures). In addition, best practice guidelines for the mechanical removal and reallocation of sediment should be developed and issued to all RoR hydropower owners, and, where it is cost beneficial, operators should be encouraged to modify structures to permit the hydraulic pass-through (or by-pass) of sediment.

Specifically for SEPA and NatureScot, we recommend expanding the use of SEPA's existing database of all RoR and storage impoundments in Scotland, which is currently used as the basis for proposing permit conditions and monitoring actions related to flows of water, to also cover the provision of permit conditions, plans and monitoring actions related to sediment management. We encourage further investigation, through field monitoring and numerical modelling, of the cumulative hydrogeomorphic consequences of run-of-river hydropower schemes and multi-year monitoring and modelling to derive sediment budgets for impacted and non-impacted sites to inform policy and practice. We conclude that there is a lack of evidence about the dynamics of sediment continuity in Scotland suitable for underpinning decisions about many aspects of RoR hydropower schemes. These include: the conditions of RoR hydropower consent, the development of adaptive sediment management plans, choices between mechanical, hydraulic and catchment-based sediment management techniques, and the likely cumulative impact of multiple schemes on the same river. We, therefore, recommend short-, medium- and long-term proposal for regulators and operators of RoR hydropower schemes. Prioritisation should be given to minimising the impact of this management practice on sediment continuity through regular excavation of headponds and site-appropriate reallocation of the excavated sediment to the downstream channel. In the medium term, it is important that SEPA expands its national database of RoR and storage impoundments to support the improvement of guidance and cataloguing of sediment management outcomes. In the longer term, the compilation of reports about the sediment management actions undertaken at different types of RoR hydropower schemes will assist SEPA staff in providing locally-specific and effective guidance on RoR operation including guidance on minimising cumulative impacts. This knowledge will underpin a better appreciation of sediment dynamics and continuity across Scottish landscapes to the benefit of multiple conservation concerns.

# Plain English summary

This project has considered solutions for sustaining sediment continuity in run-of-river (RoR) hydropower schemes in Scotland through a combination of administrative documentation, literature reviews and case study fieldwork. Such advice will benefit both RoR hydropower scheme operators, and aquatic and river corridor habitats that are functionally dependent upon coarse sediment continuity. More broadly, this knowledge will underpin a better appreciation of sediment dynamics and continuity across Scottish landscapes to the benefit of multiple conservation concerns. Field evidence indicates that impacts on sediment continuity between upstream and downstream reaches varies between schemes but is significant in some cases; such findings mirror those found in published literature. Experience gained from these surveys has allowed the development of a series of recommendations for new and existing RoR hydropower schemes. The overwhelming result is a lack of evidence about the dynamics of sediment continuity in Scotland suitable for underpinning decisions about the conditions of RoR hydropower scheme consent, and the development of sediment management plans. The situation is compounded administratively because the policy guidance for consenting RoR hydropower scheme licences is unclear and seems likely to result in inconsistency. Further, SEPA's database of existing RoR and storage impoundments in Scotland is not currently used to document sediment continuity monitoring results and sediment management decisions. Our recommendations address various aspects of these deficiencies. Short term efforts should focus on minimising the impact of this management practice on sediment continuity by the regular excavation of headponds and movement of the excavated sediment to the downstream channel. It is also imperative that SEPA staff receive clarified and updated policy guidance for consenting licences, and that such updates include a general expectation for a sediment management plan and sediment management reporting as part of granting consent. In the medium term, it is important that SEPA expands the use of its national database of RoR and storage impoundments to support improved sediment management guidance and the cataloguing of sediment management outcomes. Operators of new schemes should be encouraged to undertake modest but important monitoring and reporting of sediment continuity in the vicinity of their schemes, and to consider implementing measures for upstream sediment yield reductions in cases where sediment supplies are elevated due to man-made intervention. In parallel, SEPA should develop its knowledge about the viability of hydraulic methods for sediment management at a scale suitable for application in Scottish rivers. It should also encourage new operators to use impoundments designed to permit hydraulic methods of sediment management. Similarly, SEPA should encourage operators of existing facilities to retrofit adjustable sluice gates to existing structures where viable, thus reducing the reliance on mechanical excavation and impacts on sediment continuity. It may help if existing schemes are classified according to their impact on sediment continuity. In the longer term, the compilation of reports about sediment management actions undertaken at different types of RoR hydropower schemes will assist SEPA staff in providing locally specific and effective guidance on RoR operation including guidance on minimising cumulative impacts.

# 1.0 Introduction

There are currently over 530 feed-in-tariff (<5 MW) scale hydropower schemes installed across Scotland, with a further 30 in planning, consented (awaiting construction), or under construction in 2021 (CREW, 2020). Small scale hydropower schemes are explicitly identified in the Scottish Government's Energy Strategy (2017) to play an "*important role in our* [Scotland's] *economy and our* [Scotland's] *energy mix*". The majority of installed small-scale schemes are Run-of-River (RoR) designs consisting of an impoundment and screened intake. RoR hydropower schemes usually operate with no water storage, instead using water flowing down steep gradients to generate power (Anderson *et al.*, 2015). Generally, channel impoundments (typically weirs) regulate water levels, allowing a proportion of flow to be diverted through a pipe to a turbine before it is returned to the river further downstream. RoR hydropower schemes are often referred to as high-head schemes, since they exploit a relatively large elevation difference between the intake and the powerhouse. As such, they have been installed on steep, mountainous rivers, often using existing forestry and upland estate tracks for access. In Scotland, schemes range from having peak capacities <10 kW on smaller watercourses to >1 MW on larger rivers.

Scottish Environment Protection Agency (SEPA) guidance for developers of RoR hydropower schemes states that proposals must be assessed against criteria to ensure they comply with Water Environment (Controlled Activities) (Scotland) Regulations 2011 (CAR). One of the criteria covers the management of sediment accumulating upstream of the impoundment. In their guidance on assessing impacts from hydropower schemes on natural heritage, SEPA and NatureScot identify sediment accumulation as an issue to be considered in the Environment Impact Assessment (EIA), CAR, and planning applications (SNH, 2015). Currently, there are many hydropower schemes where there is provision in the CAR licence for sediment management but no requirement to implement it.

Best practice sediment management has the 'win-win' prospect of benefitting both river environments and the operational efficiency of hydropower generation. Concerned by the current dearth both of sediment management plans and post-construction sediment monitoring data, SEPA and NatureScot have identified the need for further research on the environmental impacts of RoR hydropower schemes. Collectively, these data could be used to guide an environmentally sensitive approach to managing existing and new RoR schemes in Scotland and elsewhere, in the context of climate change and adaptation strategies. Such knowledge is given additional emphasis because climate change is likely to result in increased sediment transport rates in Scottish river systems (Robins *et al*., 2016; Whitehead *et al*., 2009; Wilby *et al*., 2006), increasing the uncertainty of sediment delivery to, and accumulation at, intakes. Under this scenario, choosing sediment management techniques that are equally environmentally and operationally effective will be critical.

Typically in Scotland, if an impoundment is not facilitating natural sediment transport downstream past the structure, current best practice is for mechanical removal of sediment from upstream of the weir, with the excavated material deposited downstream. However, the effectiveness of this management option has not been adequately researched, including assessment of how to reallocate sediment most efficiently within the downstream river corridor, especially in a section of reduced flow. In the same vein, few RoR hydropower schemes have been developed with an associated sediment management plan specifically aimed at maintaining natural sediment transport. Most applications make some mention of managing sediment, but primarily for operational purposes and with a focus only on sediment deposited immediately behind the weir. While the coarse sediment deposit which can often be a significant distance upstream from the weir may not affect short-term operations, the consequences of breaking the continuity of coarse sediment transport can significantly impact downstream aquatic habitats and encourage erosion in the reaches downstream of RoR hydropower schemes. If accumulated sediment is mechanically excavated from the headpond, and reallocated downstream, the result is often an overload of fine sediment in the downstream channel. There is currently no good practice guidance to deal with sediment continuity issues around RoR hydropower schemes, and almost no post-construction monitoring to assess sediment movement during the operational phase of RoR hydropower schemes that could form the evidence base for such guidelines.

This report presents the findings and recommendations of a project that investigated sediment continuity in RoR hydropower schemes in Scotland through five objectives:

1. review and evaluate existing sediment management plans, and review and summarise SEPA sediment management related licence conditions (Section 2);
2. review upstream and downstream effects of sediment accumulation in RoR schemes (Section 3);
3. review fine and coarse sediment mechanical management techniques currently employed and research on weir design and operation aimed at maintaining natural sediment movement (i.e., hydraulic techniques) (Section 4);
4. for three case study sites, using site visits, review the evidence of impacts and the mitigation measures

employed and consider what further actions could be undertaken (Section 5);

5. building on the outputs above, provide specific and detailed recommendations on how RoR hydropower can result in less disruption to river habitats, while at the same time being operationally more efficient (Section 6).

In the subsequent sections of this report, we detail the findings and recommendations for each objective. A brief conclusion is provided in Section 7.

# 2.0 Sediment management plans and SEPA licence conditions

The extent to which existing RoR hydropower schemes in Scotland have been developed with sediment management plans to maintain sediment continuity was evaluated. We also reviewed planning application documents and SEPA CAR Licences which include existing sediment management licence conditions. Accessed materials are documented in Appendix A.

## 2.1 Main findings

Our main findings were as follows:

- Due to a cyber-attack, SEPA were unable to provide access to existing CAR Licences. NatureScot provided CAR licensing information for a small number of existing schemes and a list of 13 schemes known to include information on fluvial sediment in either CAR or planning documents. Of these, only one scheme was developed with a sediment management plan (see Appendix A). Therefore, although the amount of data available was limited, from a small sample it is clear that sediment management plans are not commonly produced during the CAR licensing process.
- Despite not producing sediment management plans, 12 of 13 reviewed schemes produced an Environmental Impact Assessment (EIA) Report that included sediment information. These statements detailed the baseline river morphology, judgment regarding whether the impact on sediment movement would be significant or not, and mitigation measures to ensure sediment continuity.
- The EIA for two schemes indicated that a sediment management plan would be produced to ensure any adverse sediment continuity effects were mitigated. However, in both cases, no sediment management plan was developed.
- Three EIAs indicated that 'Best Practice' sediment management would be employed. However, in all three cases there was no indication of what best practice is and there was no reference to any guidance documentation.
- The one available sediment management plan (Burn of Mar) outlined the mitigation measures that would be used, the actions that would be taken, and how post-development monitoring would be undertaken using a sediment management record (i.e. monitoring and recording the volume of sediment moved). The document was clear and informative. It included a justification, appropriately supported with evidence, details for the various mitigation measures proposed, information on how the weir design would minimise sediment accumulation, and how regular monitoring would inform mechanical removal and, if required, the careful downstream reallocation of sediment.

## 2.2 General findings

From the review of the process of obtaining a CAR Licence for a RoR hydropower scheme and how sediment management is incorporated in this procedure, we identified the following implications:

- During an application, the developer is not required to provide any information on sediment management but only to state if there will or will not be any sediment management. They are not required to provide any explanation of how they arrived at the decision that a sediment management plan is not required. Consequently, SEPA staff assessing the application have no evidential basis for evaluating the decision about whether sediment management is needed, especially if they are not able to undertake independent study of the location. Additionally, with only limited background information, staff cannot make an informed decision about any sediment management conditions to be issued with the licence. Most importantly, staff will be unable to determine whether a sediment management plan is necessary.
- The guidance for SEPA staff issuing CAR Licences is not clear. The diagram within SEPA's *Sector Specific Guidance: Hydropower*, shown in Figure 2.1, is not logical. Impoundments less than 1m high are lower risk to sediment continuity than those over 1m high yet the diagram suggests that the higher risk impoundments can be dealt with using standard conditions whereas the lower risk impoundments require site specific conditions or a sediment management plan. This should be the other way round. The diagram would make more sense if the

