The ecohydrology of rewilding: a pressing need for evidence in the restoration of upland Atlantic salmon streams.

C. Soulsby[1,2], A. Youngson[3], and J. Webb

[1] School of Geosciences, University of Aberdeen, Aberdeen, UK.

[2] Department of Ecohydrology and Biogeochemistry, Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany

[3] Environmental Research Institute, University of the Highlands and Islands, Caithness, United Kingdom

The growth of rewilding and habitat restoration

Rewilding has increased in use in the last decade as a popular but vaguely defined and often controversial term, usually broadly equated with ecosystem restoration (Jepson and Blyth, 2020). In 2021, the United Nations Decade for Ecosystem Restoration began, partly in response to the climate and biodiversity crisis. This programme defines ecosystem restoration as "assisting in the recovery of ecosystems that have been degraded or destroyed, as well as conserving ecosystems that are still intact" (UNEP, 2024). The Decade has added momentum to initiatives seeking to reduce the intensity of land- and water management, coupled with goals to "make space for nature" by restoring ecological processes, often over extensive areas, and allowing biodiversity to recover (Pettorelli et al., 2014). Such initiatives often seek to also provide nature-based solutions (NBS) to problems such as the need to increase carbon sequestration and flood alleviation. Recently, restoration schemes have been advocating upscaling to larger areas as a route to increased effectiveness and success following on from popular accounts of landscape-scale "rewilding" in farmlands, uplands or urban areas (e.g. Tree, 2018; Ashmole and Ashmole, 2020; Lachmund, 2013). These examples have gained widespread publicity and generated impetus for increasing numbers of similar schemes. However, rewilding and restoration are still elusive concepts. Although they are intuitively attractive, identifying what levels of ecosystem degradation warrant restoration, assessing the competing requirements of different ecosystem components and deciding what the desired restored state is, and how it can be achieved are often surprisingly subjective.

Role of ecohydrology and scientific evidence in landscape-scale restoration

Many landscape-scale restoration schemes are based on river basin units and often have potentially significant ecohydrological implications. However, understanding how such complex biophysical systems interact to control ecological communities at the landscape scale in order to guide restoration requires challenging, interdisciplinary science. Pre-existing data are often lacking, or at best short-term and collected at relatively small spatial scales that are difficult to extrapolate. Under these circumstances, new approaches to environmental science are required and new tools are needed to synthesise available knowledge for problem solving at larger scales (e.g. Curtin, 2015).

Experience from conservation projects – many of which fail to achieve their intended outcomes - has focused attention on the need to identify approaches to developing evidence-based decision making that can evaluate likely impacts, highlight uncertainties and assess risk in an objective way in advance (Sutherland 2022a). Expert panels and other systematic approaches to capturing and synthesising different knowledge can help clarify realistic objectives, foresee likely problems and enhance the probability of success. There is an obvious need for specialist ecohydrological input to be strengthened in many restoration projects, yet this is often lacking. For complex projects, opinions will likely vary but the challenging of emerging ideas and proposals should be viewed as a strength that increases the likely chances of successful implementation and achieving the best value for money (Kareiva et al., 2018). Indeed, conservation projects that depend heavily on individual site managers, consultants or small groups that almost inevitably lack some important knowledge and skills are particularly prone to failure (Sutherland, 2022b).

More effective approaches to incorporating ecohydrological insights into watershed restoration projects are urgently needed. The uncertainties and risks associated with the ecohydrological implications of such landscape-scale restoration are becoming increasingly apparent even as growing numbers of large projects are being implemented. A striking example is that of the restoration of larger river catchments and associated riparian rewilding which is gaining momentum internationally following celebrated examples in other spheres such as the re-introduction of wolves to Yellowstone National Park in the USA (Marris, 2017). As populations of this apex predator grew, decreasing numbers of elk (a main prey species) reduced grazing pressure in riparian areas allowing the re-establishment of riparian tree cover and the rapid development of more naturally functioning river corridors (Ripple, 2014; Beschta and Ripple, 2016). This is a conservation “good news” story that was widely publicised in the popular media, rapidly gaining acceptance and support (e.g. Monbiot, 2013). Such, stories become intuitively attractive narratives that become fixed as facts, even though science shows that the reality may be more complicated. For example,at Yellowstone, others have pointed to alternative explanations for declines in elk numbers such as simultaneous decreases in alternative food sources for apex predators generally, increases in predation by expanding bear and cougar populations, and the effects of increased elk hunting outside the park (Peterson et al., 2014; Barber-Meyer, 2015). Such qualifications are often viewed as extraneous to the original “good news” narrative and they gain much less publicity. In the same way, the apparently successful implementation of some small-scale restoration schemes has increased enthusiasm and confidence for rewilding watersheds and ambitious and large-scale plans have been developed to accelerate the process in the absence of understanding the likely impacts.