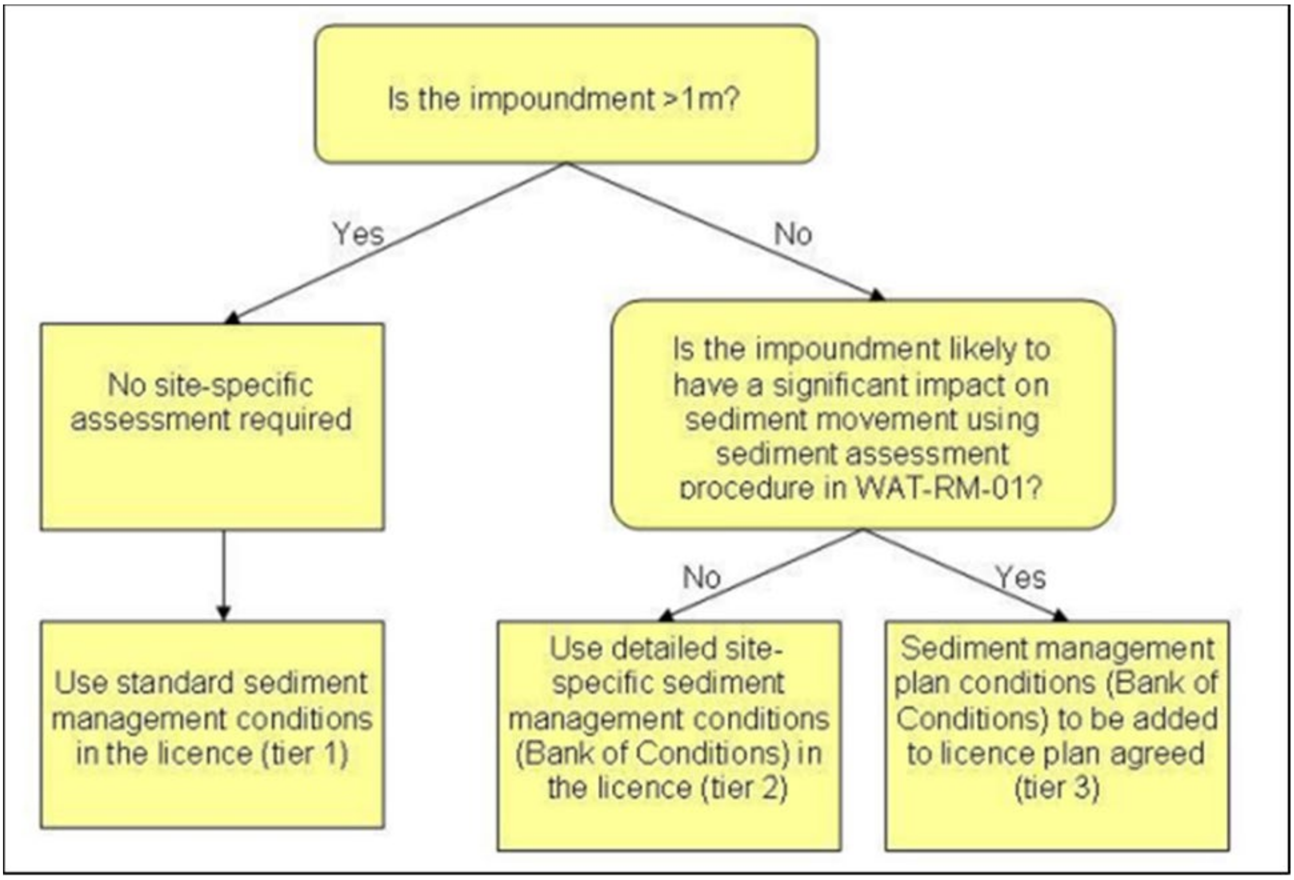


**Figure 2.1.** Tiered Approach to appropriate sediment management conditions as set out in SEPA's *Sector Specific Guidance: Hydropower*.

first 'Yes' and 'No' arrows were swapped, or the ">1m" in first box was "<1m". Additionally, the sediment assessment procedure referenced in the right-hand box on the second row of the diagram does not exist in the Regulatory Method WAT-RM-01 (SEPA, 2019a) does not exist. Justification for the use of the '1 m' threshold (assumed to be height/head of the impoundment) to distinguish between standard sediment management conditions and site-specific conditions is not provided.

- The CAR Licence Applicant guidance states that any sediment management plan created should include a description of the location, quantity and frequency of sediment removal from the headpond. It should also indicate the time of year of removal and describe how the sediment will be re-introduced downstream (SEPA, 2019b). These are suitable points to guide the initial development of a plan but are insufficient to produce a high-quality result. Additional guidance on good practice examples of sediment removal and reallocation would enable better plans to be developed to ensure more appropriate sediment management is carried out which better mitigates the ecological and geomorphological impacts.
- The Environmental Standards Test (EST) determines whether a proposed activity will result in the deterioration of morphological quality and Water Framework Directive (WFD) status. The EST test for river morphology is undertaken using an impact assessment tool called MImAS (Morphological Impact Assessment System). The EST test should be used in conjunction with the CAR Licence guidance to determine when more detailed assessments are needed, what mitigation should be sought, and whether the proposal is likely to result in significant adverse impacts on the water environment. Currently, the MImAS assessment does not evaluate sediment discontinuity, which is a deficiency, and the EST process is thus underestimating impact.
- The standard sediment management conditions issued in a CAR Licence were reviewed (see Appendix A). Fundamentally, the conditions *allow* sediment management to be carried out to facilitate operation of the scheme but do not *ensure* that it is carried out to facilitate sediment continuity. The conditions focus on sediment removal and do not cover the reallocation downstream. Indeed, one of the conditions could be interpreted to mean that sediment should not be reallocated downstream and another makes it practically impossible to do so.  Another condition limiting removal to "immediately upstream from the impoundment may prevent the removal of coarser sediment from the upstream end of the headpond. There are no conditions relating to the extent, timing or frequency of sediment management activities. It is not clear how the conditions facilitate

or control sediment management by hydraulic methods. Furthermore, the conditions do not require any monitoring after construction of the hydropower scheme or after sediment management has taken place.

# 3.0 Longitudinal connectivity issues in ROR hydropower schemes

This section summarises a literature review regarding the upstream and downstream effects of sediment accumulation arising from the development of RoR hydropower schemes. Due to a scarcity of Scottish river case studies, we included evidence from similar river types to those found in Scotland obtained elsewhere in the UK (England and Wales), Continental Europe and North America. The review covers the effects on channel morphology, sediment movement (entrainment, transport, deposition), habitat impacts, species migration, and water quality (including temperature). Details regarding the primary sources are included in Appendix B.

## 3.1 RoR fundamentals

Run-of-River (RoR) hydropower schemes disturb a river's natural sediment transport processes as they form an in-channel barrier to sediment movement (Anderson *et al*., 2015) (Figure 3.1). A typical RoR hydropower scheme has an intake where flow is diverted into a pipe to flow through turbines and produce power. In order to generate ample hydraulic head, and ensure enough water accumulates at the intake, a structure is required (Csiki and Rhoads, 2010; SNH, 2015). This structure is sometimes referred to as a dam, weir, or barrier but for consistency the term *impoundment* is used throughout this report. In most settings a RoR impoundment extends across the full width of the river channel and is less than five metres high, and generally not higher than the elevation of the adjacent channel banks (Casserly *et al*., 2020). The pool of water that is formed upstream of the impoundment due to its effect in raising water level creates a headpond. RoR hydropower scheme arrangements vary but two basic categories of scheme can be distinguished: low-head and high-head. Low-head schemes are used in low gradient reaches and have a small hydraulic head (Brackley, 2016; Anderson *et al*., 2015; SEPA, 2018). High-head schemes are used in steep, upland reaches and have a large hydraulic head that is often associated with the presence of waterfalls (Brackley, 2016). Despite their different settings, both types of scheme require an impoundment which creates an artificial barrier in the river. This barrier has two main effects: it interrupts longitudinal connectivity and so water and sediment continuity; and it changes the channel environment (Anderson *et al*., 2015; Gibeau *et al*., 2017).

## 3.2 Sediment continuity effects of RoR impoundments

Evidence given in the scientific literature reviewed supports the view that RoR hydropower schemes *can* trap sediment and so cause up- and downstream effects on channel morphology, river bed material, and aquatic habitats. However, it is important to consider that the magnitude and long-term significance of sediment accumulation behind RoR weirs varies between schemes. The storage of coarse sediment behind RoR weirs can be temporary, and some sediment may move over the weir and so limit the long-term effect of the impoundment (Csiki and Rhoads, 2014; Casserly *et al*., 2020; Magilligan *et al.* 2021; Pearson and Pizzuto, 2015; Sindelar *et al*., 2020). However, Anderson *et al*. (2015), based on a review of published literature, state that current evidence indicates that RoR schemes can significantly impact physical and ecological processes such as sediment transport and fish migration at larger spatial (i.e., network-wide) and temporal scales, particularly where multiple schemes occur on a single river, and thus alter habitat availability and the structure of biotic communities. Subsequent research has continued to report up- and downstream ecological impacts on fish resulting from RoR hydropower schemes (Baumgartner *et al*., 2019; Bilotta *et al*., 2016, 2017; Wang *et al*., 2016) and that, even with repeated sediment transport over the weir, the impact on biota can be long lasting and include, for example, reducing the number of species (Anderson *et al*., 2015; Bilotta *et al*., 2016, 2017).

## 3.3 Main findings and knowledge gaps identified

- A RoR hydropower scheme impoundment will often raise the water level upstream, changing the river's hydraulic regime and water temperature.  It can also lead to deposition of sediment in the headpond thus increasing the potential for contaminated sediment to accumulate. Accumulated sediment may also block the intake, preventing electricity production (Figure 3.1).
- Impoundments are also likely to reduce sediment supply to downstream sections of the waterbody, altering the size of downstream bed sediments and erosion and deposition patterns and leading to degradation of in-stream habitats.

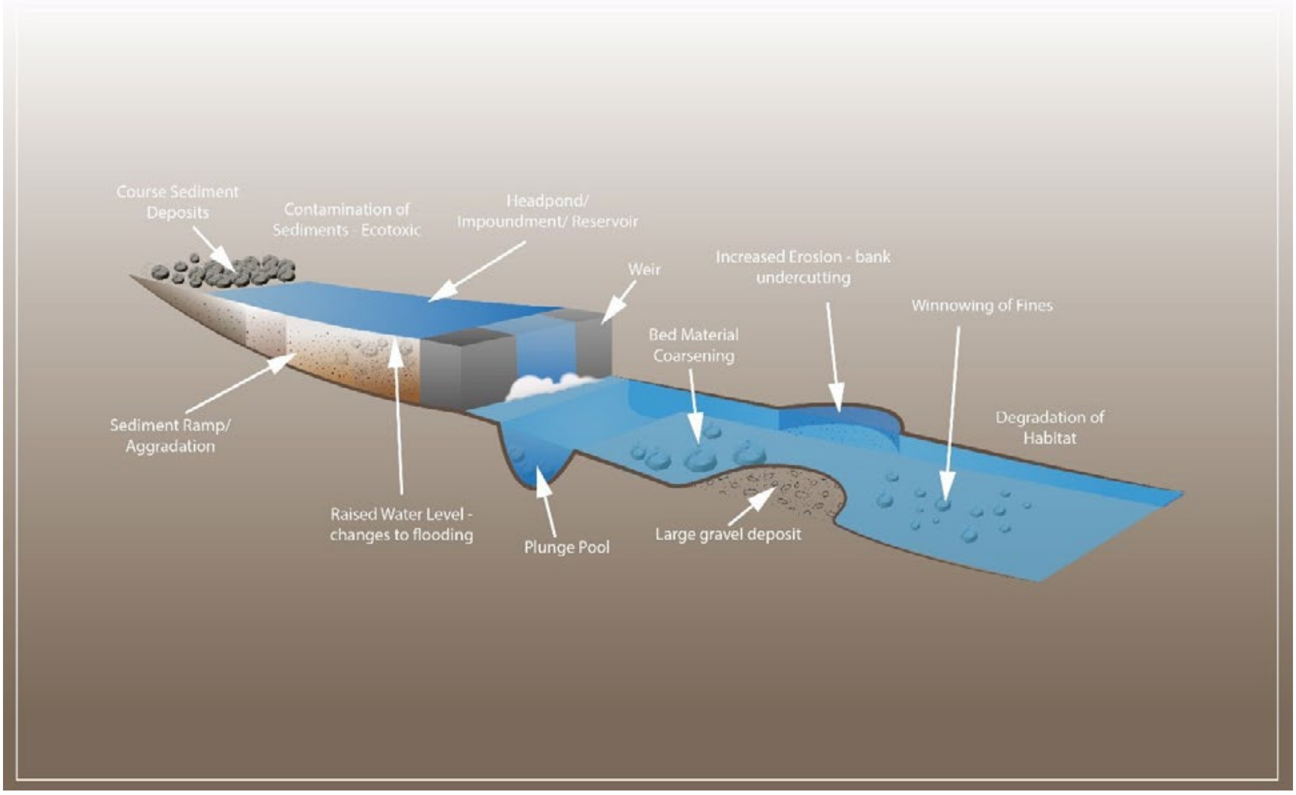

**Figure 3.1.** Schematic diagram visually showing the effects of RoR hydropower schemes on the upstream and downstream sections of a river.

- The severity of the impacts arising from RoR hydropower schemes varies according to natural rates of sediment supply (upstream and downstream of the impoundment structure) and the time it takes the headpond to fill so that further bedload material is conveyed over the weir. The longer it takes for sediment to accumulate, the greater the disruption to downstream sediment supply which is likely to increase the significance of downstream bed material and habitat change.
- In Scotland, climate change may increase the rate of sediment supply, affecting the efficiency of RoR hydropower schemes by modifying water supply and rates of headpond sedimentation.
- Because the retention of gravel and water in a RoR hydropower scheme headpond can significantly impact upstream and downstream habitats, and potentially over significant spatial and temporal scales, the potential for disturbance due to sediment transport changes should be carefully assessed before, during, and after the development of RoR hydropower schemes.
- In Scotland, many hydropower schemes are located in steep upland catchments due to their high head potential for power generation (SEPA, 2018). Since local catchment characteristics affect the accumulation of sediment at RoR hydropower schemes, it is important to analyse sediment supply and transport for each specific catchment and scheme installed. This will aid the understanding of how significantly the reaches upstream and downstream of an impoundment could be affected. Such knowledge would, in time, become useful guidance for future schemes, allowing designs with inherently lower environmental impacts, reduced sediment maintenance costs, and greater hydropower scheme efficiency.
- This review has identified evidence gaps in:
  - i. the temporal dimension of RoR structure impacts;
  - ii. specific studies of RoR hydropower scheme impacts in Scottish rivers. While we can assume that physical processes in gravel-bed rivers are similar regardless of their location, it would be highly instructive to understand the breadth of impact and nuances related to Scottish RoR hydropower scheme installations based on a comprehensive data set;
  - iii. investigations that quantify cumulative effects of multiple RoR hydropower schemes in particular catchments; and
  - iv. investigations that quantify how scheme operation and sediment management will need to adapt to climate change impacts.

# 4.0 Sediment management techniques for RoR hydropower schemes

This section describes the main sediment management techniques for RoR hydropower schemes. In the following sections, we describe hydraulic and mechanical techniques as well as non-structural procedures (i.e., broader scale river management to reduce sediment yield, such as riparian planting). Examples of management techniques and their objectives are provided in Figure 4.1.

**Hydraulic techniques** entail designing and operating impoundment structures that use flowing water to pass sediment at close-to-natural transport rates, therefore reducing disturbance to the physical and ecological processes that underpin the river environment. They are designed to minimise deposition in the headpond by routing sediment around or through the impoundment using sediment bypasses, spillways and pass-through gates or sluices, or to use hydraulic excavation methods to recover available storage volume in the headpond. *In-situ* **mechanical techniques** manage available storage volume in the headpond through the mechanical excavation of sediment and reallocation to a downstream reach of the waterbody or a specific disposal site. In contrast, catchment-wide **sediment yield reduction** represents a 'nature-based' approach that focuses on reducing sediment delivery to the RoR structure, thus reducing the rate at which a headpond fills with sediment and reducing the frequency with which hydraulic or mechanical clearing is required. Although each technique has limitations according to the specific sediment transport regime, impoundment size, operating rules and engineering designs, they are applied primarily to increase the service life of impounding structures and to maintain longitudinal sediment connectivity (Annandale *et al*., 2016; Kondolf *et al*., 2014; Morris and Fan, 1998; Morris, 2020).

Rather than being mutually exclusive strategies, mechanical, hydraulic and sediment yield reduction methods can be used in combination, depending on site and operational constraints. Further, open-source algorithms have recently been developed to help practitioners find optimal solutions for siting, designing, and establishing environmentally friendly operating rules for impoundments, including RoR hydropower schemes (e.g., Wild *et al*., 2021). Optimisation approaches offer the potential for reducing uncertainty and incorporating environmental impact in an explicitly quantitative framework, and so allowing accurate adaptive management of RoR sediment. In the following sections the potential benefits, limitations, and applicability of hydraulic, mechanical, and catchment-wide sediment yield reduction techniques are outlined.

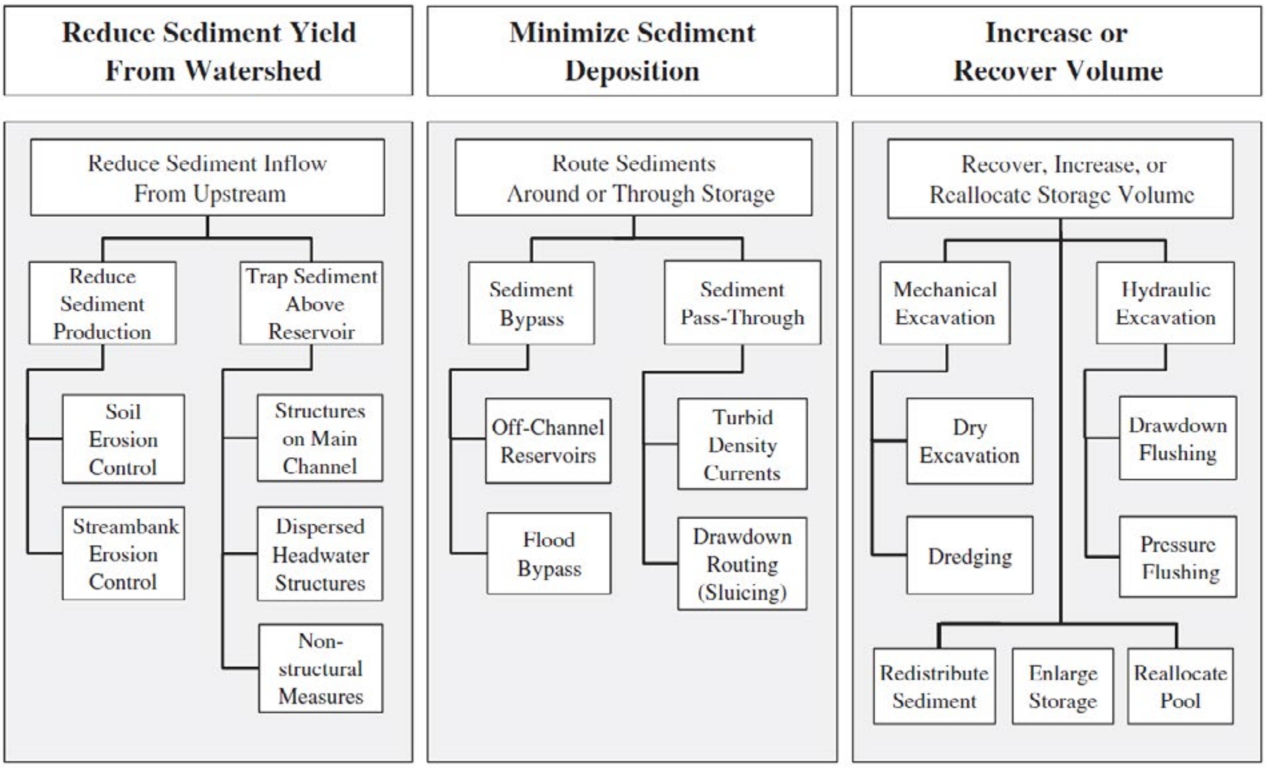


**Figure 4.1.** Classification of sediment management techniques, according to Kondolf et al. (2014). For a more detailed version of this figure/classification, refer to Morris (2016), and Morris (2020).

## 4.1 Summary of techniques

### 4.1.1 Reduce sediment yield from upstream

A variety of structural and non-structural management practices can be used to reduce sediment supply to a reach with an impoundment (Morris and Fan, 1998). Appropriate techniques should be identified in, and implemented using, catchment management plans and considered part of the sediment management plan for a RoR hydropower scheme. Adaptive management strategies, that include monitoring and evaluation, should be implemented to achieve satisfactory sediment yield reduction (Richter and Thomas, 2007; Walling and Collins, 2008).

Categories to reduce sediment yield from upstream include:

i. applying soil conservation techniques via reduction of overgrazing (Rickson, 2014);

ii. protecting, preserving, and restoring natural riparian buffer strips (Broadmeadow and Nisbet, 2004; Stutter *et al*., 2012);

iii. applying channel restoration techniques to recreate stable river geometries. Examples include restoration of peatlands by ditch blocking, installing leaky dams, and large wood structures (LWS) in streams and bunds on headwaters to reduce overland flow while increasing sediment storage and residence time (Dadson *et al*., 2017; Lane, 2017; Shields *et al*., 2003; Soar and Thorne, 2001);

iv. constructing a sediment trap upstream of the impoundment to facilitate sediment accumulation ahead of reallocating that material downstream (e.g., Piton and Recking, 2016; Schwindt *et al*., 2018); and

v. applying site-specific engineering methods to control upstream bank erosion, bed degradation, and overland flow on hillslopes, such as the implementation of LWS to protect eroding banks, and revegetating gullies (Abbe *et al*., 1997; Bizzi *et al*., 2015; Kail *et al*., 2008; Mekonnen *et al*., 2015; Piégay *et al*., 2005; Valentin *et al*., 2005).

### 4.1.2 Minimise sediment deposition through sediment routing

**Sediment routing** refers to the manipulation of an impoundment's hydraulics, geometry, or both, to pass sediment through or around the structure while ensuring minimal deposition in the headpond (Morris, 2016; Sumi and Hirose, 2009). This approach aims to separate the inflow of sediment-rich discharges from clear water to avoid or minimise sediment deposition upstream of the structure (Figure 4.2). Sediment routing differs from flushing techniques which focus on the hydraulic excavation of sediments already deposited in the headpond. Routing aims to reduce deposition or maintain sediment transport through or around the impoundment during flood flows (Kondolf *et al*., 2014; Morris and Fan, 1998; Sumi *et al*., 2004) and thus avoid headpond sediment accumulation. Sediment routing techniques can be grouped into two strategies: *sediment pass-through* and *sediment bypass* (Morris, 2020; Sumi and Kantoush, 2010). *Sediment pass-through* strategies encompass (i) water level drawdown to pass sediment-rich floods along the impoundment at a high velocity to reduce deposition, and (ii) venting of turbid density currents (very densely concentrated sediments) through a low-level gate. *Sediment bypass strategies* include (i) diverting clear water into an off-stream reservoir while excluding sediment-rich flood flows (Figure 4.3), and (ii) bypassing sediment-rich flood flows around an on-stream impoundment (Figure 4.4).

Although it can have downstream ecological impacts on the abundance, biomass, diversity and richness of species, (Frémion *et al*., 2016; Nukazawa *et al*., 2020), sediment routing is often considered the most environmentally-friendly sediment management technique because sediment releases can be timed to coincide with naturally occurring high flows and seasonal fish migration (Jutagate *et al*., 2005, 2007; Morris and Fan, 1998). It can also be operated in a catchment by following upstream to downstream process that triggers the opening of sluice gates according to the arrival time of the flood wave, with gates closing as the high flow recedes, mimicking natural sediment transport processes (Kondolf *et al*., 2014; Ostadrahimi *et al*., 2012; Zhang *et al*., 2013). Given that achieving sediment-rich flows typically requires flows near to the bank top or higher, especially in gravel-bed rivers that are common to many Scottish RoR hydropower schemes, sediment routing during flood events can be highly effective at removing fine and coarse sediment, consequently reducing the requirement for mechanical sediment excavation and reallocation downstream.

### 4.1.3 Increase or recover impoundment volume through mechanical or hydraulic excavation

The hydraulic flushing of sediment involves drawing down and emptying a headpond by opening a low-level outlet to permit free-flowing transport processes that entrain and subsequently flush existing deposits downstream (Campisano *et al*., 2016; White, 2001). Hydraulic flushing differs from sediment routing by focusing on the removal of deposited material and an operation time that is not necessarily coincident with the natural occurrence of high flows. There are two groups of hydraulic flushing techniques: empty or *free flow flushing*; and *pressure flushing*, which is less effective and less commonly applied (Morris, 2016).

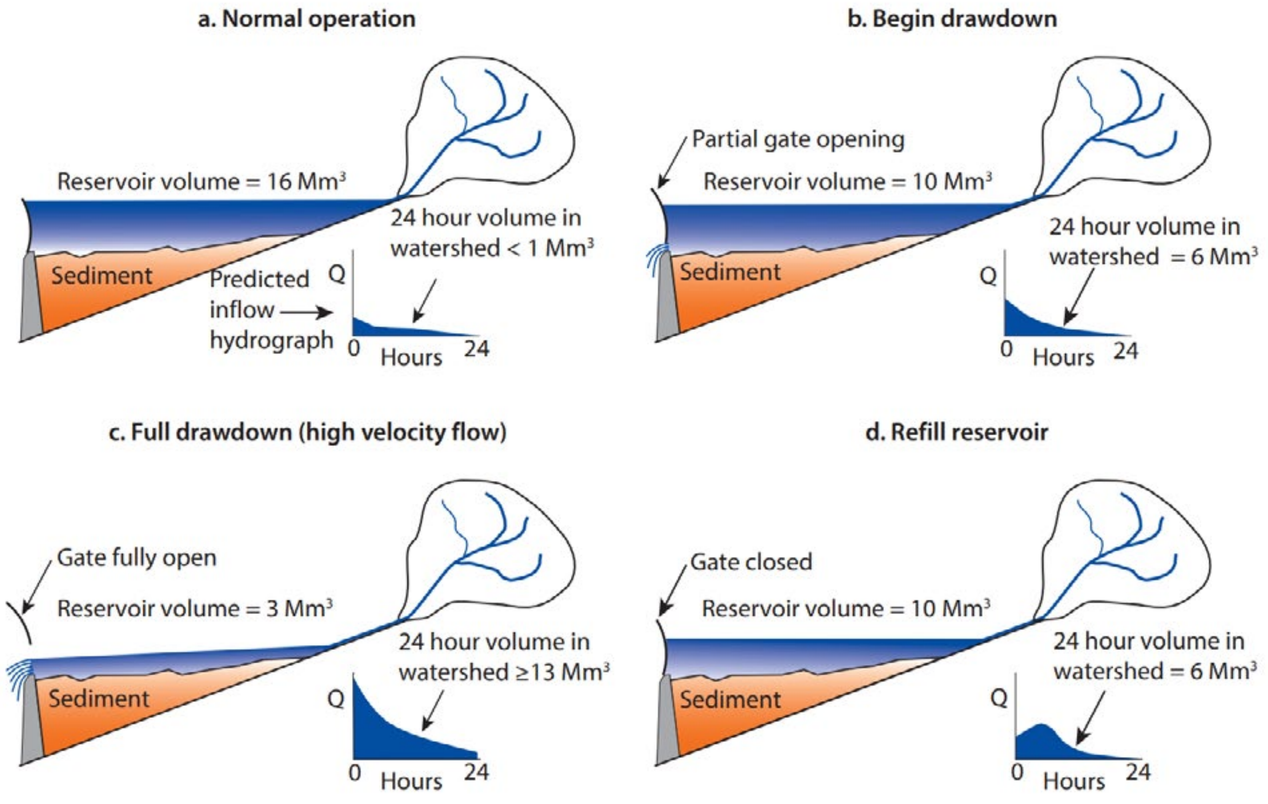


**Figure 4.2.** Example of a sediment pass-through (sluicing) in a storage reservoir during a short-duration flood. (a) During normal operation the impoundment gates remain closed or are opened to pass small floods only, while the monitoring system continuously collects rainfall and streamflow data to keep soil moisture computations updated in the model. (b) When the real-time model predicts an increase in discharge that can reach the impoundment, the gates are progressively opened so that the volume of water released equals that predicted to enter in the reservoir in 24 hours. (c) With the reservoir working as a free-flowing channel, the real-time model calculates continuously if the incoming volume reaching the impoundment in the next 24 hours is sufficient to refill it. (d) As rainfall decreases, the real-time hydrological model will define the best gate closing rate to ensure the impoundment refills in 24 hours. Source: Morris (2016), adapted from Morris and Fan (1998).