The rewilding of Scottish rivers

A current UK example is the “Riverwoods” initiative in Scotland which involves a consortium of government agencies and NGOs promoting the widespread benefits of riparian woodlands and calling for large-scale rewilding in Scotland’s river basins (Riverwoods, 2024). Motivations for this include increasing Scotland’s low forest cover following a long history of forest clearance, improving biodiversity and freshwater habitats, providing shade to moderate stream temperatures in the face of climate change, and Natural Flood Management (NFM). The momentum for change has increased dramatically in recent years. In part, this is linked to sophisticated multi-media promotion and stakeholder engagement often built around a narrative of restoring rivers and landscapes by reforesting riparian landscapes to improve habitat for Atlantic salmon populations. Unfortunately, the science base for delivering some of these benefits is often not as strong as intuitively thought (Ogilvy et al., 2022).

Atlantic salmon are an iconic species in Scottish rivers and are viewed as having high conservation value as a keystone species in many upland streams, as well as being economically important as a focus of game fishing. Salmon have a complex lifecycle. They hatch from eggs deposited by adult female fish in river gravels in clean, cold-water streams. Juvenile fish typically spend two or three years growing before emigrating to the North Atlantic where they spend up to 3 years feeding and growing before adult fish return again to spawn, usually in their natal rivers. Enduring such a complex, prolonged lifecycle and surviving multiple threats along global migratory paths, returning adult salmon are a potent symbol of "wild" nature. This is also part of the challenge and appeal of recreational angling. Along with other species such as golden eagles and red deer, salmon and stunning rivers and mountain scenery are key elements in the tourism "brand" for the Scottish Highlands.

In Scotland and other North Atlantic countries, salmon populations have declined in recent decades; climate change and reduced food sources in marine feeding grounds are the likely main causes (Figure 1). However, collateral harvesting in marine fisheries, impacts of dams and water abstractions, freshwater pollution and higher river temperatures in natal streams are just a few of the many other accelerating pressures that salmon face. Unsurprisingly, addressing threats to salmon to prevent the extinction of the species is a powerful narrative for capturing the public imagination and galvanising support for river restoration schemes. This comes at a time when substantial public funds are becoming available for restoration work aimed at addressing the climate and biodiversity crises. Unfortunately, as the main issues of salmon decline are marine in origin, improving freshwater habitat in most salmon rivers is likely to have only marginal, if any, impact on declining numbers of returning fish. However, given the growing concern over salmon declines, fishery managers are often under pressure from proprietors and anglers to "do something". Moreover, frustration at the limited options for addressing the marine origins of salmon declines sometimes force managers into "displacement activity" in areas where they can act. Consequently, a number of increasingly ambitious landscape-scale restoration projects are already being implemented through government funding including salmon-focused schemes in several relatively large river basins.

Lack of a scientific evidence base for restoration activities

It might seem that such restoration projects are positive developments. However, as many have the potential to exert unknown landscape-scale ecohydrological impacts, as well as having extensive in-stream implications for salmon and other components of freshwater ecosystems, there is certainly a need for caution and reflection. Particular concerns are the limited evidence-base for assessing (i) the actual need for restoration, (ii) whether proposed interventions attempt to address the key issues, (iii) whether the actual restoration practices are likely to be effective, (iv) whether negative effects are likely and (v) whether any collateral damage is likely to be significant. Notably, a recent review has stressed how the science base for assessing restoration proposals and novel NBS techniques in freshwaters is still very weak (van Rees et al., 2023).