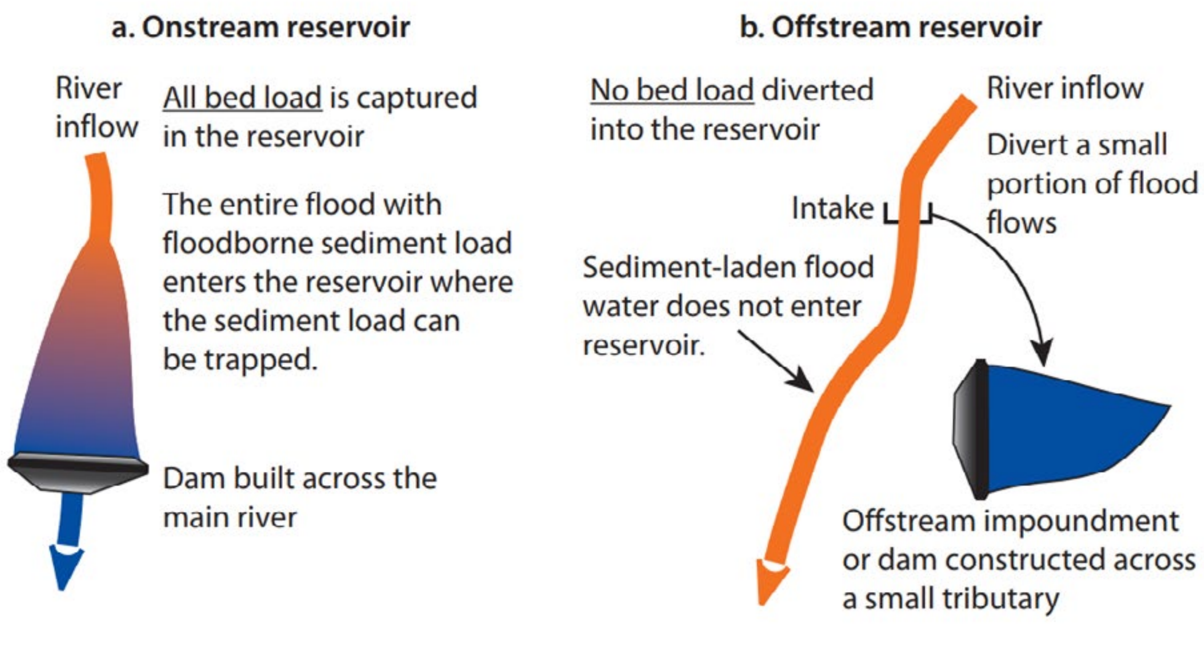


**Figure 4.3.** Generic design features of an (a) on-stream reservoir, where all bed load is trapped, and (b) an off-stream reservoir where no bedload is diverted. These management techniques can be used in RoR hydropower schemes when topographic constraints permit. Source: Morris (2016).

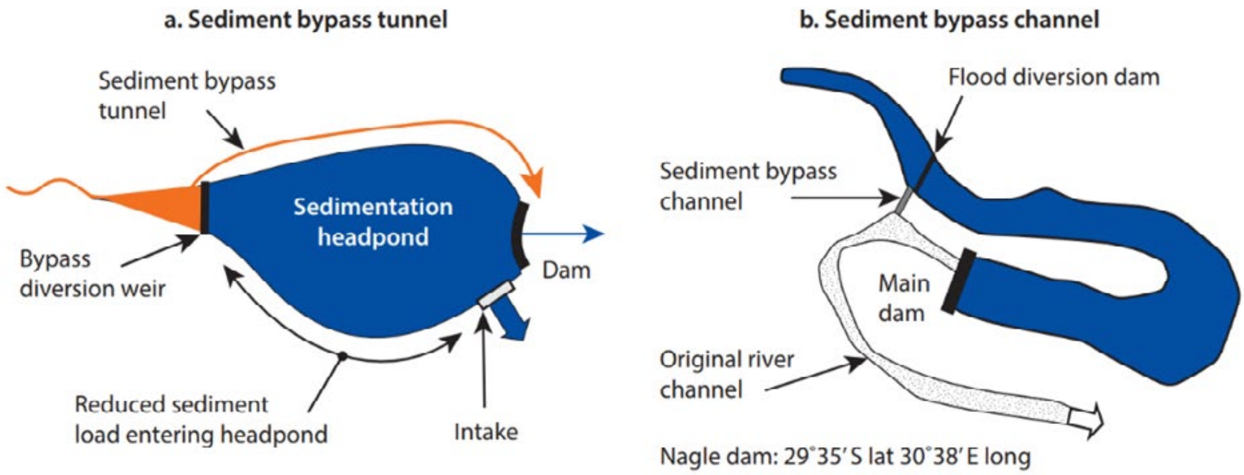


**Figure 4.4.** Generic design features of an (a) sediment bypass tunnel, and (b) a sediment bypass channel. In (b), the bypass can be either a tunnel or a channel. The main difference between a) and b) is the geometry of the river course. The tightly curved example in (b) is much more favourable as the diversion channel or tunnel will have a steep slope that allows it to transport more (and coarser) sediment. However, this ideal channel geometry is rarely available. Source: Morris (2016).

Empty or free flow flushing refers to opening a low-level outlet to completely draw-down the impoundment and so scour out deposited sediment (Isaac and Eldho, 2019; Wang and Chunhong, 2009). Sequential flushing, when two or more impoundments are flushed simultaneously, can be implemented in catchments with multiple impoundments to allow a sediment wave to flow through a system without retention, requiring a level of communication between developers (Chow and Wu, 2016; Kondolf *et al*., 2014; Wu *et al*., 2020). An idealised sequence of flushing, when sediment is scoured, reworked, and moved closer to a dam when the water levels are reduced, is depicted in Figure 4.5.

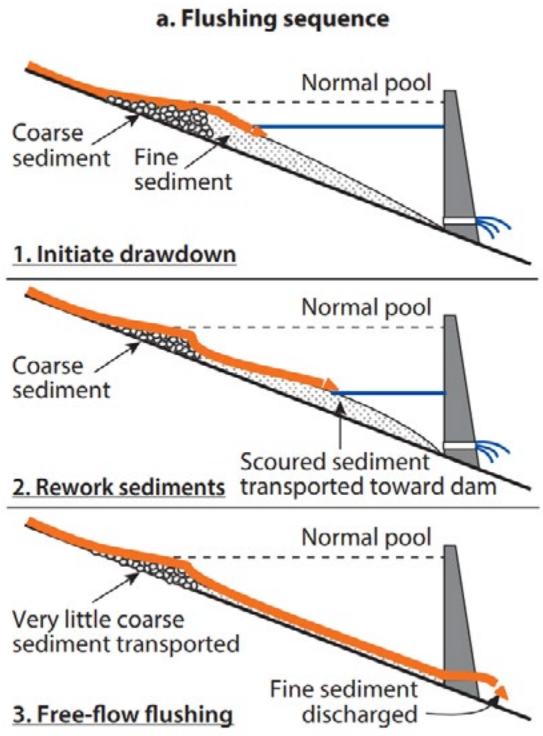


**Figure 4.5.** Flushing sequence of an impoundment. Sources: Adapted Morris (2016), adapted from Morris and Fan (1998).

One of the main limitations of using flushing as a sediment management technique for RoR hydropower is the unnatural increase in suspended sediment load (and so turbidity) in downstream reaches in situations when there is (i) a high fine sediment supply available and (ii) when flushing is not timed with a high flow event (which would mean a naturally high suspended load). In addition, flushing can also increase the risk of initiating headcutting (an upstream-migrating erosional feature with an abrupt vertical drop, also known as a knickpoint, in the stream bed) through the sediment accumulated upstream of the impoundment, which can lead to an increased rate of sediment supply to the impoundment and more frequent sediment management interventions. These impacts can influence sediment dynamics and ecological functioning by altering light availability and riverbed roughness due to high fine sediment load (Baoligao *et al*., 2016; Doretto *et al*., 2019; Espa *et al*., 2016, 2019). Additionally, if flushing flows are of only moderate magnitude and over short durations, they may be unable to carry the coarser particles of the channel bed and may indeed result in further deposition in the impounded reach (Lisle and Church, 2002). Overall, flushing requires very careful planning and design (detailed in Kondolf *et al*., 2014). Measures to reduce the environmental impacts of reservoir flushing include avoiding environmentally sensitive periods (such as those favoured for fish spawning), providing large dilution flows from either natural runoff events or releases from other dams, and flushing more frequently so that each event releases a smaller amount of sediment that can be closer to a natural load in the downstream environment (Cattanéo *et al*., 2021; Hauer *et al*., 2020; Reckendorfer *et al*., 2019). A successful case of simultaneously operating several large RoR impoundments occurs in sequential hydropower dam schemes on the River Rhône catchment in Switzerland and France. The timing of flushing is coordinated from upstream to

**Figure 4.6.** Wet excavation being conducted at a RoR hydropower scheme in a Scottish Highland catchment. Note that sediment removal is creating a headcut which could move upstream causing bed and bank erosion as it migrates and increasing sediment supply to the headpond.

downstream as the sediment wave propagates to minimise potential sediment deposition, and sediment laden flows are diluted by clearwater releases to maintain relatively low suspended sediment concentrations and so minimize ecological impacts (Compagnie National du Rhône, 2010).

Sediment can be mechanically removed from hydropower reservoirs by hydraulic dredging, dry excavation (i.e., when the water flow is blocked and the area is dry) or wet excavation (i.e., when flowing water is present – example in Figure 4.6). The choice of excavation technique will depend on factors such as sediment volume, grain size, available disposal and reuse options, water levels, and environmental protection criteria (Bagarani *et al*., 2020; De Vincenzo *et al*., 2019; Morris and Fan, 1998). Mechanical excavation methods are generally costly (Kondolf *et al.*, 2014; Morris, 2066; Tigrek and Aras, 2011), however, for many sediment accumulation problems, excavation is often the only management option possible (Morris, 2016), for instance when hydraulic techniques pose unacceptable risks to navigability or environmental factors, such as in the Lower Rhône in France where disruptions to navigation must be arranged a year in advance (Compagnie National du Rhône, 2010; Kondolf *et al*., 2014).

There are no established protocols for how accumulated sediment should be reallocated downstream or removed to a disposal site, but lessons may be drawn from studies of gravel augmentation impacts (e.g., Ock *et al*., 2013), from river restoration plans guided by sediment modelling (e.g., Downs *et al*., 2011), and from laboratory experiments (Battisacco *et al*., 2016; Rachelly *et al*., 2021). Decisions must be site-specific and will depend on the volume and grain size of the sediment removed, the downstream sediment transport capacity, hydrograph characteristics, and local ecological considerations (Morris and Fan, 1998). Concerns will often be related to the impact of fines (clay/silt) on ecological, physical, and chemical aspects of riverine habitat, although this can sometimes be less of a concern in Scottish RoR hydropower where coarse sediment particles (gravel and larger grain sizes) predominate. In such settings, mechanical redistribution of sediment downstream of impoundments has been undertaken to improve the stability of the channel bed and promote the formation of bar forms, providing greater morphological diversity and improving habitat conditions (Arnaud *et al*., 2017; Gaeuman, 2014; Rheinheimer and Yarnell, 2017; Staentzel *et al*., 2020).

Sediment augmentation techniques can be employed to effectively reallocate sediment from the headponds to downstream reaches (Brousse *et al.,* 2020; Staentzel *et al*., 2020; Stähly *et al.,* 2020; Zeug *et al.,* 2014). Recent experimental studies have explored how to achieve an optimal stockpile design (e.g., Battisacco *et al.,* 2016; Chardon *et al.,* 2021) and how it can be used to restore

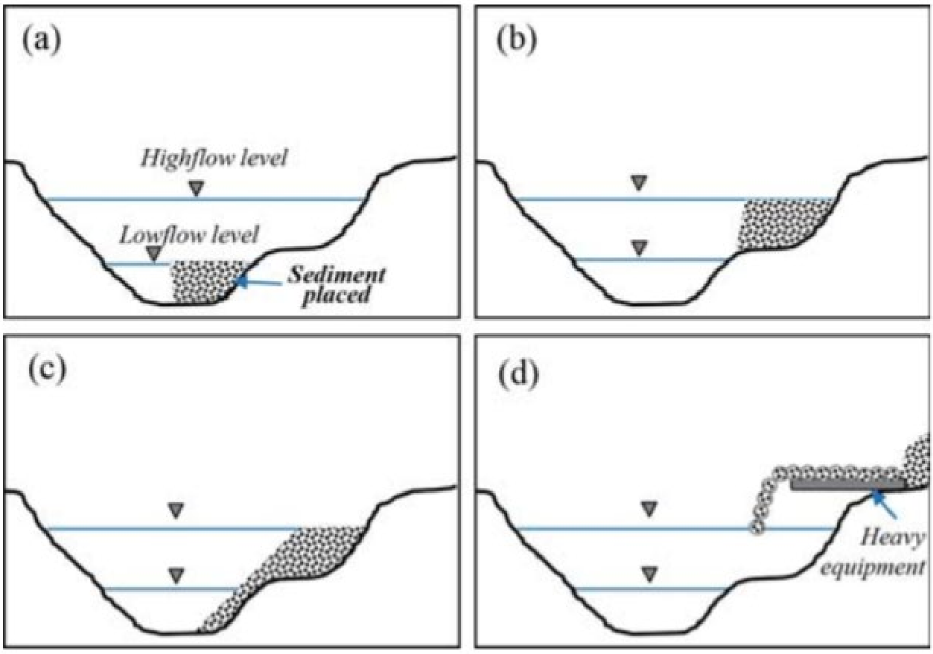


**Figure 4.7.** Sediment replenishment methods according to sediment placement or injection types. (a) In-channel bed stockpile, (b) High-flow stockpile, (c) Point bar stockpile and (d) High-flow direct injection. Figure from Ock et al. (2013 [Figure 1]).

**Table 4.1. The characteristics associated with different methods of coarse sediment augmentation. Adapted from Table I in Ock et al. (2013), which is partially derived from data published by Kondolf and Minear (2004), McBain and Trush (2004) and Harvey et al. (2005).**

| Type | Character |
|---|---|
| In-channel bed stockpile | – creates and augments immediately usable habitat features such as spawning riffles, using mechanical sculpting: can be applied extensively<br>– sediment transport relies on flows sufficient to allow entrainment: this may be achieved during a fairly moderate flood flow or spill but can be rare in lowland or heavily regulated settings<br>- constructed features will be progressively modified by flood events |
| High-flow stockpile | – coarse sediment is entrained during flood events large enough to scour the toe and face of the deposit.  The transport distance of augmented sediment depends largely on the duration of spill flow<br>– large volumes and sizes of sediment are added at a relatively low cost, and the same site be used repeatedly when sediment is regularly transported<br>– an 'efficient' approach in that little in-channel construction is required and the number of river access sites is minimised<br>– approach allows 'the channel to do the work' in transporting sediments to natural zones of deposition |
| Point bar stockpile | – in-channel bar features can be created within long uniform reaches where spawning habitats are currently limited<br>– alternate bar morphology that potentially has a high habitat value is created, and will evolve during high flows<br>- point bar locations are a natural depositional setting in the 'jerky conveyor belt' of coarse sediment transport |
| High-flow direct injection | – coarse sediment is introduced during high magnitude flood events with the capacity for immediate sediment transport<br>– larger volumes of gravel can be added during longer peak flows<br>– during larger magnitude and longer duration events, quite considerable distances of sediment transport may be achieved, speeding up the process of sediment dispersal<br>- the process of injection during high flows introduces the potential of hazardous working conditions |

longitudinal continuity (e.g., Katano *et al.,* 2021; Stähly *et al*., 2019). In general, sediment augmentation techniques can be grouped into four approaches: in-channel bed stockpile, high-flow stockpile, point bar stockpile, and high-flow direct injection (Ock *et al*., 2013) (Figure 4.7). The *in-channel bed* stockpile method involves placing coarse sediment within the low flow channel to provide immediately usable habitat features, thus mimicking natural bedforms (Figure 4.7a). The *high-flow* stockpile method involves placing coarse sediment along the upper bank face to be distributed downstream by high flows; the assumption made is that the river itself will transport sediment and reshape the channel during high flow events (Figure 4.7b). The *point bar stockpile* method introduces coarse sediment to augment or create a point bar, whose dimensions are determined using site-specific low flow and bankfull channel geometry (Figure 4.7c). Lastly, the *high-flow direct injection* introduces gravel directly to the river channel during a high flow event using heavy equipment such as a conveyor belt, allowing the sediment to be readily transported (Figure 4.7d). Summary characteristics of each method of augmentation is given in Table 4.1: note that in-channel (a) and point bar (c) methods are entirely complementary and could form part of the same strategy.

## 4.2 Limitations

- The international literature on sediment management techniques for RoR hydropower schemes draws mostly on case studies from relatively large rivers with high discharge. Therefore, there is a selection bias to RoR hydropower schemes that are larger than those typically found in Scotland.
- Some of these methods require real time monitoring of discharge and precipitation, and weather forecasting for remote operation; these requirements are generally absent in Scottish hydropower schemes.
- Some of the techniques in this section may be only rarely suitable for application in Scottish RoR schemes. For instance, the hydraulic excavation technique requires a deep impoundment, with very low velocities to operate, conditions which are not typical of Scottish RoR hydropower schemes. Further most Scottish RoR schemes occur in rivers characterised by coarse sediment (gravel, cobble), whereas most flushing methods are intended for fine sediment accumulations and so has limited application. Of the augmentation methods, direct high flow injection relies mostly on long duration snowmelt flood events, or high flow releases from large dams and is unlikely to be feasible in Scottish RoR hydropower schemes where flood flows are likely to be generated rapidly and have only a short duration.

The lessons drawn from this review, along with findings from the case studies in the next section, are used to derive the recommendations listed in Section 6.

# 5.0 Case studies

A selection of five RoR hydropower schemes in Scotland were assessed to determine the magnitude and extent of their geomorphological impacts. The sites were selected in collaboration with the CREW Project Steering Group and were chosen to illustrate a range of situations encountered in Scotland, such as: individual and cumulative impacts; different degrees of upstream/downstream impact; different river types/sediment loads; structures more or less difficult to retrofit; and more or less difficult to get heavy plant on site and to points of sediment removal and reallocation. We then assessed whether existing maintenance measures appeared sufficient to efficiently manage sediment continuity concerns. For each scheme, a site walkover was conducted encompassing the impoundment area and sections of the upstream and downstream river corridor. In addition, historical maps, aerial imagery, and any pertinent documentation were analysed.

Note that in the descriptions below we use 'left' and 'right' to refer to sides of the river when the river is viewed looking in a downstream direction.

## 5.1 Summary results

### 5.1.1 Case study One

The first case study encompasses a single structure, constructed in April 2015, and consisting of an impounding weir and intake (Figure 5.1). The outfall is ≈ 1.5 km downstream close to the river's terminus into a loch. The impacted reach is ≈0.7 km long. In the catchment upstream from the impoundment, river type is dominantly step-pool with sections of bedrock, pool-riffle, plane bed and peat interspersed. Between the impoundment and the outfall it is dominantly step-pool and downstream from the outfall it is initially step-pool but then changes to plane bed and pool riffle.

At the intake headpond, a sediment bar has formed immediately upstream from the weir (Figure 5.2). The bar was partially obstructing the orifice on the right side of the structure that delivers water during low flows (i.e., 'hands-off-flow') to the depleted reach downstream (Figure 5.2). As a result, the water level at the orifice was lower than the weir crest but water was overtopping the weir along the left-hand side. Despite the local hydraulic changes caused by deposition of sediment in the headpond, there was a flow path between the headpond and the orifice such that some flow was being delivered to the depleted reach downstream. The grain size distribution of the surface layer of the headpond bar was 5–130 mm (Wolman, 1954, method). The $D_{16}$, $D_{50}$, and $D_{84}$[1] of the surface layer were 21, 49, and 101 mm, respectively.

The main depositional features downstream occur approximately 700 m downstream from the weir, where three sediment bars occur on alternating sides of the river (Figure 5.3) are followed by delta deposit (Figure 5.4) just upstream of the river's entry to a loch.  The grain size distribution of the surface layer of the bars was 10–200 mm and the $D_{16}$, $D_{50}$, and $D_{84}$ of the surface layer are 21, 58, and 115 mm, respectively, very similar statistics to the headpond deposit. Whilst the bar in the headpond attests that some sediment retention has occurred here the depositional features and the grain size similarity between the bar upstream of the weir and those downstream suggests that sediment now passing over the weir during high flow events providing some evidence of sediment continuity due to natural hydraulic movement and this is maintaining channel morphology downstream.

No evidence of mechanical reallocation of sediment from the headpond was found on the riverbed or riverbanks downstream from the impoundment.  Overall, this suggests that, while the impoundment initially created some sediment discontinuity, the relatively small volume of the headpond quickly infilled with sediment allowing later sediment to pass over the weir and maintain near-natural sediment transport rates in the river downstream.  Were it not for the potential blockage of the hands-off-flow orifice at this impoundment, no 'active' sediment management would be required. In this case, regular inspection will be required to ensure that further deposition in the headpond does not compromise the delivery of hands-off flow.

1 Sediment mixtures of different particle sizes can be distinguished by comparing the percentile values of the distributions. The notation used is $D_x$ 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. $D_{50}$ is the median grain size.

**Figure 5.1.** RoR case study One, hydropower scheme intake and weir. Note the sediment deposit in the headpond.

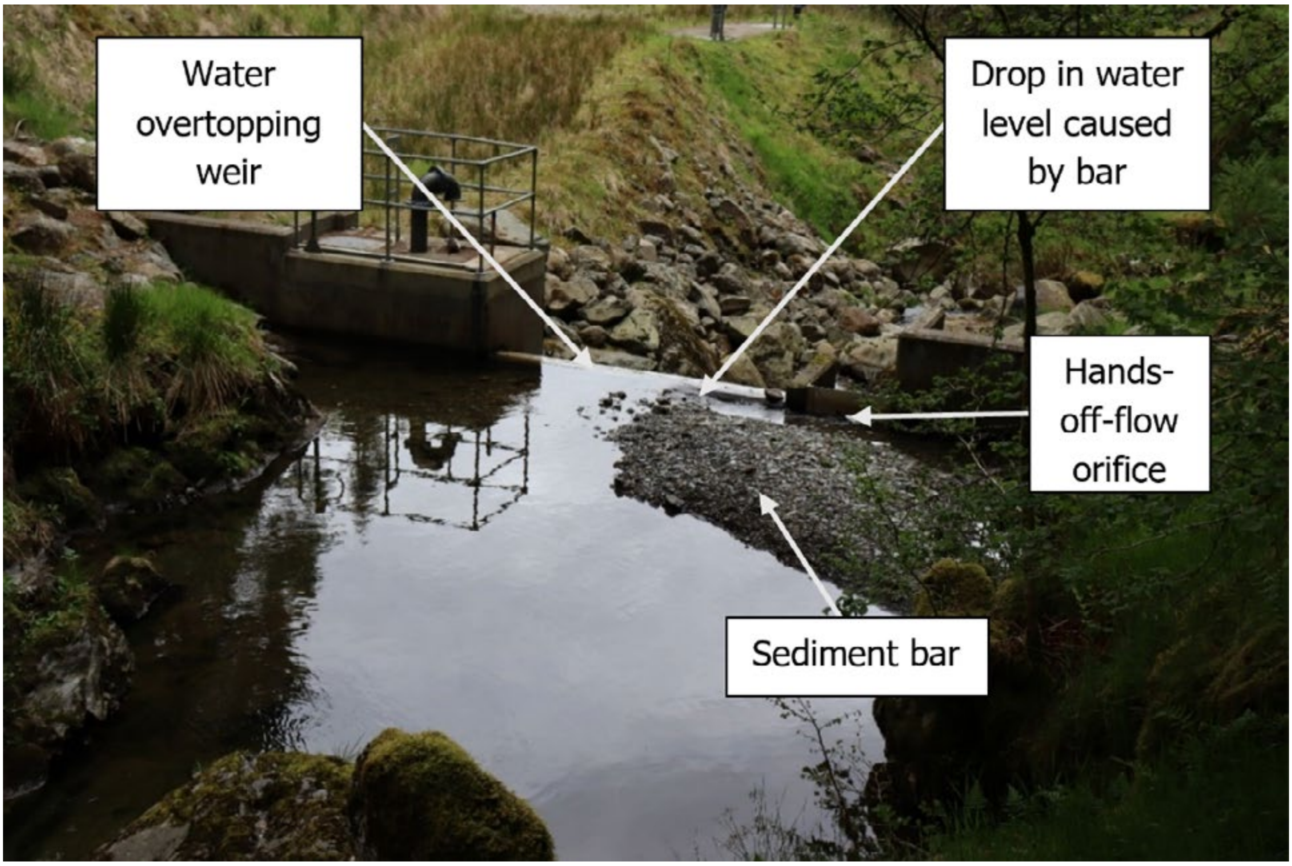


**Figure 5.2.** Headpond of RoR case study One, looking downstream. Note how the sediment bar partially blocks the orifice (on river right) and forces water to flow over the weir crest (on river left).

**Figure 5.3.** RoR case study One, coarse sediment bars deposited downstream of the impoundment. Photograph looking upstream.

**Figure 5.4.** RoR case study One, terminal delta just upstream of the confluence with a loch. Photograph looking upstream.