Hitherto, most river restoration schemes in the UK have been reach-scale demonstration sites where rivers have been re-engineered over a kilometre or so and their riparian zones enhanced (e.g. Spray et al., 2022). These are usually agricultural or urban streams that have been heavily degraded historically by drainage and channelisation and they are improved by restoring previous features (e.g. reinstating meanders, reducing channel gradients), diversifying in-stream habitat (e.g. reinstating pools, installing woody debris), and creating riparian buffer zones (e.g. by tree planting). Intuitively, such schemes match maximum need with maximum pay-off and seem likely to be beneficial. Even so, scientifically robust monitoring to establish with clarity how biodiversity responds to river restoration efforts is notoriously uncommon (Jahnig et al., 2011). When it comes to less disturbed rivers the case for whether restoration is needed at all and what approaches are suitable is much more contentious. This is the case in many Scottish salmon rivers where channels are less severely impacted by anthropogenic effects, geomorphologically functional and largely adjusted to prevailing catchment-scale controls.

The stated objectives of current large-scale restoration schemes on Scottish salmon rivers are often quite generic - for example "improving fish habitat" or "improving biodiversity". Given the lack of specific targets, assessing the likely effectiveness of a particular scheme in bringing about desired change is problematic. For example, populations in complex biophysical systems may fluctuate naturally and many years of data are needed before and after restoration to establish any statistically robust causal link with any management intervention. Salmon transition from egg to alevin to fry to parr over several years in fresh water before they smolt and go to sea and they show different, often poorly defined, habitat requirements and preferences at each stage. As a result, even the simplest biological interventions sometimes fail to result in the expected effect (Glover et al, 2018). Crucially, complex intra- and inter-species density dependence may affect each life stage in ways that interact over time. There are very few sites globally where such processes are understood in an integrated way (Soulsby et al., 2024). So, in most cases, knowledge is lacking on how local habitats can be restored in a way that will arrest declines in the number of out-migrating salmon smolts or increase the number of returning adults.

Catchment conditions often still reflect legacy effects on hydrological and geomorphological regimes from deforestation, land drainage, urbanisation etc. How "restoration" at the reach scale can equilibrate with residual catchment-scale controls remains an open question. Ignoring this geomorphic context and lack of knowledge of response times to change has the potential to undermine the sustainability of many restoration schemes and cause unexpected problems, including negative impacts (Wohl et al., 2023; 2024). Many restoration techniques are still largely untested with unclear or poorly established benefits, ill-defined risks and uncertain outcomes. Unfortunately, evidence from large-scale river restoration schemes targeted at various Pacific salmon species in North America suggests that there can be little expectation of success with Atlantic salmon, largely because the common interventions fail to address the primary cause of decline (Bilby, 2023). Despite all these uncertainties, salmon-focused restoration schemes are rapidly being scaled up from local reach-scale interventions to multiple interventions on large rivers resulting in catchment-scale changes. In theory, Before-After-Control-Impact (BACI) assessments might be used for retrospective evaluation but rewilding projects are only rarely conducted within a robust BACI design capable of supporting robust evaluation (Christie et al., 2020).

Restoration or ruin?

In many Scottish upland landscapes, a combination of extensive riparian tree planting and installation of so-called Large Wood Structures (LWS) in streams is becoming a standard approach to catchment "restoration" for salmon. Surprisingly, such large-scale projects are being implemented with only limited environmental assessment.

Riparian planting is being particularly promoted to help salmon and other wildlife by mitigating rising stream temperatures via creating shade and increasing nutrient inputs to streams. In time, as dead or undercut trees fall into rivers, they are also expected to contribute to habitat diversity through the natural recruitment of large woody debris. The scientific basis for such proposals is established only in the sense that riparian tree cover has been shown to reduce water temperatures (e.g. Hannah et al., 2008; Fabris et al., 2017) and will mitigate heating where climate change has been shown to be increasing temperatures (Langan et al., 2001). Naturally recruited, in-river woody debris may also be potentially beneficial in diversifying habitats. On the other hand, the trophic structure, species composition and phenology of streams with developing tree cover will also change and the potential downside for juvenile salmon includes increased predation, benefits to competitor species, changed food sources and, paradoxically, reduced flows and increased temperature in "unrestored" reaches located downstream (Loch et al., 2020).