## 5.1.2 Case study Two

The second case study concerns a single RoR intake structure, buried pipeline, powerhouse, and tailrace that was constructed in 2006-7. The scheme is set within a steep, high energy upland channel that flows ≈ 10 km through a confined to semi-confined valley with a significant bedrock gorge section, to its outfall at a loch. The mainstem river is fed by steep, high-energy tributaries that are predominately sediment supply-limited. River bed material comprises boulders, cobbles, gravels and sands that reflect not only the energy regime of the river, but also the supply of sand, gravel, and cobble sized material from eroding fluvio-glacial terraces and banks.

At the impoundment, large volumes of sediment are deposited in the headpond on a frequent basis. At the time of the survey, sediment had recently been removed from the headpond and placed on both banks downstream from the impoundment (Figure 5.5, Figure 5.6, and Figure 5.7). Sediment re-allocated to the left bank has consistent grain size characteristics from the bottom to the top of the deposit whereas those on the right bank have a well-defined angular boulder layer at the toe of the bank overtopped with gravel and sand. The grain size distribution on the top of the right bank deposit was 10–120 mm ($D_{16}$ = 10 mm, $D_{50}$ = 22 mm, and $D_{84}$ = 55 mm), whilst on the top of the left bank deposit it was 10–140 mm ($D_{16}$ = 20 mm, $D_{50}$ = 40 mm, and $D_{84}$ = 80 mm). The estimated volume of reallocated sediment on the right bank was 1,225 $m^3$ and on the left bank 285 $m^3$.

Sediment dredged from the headpond has also been used as pavement material on the river right, upstream from the weir (Figure 5.8). The total area of the pavement constructed with dredged material was ≈ 472 $m^2$. It was not possible to estimate volume from this section.

No sediment bars were observed in the channel for ≈ 200 m downstream of the impoundment and therefore a longitudinal analysis of patterns of grain size change was not possible. However, the absence of depositional sites, together with bedrock exposure and boulder-sized particles, indicated that the downstream section seemed to be coarser and sediment-starved when compared to the upper sections.

Aerial imagery taken just before the scheme was constructed (2005) shows a longitudinal continuum of bars in the river. At the site of the impoundment there was a relatively small (≈ 40 $m^2$) bar on the right of the channel however, there was no excessive aggradation. Similarly, localised scour and bedrock exposure downstream of the impoundment did not appear to be extensive before the impoundment was constructed but is now.

Evidence, primarily from the significant volume of material that has been reallocated downstream (but not entrained) following headpond excavation, but also from the paucity of downstream alluvial features, suggests that sediment continuity has been substantially altered. This is likely due to the reduction in sediment supply downstream of the impoundment and consequent increase in erosion of pre-existing bars. The downstream sediment supply reduction is further supported by the volume of sediment mechanically reallocated to the downstream riverbanks (≈ 1,510 $m^3$, without considering the constructed pavement) and the volume of water observed in the impoundment on the survey day (≈ 1,560 $m^3$), indicating that the headpond might have been full of sediment had management techniques not been conducted.

Surface samples of sediment grain size indicated that sediments were much coarser in a bar deposited just upstream of the headpond than from two samples taken from the mechanically reallocated sediment downstream. It is possible that this occurs because the sampled headpond sediment has been hydraulically sorted, resulting in coarser sediments at the surface and finer underneath, whereas the mechanically deposited material is unsorted and will contain a wide mixture of grain sizes at the surface. Alternatively, the result may indicate that longitudinal sediment sorting takes place approaching the headpond whereby coarser sediments are deposited first. As such, finer sediment is deposited closer to the impoundment structure, and it is these sediments that were subsequently sampled after their excavation and reallocation downstream. As such, focussing sediment excavation near the impoundment would result in finer material dominating the sediment reallocated downstream. Whichever is the explanation, the predominance of finer sediment at the surface of the reallocated material downstream means that during flood events there will be a bias towards the entrainment and transport of finer material, potentially altering sediment sizes downstream.

**Figure 5.5.** RoR Case study Two intake structure . Photograph looking upstream.

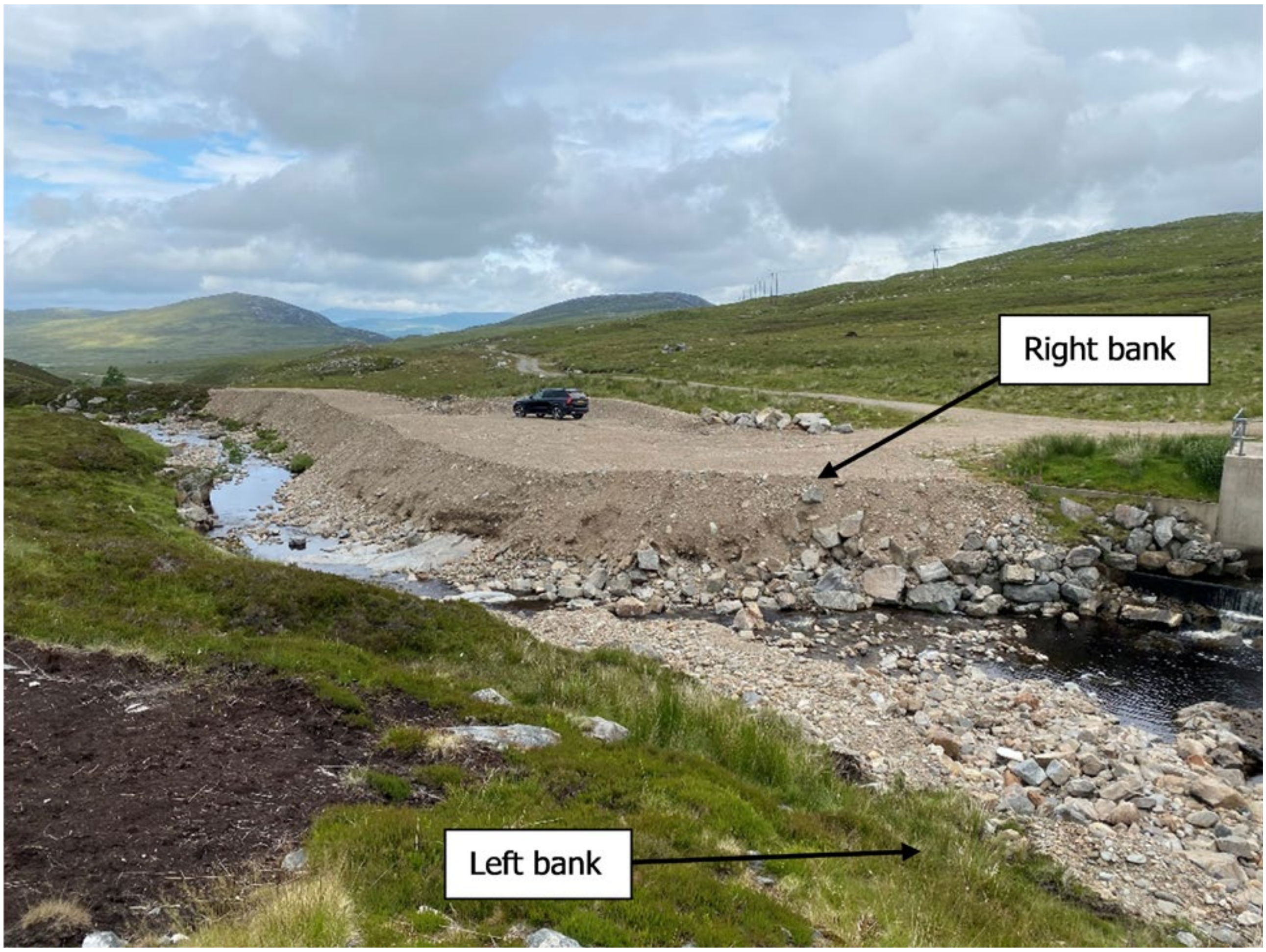


**Figure 5.6.** Sediment dredged from the headpond of RoR Case study Two has been mechanically reallocated mainly to the right bank, with a secondary deposit on the left bank. Photograph looking downstream from the impoundment.

**Figure 5.7.** RoR Case study Two, The river channel immediately downstream of the impoundment of RoR Case study Two. Photograph looking downstream.

**Figure 5.8.** Pavement built on the right bank of the headpond of RoR Case study Two, using dredged material. Photograph looking downstream.

### 5.1.3 Case study Three

The third case study is not a run-of-river structure but was suggested by the Steering Group as an illustrative example of multi-impoundment impacts in Scotland (i.e., of catchments with more than one impoundment). The upper sections of the catchment are characterised by steep terrain leading to bedrock cascades and plane-bed/pool-riffle morphologies. The tributaries prior to their confluence flow through steep-sided valleys characterised by scree slopes as well as a large amount of exposed bedrock, and several wooded gorges. Following the confluence of three small watercourses, the main river retains a similar character throughout its course comprising a cobble and boulder plane-bed/pool-riffle morphology.

One impoundment structure has been constructed approximately 0.8–1 km upstream from the river mouth. The structure is an upstream-arching concrete dam, approximately 4 m high and with a roughly equally deep pool directly upstream (Figure 5.9). On the day of the survey a small flow was being released downstream from a 1m wide orifice at the base of the dam. There was also evidence for overtopping of the dam during periods of high discharge. Abstracted flow is redirected via a side intake just upstream from the dam into the downstream loch and from there used for hydro-electric power generation. The survey was conducted along 500 m reach, 250 m down and up-stream of the impoundment).

Coarse sediment bars were found approximately 23 m upstream from the dam crest (Figure 5.10). The left bank bar was ≈ 539 m² in area (11 m wide x 49 m long), with a maximum estimated volume of ≈ 404 m³ (0.75 m of thickness). Surface grain sizes varied from 32 to 256 mm ($D_{16}$ = 54 mm, $D_{50}$ = 92 mm, and $D_{84}$ = 127 mm). The right bank bar area was ≈ 72 m² (4 m wide x 18 m long), with a maximum estimated volume of ≈ 54 m³ (0.75 m of thickness). Surface grain sizes in this bar varied from 11 to 180 mm ($D_{16}$ = 34 mm, $D_{50}$ = 54 mm, and $D_{84}$ = 102 mm). Aerial imagery from three different years (12/2005, 06/2010, and 04/2015) indicated that the sediment deposits upstream from the impoundment have changed considerably during the decade, with on-going accumulation changing the river planform substantially.

Downstream of the structure, sediment that has been removed from the headpond has been reallocated to the right bank (Figure 5.11). The mechanically reallocated sediments on the right bank have grain sizes varying from 8 to 128 mm ($D_{16}$ = 21 mm, $D_{50}$ = 38 mm, and $D_{84}$ = 60 mm). Downstream from the impoundment small accumulations of sediment were observed in the channel which was otherwise dominated by bedrock (Figure 5.12). Three of those accumulations were sampled for grain size distribution. The clasts at those sites vary from 11 to 64 mm ($D_{16}$ = 22 mm, $D_{50}$ = 42 mm, and $D_{84}$ = 57 mm), indicating a medium to coarse gravel grain size range.

Overall, grain size evidence indicates that the sediments mechanically reallocated downstream of the structure and occurring in the small downstream deposits are far finer than those occurring in the extensive barforms deposited upstream of the impoundment. Like case study two, evidence suggests that coarse materials are deposited approaching the reservoir whereas finer materials fill the bulk of the reservoir space. Those finer materials have been subsequently dredged and replaced downstream whereby, following entrainment, they are temporarily stored as small deposits before further transport in subsequent high flow events.

**Figure 5.9.** Concrete dam on RoR Case study three, illustrating a small orifice low in the structure. Photograph looking upstream.

**Figure 5.10.** Sediment bars found upstream of the impoundment. Photograph looking upstream.

**Figure 5.11.** Mechanically reallocated sediments on the river right bank (left side of the picture), just downstream of the impoundment.

**Figure 5.12.** Sediment accumulations in bedrock channel downstream of the impoundment structure. The clasts vary from medium to coarse gravel. Photograph looking downstream.

### 5.1.4 Case study Four

The fourth case study involves a RoR structure completed in 2011, and consisting of several small, notched structures with pools between that allow permanent provision of baseflows downstream (Figure 5.13). On the river right bank, just upstream of the weir, there is a 4 m-long intake with a trash screen. The outfall occurs ≈ 1.7 km downstream. The host river is typical of an upland, spate-driven river flow regime, and is dominated by long reaches where pockets of mobile, gravel-sized bed material are interspersed between much coarser substrate of large cobbles and boulders, which are more stable. Sediment inputs are derived from eroding banks, tributaries, and valley side slips. Aerial imagery provides evidence for lower gradient sections where gravel and cobble sized sediment dominate bed materials and channel morphology takes on pool-riffle characteristics with sediment bars on the inside of bends. The most notable of these sections is approximately 400–700 m upstream from the RoR scheme impoundment where there are significant sediment bars. This indicates regular transport of gravel and cobble sized material in the river at this point.

The channel morphology along the surveyed reach upstream and downstream from the impoundment was transitional between step-pool, cascade and bedrock. The river substrate was coarse (boulder-cobble sized), angular and the channel exhibits bedrock exposure in several parts (Figure 5.14). Due to the absence of depositional sites and the coarse substrate and bedrock exposure, grain size distribution was not assessed. The absence of alluvial bars is consistent with the channel morphology (see Montgomery and Buffington, 1997), which promotes sediment removal and transport during high flows to create a sediment supply-limited channel.

While pre- and post-construction aerial imagery indicates few changes in grain types or depositional sites, imagery from 2015 and 2019 suggests that a sediment management operation occurred at the RoR impoundment sometime between these dates. The headpond is larger in the 2019 imagery and the ground on the left bank has been disturbed indicating machinery has accessed the headpond. It seems likely that sediment accumulation was impacting on the operation of the intake necessitating removal. It is not known if the removed sediment was returned to the river downstream. That sediment management appears to have been required, despite the high channel steepness, the construction of a relatively small structure compared to the channel size, and the notches that sustain sediment passage over and through the structure, suggests that the structure can still cause sediment accumulation sufficient to cause problems as the offtake.

**Figure 5.13.** RoR Case study Four impoundment illustrating multiple small, notched structures. The upper v-notch is approximately 1 m-wide and the two steps are 0.5 and 0.25 m high. Photograph looking upstream.

**Figure 5.14.** Step-pool/cascade river morphology found along reach of Case study Four. Note the boulders on hillslopes that feed the channel during shallow landslides. Photograph looking downstream.

### 5.1.5 Case study Five

This scheme, from the Scottish Highlands, consists of an impoundment structure, spillway, intake and detention pool, and the structure has stop logs which can be removed to allow some scouring of the headpond (Figure 5.15). The opening is narrow and does not facilitate flushing of the coarser material which still accumulates in the upper headpond. The chosen method of management is mechanical removal and downstream reallocation using an excavator (Figure 4.5, Section 4.2.3). According to the operators, "*Sediment flushing (via the removable stop-logs) was not considered suitable as this process involves drawing down the intake weir for a period of time which would adversely affect the revenue of the scheme, as well as resulting in considerable river siltation*."

**Figure 5.15.** A Scottish Highlands RoR hydropower scheme. Photograph looking upstream.

During a recent sediment management operation, a head-cut was unintentionally created at the upstream end of the headpond. This could migrate upstream, erode the bed and banks and increase sediment supply to the impoundment. The operator has observed that sediment removal volumes have increased over time, suggesting that upstream processes have enhanced sediment supply. The increase in sediment removal volumes, together with a RoR design that does not allow hydraulic techniques to be implemented easily, are the main sources of disruption to sediment connectivity in this case. Further, as more sediment excavation has been required in recent years, the likelihood is that maintenance costs have increased.

## 5.2 Implications

### 5.2.1 Sediment continuity in RoR hydropower

The case studies indicate that the impacts on sediment continuity of RoR hydropower in Scotland is variable and related to the size and type of structure and the regional rate of sediment supply upstream of the scheme. Where sediment supply rates are high and the structure encourages a voluminous headpond (determined by the height of the structure versus the gradient of the river), large volumes of sediment accumulation can occur (Case study Two). Such accumulation can be equivalent to that resulting from non-RoR impoundment structures (Case study Three) and demonstrates that RoR impacts on sediment continuity can be highly significant. Conversely, where rates of sediment supply are low, and/or the headpond is of limited volume (smaller structure or steeper river), the headpond can fill and permit sediment transport through the scheme, albeit at some risk to the scheme's operation (case studies One and Four). In these cases, impacts on sediment continuity appear limited enough to prevent significant change to downstream habitats but may still be judged to require sediment management (Case study Four).

It is also apparent that, while notches in the impoundment structure can encourage sediment pass-through (case studies Four and Five), facilitating the passage of coarse sediment requires knowledge of likely rates and patterns of coarse sediment transfer through the site. This is unlikely to have been monitored ahead of scheme design and, of course, will be altered by the scheme itself. Further, the intricacies of structure design in combination with the steep gradients and very coarse particles involved in many RoR schemes in Scotland is not well accommodated by current sediment models. These difficulties need addressing because of the clear operational and environmental benefits of facilitating coarse sediment passage through RoR schemes.

An additional mechanical excavation challenge when disruption to sediment continuity is high (i.e., where there are large volumes of upstream sediment accumulation), is where and how to reallocate the large volume of excavated sediment downstream. As demonstrated in Case study Two, reallocating the material locally can bring about quite considerable structural changes to the river's morphology and habitats. Further, sediment excavation itself is not without risks: Case study Five demonstrated that care is needed not to create a headcut when excavating, as it brings the risk of accelerating sediment delivery to the headpond, exacerbating the management challenge.

Finally, in RoR schemes characterised by a wide range of riverbed sediment sizes (e.g., from sand to boulders), excavating accumulated sediment from close to the impoundment appears to result in the preferential removal of finer sediment (e.g., case studies Two and Three). The risk is that, by then preferentially reallocating this finer material, downstream river morphology will be progressively characterised by finer sediment and so potentially affect the type and quality of aquatic habitats.

### 5.2.2 Limitations

- The data collected in this study represents only a snapshot of long-term sediment dynamics along reaches impacted by RoR hydropower schemes. Therefore, to understand residence time and quantify variability and changes in sediment transport rates, longer term monitoring is required. This is a research gap.
- Little operator-shared information was available about sediment management practices. This information would help considerably in understanding routine sediment management decision and would be highly beneficial to further studies.

# 6.0 Recommendations for existing and new RoR hydropower schemes in Scotland

Based on the outcomes of previous sections, a series of sediment management recommendations for existing and new RoR hydropower schemes in Scotland follows. They cover various aspects of the RoR operation from licensing and consenting to practical sediment management techniques and research needs.

## 6.1 Sediment management plans and SEPA licence conditions

a. Ensure that mitigation measures for RoR schemes proposed in an EIA report are incorporated into CAR Licence conditions (see Section 2.1).

b. Create clear guidance on the sediment management information developers must submit in their application, including the evidence needed to conclude that no sediment management is necessary (see Section 2.2).

c. Create clear guidance for SEPA staff granting CAR Licences. This should detail how to determine if standard conditions are sufficient, if site-specific conditions are required, or if a sediment management plan should be requested. This could be based on factors surrounding baseline morphology conditions, the size of the impoundment and headpond, protected areas, and species and/or proposed mitigation measures. Where there are multiple impoundments in a catchment, this is likely to make sediment management more complex and require planning beyond the scope of standard conditions (see section 3.2).

d. Expand guidance on the requirements of a sediment management plan. A suggestion for good practice sediment excavation and reallocation is provided in Box 1, below. This could be developed further using evidence from future research (see Section 6.5).

e. Standard sediment management conditions should include best practice for sediment reallocation downstream and encourage post-development sediment budget monitoring for all schemes (see Section 6.3). Further, when material is excavated as part of maintenance practises, SEPA should require information on the reallocation date, volume and grain size estimates so that, over time, sediment budget changes can be established.

f. MImAS should be updated to include sediment discontinuity assessment in its formulation. Currently MImAS does not assess sediment discontinuity, which limits understanding of the pre and post construction effects of hydropower schemes on the Scottish Government's environmental standards classification for river morphology.

## 6.2 General principles for sediment management in RoR hydropower schemes

a. The case studies reviewed in this work demonstrated that sediment accumulation in headponds is frequently a significant issue and has impacts on the fluvial environment (dynamics, habitats and species) and RoR operational efficiency (see Section 5.2). The disposal of excavated material is challenging. As such, it is logical to employ a combination of measures that (a) reduce sediment yield to the headpond (where sediment yield is unnaturally high), (b) minimize sediment deposition in the headpond, and (c) recover lost headpond volume. Available techniques are indicated in Figure 4.1 and include options such as catchment management and hydraulic strategies that better enable sediments to be re-entrained and transported downstream. These strategies can be coupled to produce a financially-efficient and environmentally-sustainable operation that incorporates essential physical, chemical, ecological, climatic, financial, and societal aspects in a quantitative assessment framework.

b. The literature review of management techniques suggested that, where sediment yield is unnaturally high, sediment yield reduction procedures (such as those developed in catchment management plans) and hydraulic sediment routing techniques and procedures can be, overall, less environmentally-damaging than mechanical techniques (see Sections 4.1.1 and 4.1.2). While sediment yield reduction procedures should reduce the necessary frequency of headpond excavation, hydraulic by-pass or pass-through techniques inherently facilitate longitudinal connectivity of sediments and can eliminate the requirement for mechanical sediment reallocation.

c. Successful strategies for sediment management in multi-impoundment RoR hydropower schemes in gravel-bed rivers, such as those from Japan and Switzerland (e.g., Boes and Hangman, 2015; Compagnie National du Rhône, 2010; Sumi *et al*., 2004, 2012), can provide useful benchmarks to guide and assess the prioritisation of sediment management techniques in Scotland. The primary requirement is for coordination between schemes, for instance, to achieve successful flushing of sediment.

d. Site-specific physical characteristics must be considered when applying sediment management techniques to RoR hydropower schemes in Scottish rivers. For instance, construction costs associated with hydraulic techniques such as sediment bypasses are likely to be greater, and so their implementation may only be justified in rivers with higher discharge and sediment loads, where the costs of mechanical removal are also greater. Techniques suitable for rivers with high suspended sediment load and large impoundment areas, such as pass-through methods that focus on sediment-laden turbidity currents, are less likely to be suitable in Scottish RoR hydropower schemes due to the relatively coarse sediment supply and the generally small catchment areas involved (see Section 5).

e. We found no guidelines on how frequently sediment removal should be conducted. This is likely because such guidelines can only ever be site-specific to a combination of catchment sediment yield and the RoR structure design. Overcoming this limitation requires a long-term monitoring programme specific to Scottish rivers where sediment removal and reallocation are monitored (see Section 6.3). We also recommend adopting an *adaptive management* approach, whereby sediment removal is triggered by certain conditions (such as large or long-lasting flood events), but where actions are actively monitored and modified according to their effectiveness. Such evidence would be valuable in developing future guidelines.

f. Climate change projections for Scotland suggest there will be an increase in the frequency of flood events and, consequently, an increase in rates of sediment supply and transport. While climate change impacts on fluvial systems are difficult to forecast as they are a tertiary impact (changes in precipitation interact with (changes in) vegetation to cause changes in catchment runoff and thus changes in flow patterns and sediment erosion), the most likely scenario appears to be an increase in sediment arriving into headponds. RoR schemes that rely on sediment management by mechanical excavation are thus likely to be the most adversely affected from a financial standpoint because excavation will be required more frequently. From an operating perspective, catchments with multiple impoundments may thus require greater coordination in the face of climate change, for

**Box 1: General best-practise principles for mechanical excavation and reallocation of sediment**

This box contains a set of general principles for the mechanical management of sediment trapped in RoR hydropower headponds. These general principles should be used to generate site specific operating rules, informed by a catchment's geomorphology and ecology.

1. The volume of gravel deposited in a headpond will vary annually depending on the number and size of storm events, thus sediment management practices need to be adaptable.
2. Where upstream erosion from fields, plantations, terraces, hillslopes or riverbanks is producing unnaturally elevated levels of fine sediment, consider removing fine material deposits from the headpond and depositing them to land before targeting the coarser material for reallocation into the river (see Section 6.5(e)). Unnaturally elevated levels of fine sediment can be harmful to fauna such as salmonids and freshwater pearl mussels, but fine sediment provides important habitat for other species such as lamprey.
3. As a default, gravel management should be undertaken annually, so that downstream reaches are not starved of sediment and reintroduced sediment doesn't overwhelm the system with more sediment than the river can transport in an average year. The frequency of mechanical removal should be reviewed according to prevailing climate conditions: removal may not be needed annually during drought years, whereas multiple removals may be advisable during years with multiple, high magnitude, flood events.
4. When coarse sediment is mechanically moved to a position downstream of an impoundment, it should be placed within the river where high flows can entrain it, but not in sensitive habitats such as mosses. Existing gravel features such as bars make ideal sites as these are areas of natural deposition, but care should be taken not to swamp the channel with material (see Section 6.4(e)(ii).
5. Gravel should be piled only as high as the natural riverbanks, which is typically < 1 m for river reaches that contain most RoR impoundments in Scotland.
6. To mimic natural systems, reallocate gravel and cobble materials within the bankfull channel where it can be progressively entrained by large flow events. Likewise, reallocate silt and sand on the bank top or upper bank face, to be entrained only during overbank flood events (see Section 6.5(e)).
7. Do not compact sediment. Compacted material is harder for a river to erode.
8. Slope material back to the bank. The high point of piled sediment should occur adjacent to the bank, not be in the middle of the heap.
9. Move material only during the appropriate ecological working window.
10. Annually record what is seen at the headpond using fixed-point photography, sketches, etc. If sediment is moved, record the volume and type (silt/sand/gravel/cobble) that is extracted and reallocated, to enable adaptive management.

instance, in synchronising the operation of sluice gates following peak flows to allow for sediment continuity. Operators should thus apply particular focus on applying operating rules that facilitate longitudinal connectivity of sediment transport through RoR structures (and where appropriate, through multiple structures) including the modification of fixed weir structures to permit sediment routing (hydraulic pass-through or by-pass) or flushing of sediment. In addition, measures that reduce the incoming sediment yield, such as river restoration and riparian management, may become increasingly cost beneficial in addition to their environmental benefits.

g. A set of general principles related to best practise methods for the mechanical excavation of sediments accumulated in headponds is advanced in Box 1, below. This guidance is partly based upon practices developed by the Environment Agency from experience of managing water intakes along gravel-bed rivers in Cumbria.

## 6.3 Sediment management priorities in Consenting of new schemes

a. *Sediment supply management*: where suitable, new schemes should be encouraged to establish, restore and maintain a natural riparian corridor that (i) buffers sediment supply into the channel and (ii) encourages the full expression of in-channel fluvial sedimentary process. These measures will maximise upstream sediment storage in the river corridor and thus achieve sediment yield reduction to the RoR headpond. Such measures may have the additional benefit of improving ecological function and the WFD status of the water bodies. Furthermore, installing one or more sediment traps could enhance sediment reallocation efficiency, especially when non-structural techniques are insufficient or not applicable (see Section 4.1.1). Implementing these techniques will require scheme operators to engage with upstream landowners.

*b.* *Structure design*: new schemes should be encouraged to incorporate sediment sluices, bypasses, or similar structures to enable the hydraulic transfer of sediment around, through or over the weir during high flows. In cases where the impoundment is allowed to fill for sediment to flow over the weir crest, the structure's design should ensure that sediment deposition does not block flow to the turbines or the hands-off flow notch/orifice. All weir structures surveyed in this study were static (i.e., could not be opened manually or remotely to allow flow change), which makes hydraulic pass-through techniques unviable despite their intrinsic operational and environmental advantages (see Sections 5.1.1 to 5.1.5). In some cases reported by operators, sluices allow some hydraulic transfer, but do not have sufficient capacity to allow sediment pass-through. Pass-through techniques are likely only to be cost effective where the need for mechanical removal can be virtually eliminated.

*c.* *Sediment connectivity*: for rivers possessing multiple impoundments (and potentially both RoR and storage), new schemes should be encouraged to develop coordinated operating rules that promote longitudinal connectivity and sediment transport throughout the catchment to reduce the chance of cumulative impacts (see Section 4.1.2). Such coordination is especially important if individual schemes are run by different operators. This also implies a requirement for a wider assessment of sediment connectivity and cumulative impact at the consenting stage. Assessment should consider the likely increase in sediment yield and transport caused by climate change.

*d.* *Vehicular/plant access*: where mechanical removal of sediment is necessary, new schemes should be encouraged to implement vehicular access to enable both the mechanical removal and reallocation of sediment. Even where new schemes focus primarily on the hydraulic routing of sediments, access for infrequent mechanical removal may still be required. However, where hydraulic techniques are sufficient for sediment management, access tracks should be removed, and low impact machinery used to work on the structure if required.

*e.* *Modelling and field studies*: many river management activities are now informed by hydraulic or morphodynamic numerical models. Models are becoming increasingly accurate at estimating the re-working of local sediment and thus can be a valuable tool in, for instance, river restoration design. However, models are less well-suited to rivers with steep gradients and where there are large roughness elements (e.g., boulders), and are critically dependent on an accurate estimate of sediment supply. Unfortunately, planning for new RoR hydropower in Scotland is quite likely to trigger each of these concerns. The sediment supply issue is particularly critical because coarse sediment load in rivers is generally transported at far less than its theoretical capacity for transport (e.g., maybe at only 10% of capacity, Gomez, 2006) because of supply restrictions. At present, it may thus be more appropriate to invest effort in robustly enumerating the sediment budget approaching the RoR impoundment (a recent example, Downs *et al*., 2018) than in numerical modelling.

*f.* *Monitoring:* New licenses or compliance verification of existing schemes could encourage monitoring and managing sediment accumulation in headponds to reduce knowledge gap of hydropower scheme impacts in Scotland. Possible monitoring good practise could include:

i. Topographic/bathymetric survey prior to the implementation of the scheme for a distance upstream in excess of the expected headpond distance and downstream beyond the first natural depositional zone using a grid method to create a three-dimensional elevation surface.

ii. To regularly repeated the topographic/bathymetric surveys outlined above (e.g., with a frequency aligned to that of the sediment management interventions) to construct a timeseries documenting the efficiency of mechanical and hydraulic techniques on sediment movement in Scottish rivers.

iii. A regular analysis of the WFD status of the RoR scheme waterbodies should be conducted to test for improvement or deterioration following implementation of new procedures.

## 6.4 Sediment management in existing schemes

*a.* *Catchment management*: where possible, plans should be developed for sediment yield reduction from upstream catchment areas to reduce rates of headpond sediment accumulation (see Section 4.1.1). Beyond those techniques outlined in Figure 4.1, in degraded riparian corridors this may be achieved by riparian restoration measures both to reduce direct input of sediment from de-stabilised river channels and to create a buffer that prevents eroded hillslope sediments from entering the river channel.

*b.* *Performance reviews*: reviews of existing schemes should assess how sediment connectivity has been managed to date, and what mitigating actions have been employed. Where sediment management is found to be necessary but is not occurring or where sediment management conditions exist but are not being adhered to by the operator, SEPA should request an update and/or enforce licence conditions.

*c.* *Operating rules or structure modification for sediment connectivity*: where sluice gates are present, schemes should be encouraged to develop operating rules that facilitate longitudinal connectivity of sediment transport through the scheme (and where appropriate, through multiple structures). Where it is cost beneficial, operators should be encouraged to modify fixed weir structures to permit sediment routing or flushing. Given the site-specificity of most sediment management requirements, the challenge will be to ensure that the cost-benefit analysis accurately identifies all future costs and benefits, including those arising from climate change scenarios. In some cases, modification may benefit the scheme's operational efficiency as well as providing environmental benefits.

*d.* *Mechanical excavation:* decisions regarding the requirement for mechanical excavation can be based on observations of progressive deposition or on repeat bathymetric surveys. Excavation is likely to be needed where either (i) the integrity of the hydropower facility has been compromised by deposition close to critical infrastructure, (ii) where progressive infilling of the headpond threatens future operation of the scheme or (iii) where (coarse) sediment deposition upstream is causing excessive bank erosion. Material should be excavated only to the level of the original riverbed, to reduce the chance of generating a headcut (see section 4.1.3). Schemes should be excavated annually unless evidence suggests a different frequency is more appropriate (see Box 1).

*e.* *Sediment reallocation downstream:* because of differences in the dynamics of fine and coarse sediment transport, reallocation procedures should mimic natural depositional sites to the extent possible.

*i.* *For predominantly fine sediment:* reallocation should place predominantly fine sediment (silt, sand) on bank tops where it will only be entrained in large future flood events. Depositing fine sediment as a large mass in the channel runs the likelihood that it will move downstream as a 'blanket' of sediment that smothers habitats.

*ii.* *For predominantly coarse sediment:* the most appropriate reallocation method and location for predominantly coarse sediment mixtures (gravel- and cobble-based) will depend on the energetics and sediment supply of the individual river and should be agreed in advance. In high energy settings, sediment can be spread roughly across the channel where it will be entrained and redistributed in the next large flood event ('high flow stockpile' in Figure 4.7, Table 4.1). In moderate energy settings, sediment should be reallocated to naturally depositional settings, that is, as a relatively thin sheet at natural riffle locations ('in-channel stockpile') and as a deposit with an elevation of less than bank height at point bars on the inside of bends ('point bar stockpile'), so that progressive entrainment of material can occur over several years. In low energy settings, where coarse sediment has very low mobility, reallocation may need to take the form of carefully sculpted bedforms that are suitable as habitat for in-channel fauna for multiple years thereafter. Unlike fine sediment, predominantly coarse sediment will disperse and fan out from its point of reallocation, becoming a thinner deposit downstream, and so problems relating to excess deposition should rarely manifest themselves. Sediment mixtures that contain both coarse and a significant amount of fine material will have transport characteristics between these two extremes. Recent laboratory flume experiments with multiple reallocated deposits suggest that different barform types can be promoted according to whether the deposits are placed in parallel or alternating configurations and, as might be expected, greater dispersal is achieved when deposits are completely submerged by flood events (Battisacco *et al*., 2016). However, such tendencies might be over-ridden by the morphological variety and dynamics of natural channels, relative to the uniform and static nature of a laboratory flume.

f. *Monitoring:* should be undertaken to test the effectiveness of both mechanical and hydraulic sediment removal techniques (reviewed in Section 4). Because few existing structures have the capacity necessary to sustain routing or flushing flows through the impoundment, data collected during a long-term monitoring programme could be used to develop a performance analysis of the most efficient sediment management techniques for existing schemes. Similarly, long-term monitoring of different sediment reallocation techniques following mechanical excavation would provide evidence for the most suitable reallocation strategies for Scottish RoR hydropower schemes (see Figure 4.7 for basic strategies). Monitoring results would also be useful for regulators during permit reviews of operational efficiency and sediment connectivity possessed by existing schemes and thus in setting future licensing conditions.

## 6.5 Research and administration

The following suggestions are intended for SEPA and NatureScot, and do not involve operators and landowners.

a. *Coordination*: SEPA's existing database of all impoundments (RoR and storage) in Scotland should be used as the basis for proposing conditions, monitoring actions, and sediment management plans as part of the consent process.

b. *Cumulative impact*: Further investigation is required to establish the cumulative geomorphological consequences of all impoundments (RoR and storage) in a catchment.

c. *Provision of best practice guidelines for the mechanical removal and reallocation of sediment:* best practice guidelines for the mechanical removal and reallocation of sediment should be developed based on the recommendations in Box 1 and issued to all RoR hydropower owners. Because there is no well-established guidance in existing literature, and because such guidance needs to be appropriate to the regional geology and geomorphology, the guidelines should be revised once results from long-term monitoring and adaptive management experiments in mechanical sediment removal and downstream transfer become available. The development and monitoring of experiments to test different mechanical reallocation approaches would yield a strong evidence base for future sediment management advice.

d. *Impact monitoring*: multi-year monitoring and modelling is needed to derive sediment budgets for impacted and non-impacted sites to inform policy and practice. This should include monitoring the effectiveness of river restoration in reducing upstream sediment supply to impoundments.

# 7.0 Conclusion

This project has considered provisions for sustaining sediment continuity in run-of-river (RoR) hydropower schemes in Scotland through a combination of administrative and literature reviews, and case study fieldwork. Field evidence indicates that impacts on sediment continuity are variable between schemes but are significant in some cases. Such findings mirror those found in published literature. Experience gained from these surveys has allowed the development of a series of recommendations for new and existing RoR hydropower schemes (Section 6).

The overwhelming conclusion is that there is a lack of empirical evidence regarding the dynamics of sediment continuity in Scotland suitable for underpinning decisions regarding the conditions of RoR hydropower consent, the development of adaptive sediment management plans, choices between mechanical, hydraulic and catchment-based sediment management techniques, and the likely cumulative impact of multiple schemes on the same river. Such lack of knowledge is not unique to Scotland but is given particular emphasis by the popularity of RoR hydropower and the operational inefficiencies and environmental impacts that will accrue from poor sediment management decisions. The situation is compounded administratively because the policy guidance for consenting RoR licences is unclear and seems likely to result in inconsistency. Further, SEPA's database of existing RoR and storage impoundments is not currently used to record sediment management decisions and outcomes. Doing so would help to improve future decision-making. Our recommendations address various aspects of these deficiencies

Given that nearly all RoR hydropower schemes currently utilise mechanical excavation techniques to manage sediment accumulation in headponds, short term efforts should focus on minimising the impact of this management practice on sediment continuity through regular excavation of headponds and site-appropriate downstream reallocation of the excavated sediment. This will require significant engagement with RoR stakeholders to implement operational improvements. We provide a series of principles for mechanical excavation and reallocation of sediment in Box 1 (Section 6.2) and in Section 6.4 as the basis from which such best practice guidelines might be produced. Critically, it is also imperative that SEPA staff receive clarified and updated policy guidance for consenting licenses, and that such updates include a general expectation for a sediment management plan and sediment management reporting as part of granting consent. Such measures need not be onerous for the operator and will result in a much-improved basis for decision making that benefits both the operator and the environment.

In the medium term, it is important that SEPA expands the use of its database of RoR and storage impoundments to improve sediment management guidance and to catalogue sediment management decision making and outcomes. Operators of new schemes should be encouraged to undertake modest but important monitoring and reporting of sediment continuity in the vicinity of their schemes, and to consider implementing measures for upstream sediment yield reductions in cases where sediment supplies are elevated. Such measures may become increasingly critical to the financial viability of schemes as climate change increases rates of sediment transport into RoR headponds. In parallel, operators, perhaps in partnership with SEPA, should develop knowledge regarding the viability of hydraulic methods of sediment management at a scale suitable for application in Scottish rivers. Operators of new impoundments should be encouraged to use designs that permit hydraulic methods of sediment management, while operators of existing facilities should consider retrofitting adjustable, high capacity, sluice gates to existing structures where viable and cost-beneficial, thus reducing their reliance on mechanical excavation and impacts on sediment continuity. In determining viability, it may help if existing schemes are classified according to their impact on sediment continuity.

In the longer term, the compilation of reports regarding sediment management actions in relation to RoR hydropower schemes of different types will assist SEPA staff in providing locally specific and effective guidance on RoR operation, including guidance on minimising cumulative impacts. Such advice will benefit both RoR operators and the valued in-channel and river corridor habitats that are functionally dependent upon coarse sediment continuity. More broadly, this knowledge will underpin a better appreciation of sediment dynamics and continuity across Scottish landscapes to the benefit of multiple conservation concerns and to enhance operational and environmental resilience under conditions of a changing climate.

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