Other cited benefits of riparian planning include contributions to NFM where the greater "use" of water by trees in evapotranspiration is exploited to increase soil moisture deficits in order to increase subsurface storage, absorb precipitation and mitigate floods by "slowing the flow" (Lane, 2017). However, field data and the results of modelling studies show that effectiveness is likely to be restricted to smaller or moderate floods, especially in summer when seasonal moisture deficits are highest (Dadson et al., 2017). Mitigation is likely to be limited in the largest wet-season flood events that usually do the most extensive and costly damage (Soulsby et al., 2018; Peskett et al. 2023). Moreover, an often-overlooked corollary of increased water use by trees can significantly reduce baseflows which may reduce water availability and have undesirable effects on aquatic habitat or water quality during periods of low flow (Neill et al., 2021).

Because the re-establishment of riparian cover and natural recruitment of large wood to rivers can take decades to become effective, in-stream habitat diversification is being accelerated by the implementation of LWS (Fig. 2). These are engineered structures, installed by the extensive excavation of the active channel with the emplacement of typically one to three tree stems, ~10m long with 2-3m diameter root boles attached (Fig. 3) (Scottish Government. 2022). These are pinned in place using large boulders scavenged from the surrounding channel and banks which in many cases already provide cover for fish (Figure 2). Densities vary, but in some schemes, closely spaced structures at 20m to 100m intervals along several kilometres of stream channel have been used. It is argued that these will create additional habitat diversity, often specifying benefits for enhancing juvenile and adult salmon habitats such as physical cover from predators, thermal refugia in scour pools and encouraging the accumulation of spawning sediment. The logic for this is that catchments in Scotland would once have been naturally forested and LWS is an important - but missing - component of habitat diversity that salmon have evolved to exploit. Soon, many thousands of these structures will be rapidly installed – at significant public expense - across Scotland, many of them at high density in rivers with conservation designations. This is another superficially attractive "good news" story that is being widely promoted in the media. However, there is often no formal evidence that the lack of suitable habitat is a constraint on salmon productivity in the targeted streams.

Of course, it is many centuries or even millennia since the original forests of Scotland were cleared, and hundreds of years since top predators were extirpated leaving a long history of over-grazing and fire management that makes the current appearance of the Scottish Highlands a cultural landscape. The hydrology and fluvial geomorphology of Scotland's rivers have been adjusting to this changed context and boundary conditions for centuries, and salmon have probably also been adapting, too (Garcia de Leaniz et al., 2007). There are no analogues for how much large wood was in these rivers at any stage, how big the structures were, their spatial distribution, their temporal dynamics or whether they were retained in the active channel or at the margins; the size, species composition or longevity of the wood accumulation are all also unknown. Ironically, installation of LWS in geomorphologically functioning streams can degrade extensive areas of pre-existing habitat successfully used by both juvenile and adult salmon with the perhaps vain hope that humans can somehow engineer something better.

To install fixed LWS on such a large scale is a potentially interesting experiment but artificially re-engineering rivers that have been known to have high production capacity is not – arguably – restoration (Figure 3). Where rivers have not been severely degraded they have geomorphic functionality that has sustained vigorous salmon populations for centuries until the recent declines. Unsurprisingly, there is no compelling reason to expect that the impact of LWS will increase the number of out-migrating or returning salmon (Roni et al., 2015). Indeed, a recent synthesis of data from ~3500 sites in Sweden showed no positive correlation between Atlantic salmon and natural wood features in rivers, whilst a positive correlation was found with trout (Donaldi et al., 2019). This suggests that LWS may inadvertently benefit competitor species underlining the risks of implementing restoration measures without any assessment or firm evidence base. Moreover, a recent review of wood in rivers, suggests that fixed wood like LWS should only be used as "a last resort" and reserved for the most severely degraded streams lacking diverse geomorphic form and function (Wohl et al., 2023). Where multiple installations are carried out on the same stream, the associated excavation of stream beds and banks can create fine sediment plumes lasting for prolonged periods, usually in summer when temperatures are high and flows are low (Fig. 3). The cumulative effects of such disturbance, in addition to the compaction and disturbance impacts of large heavy machinery operating within the channel, on threatened juvenile and adult salmon are unknown. Typically, no juvenile fish rescues are undertaken prior to installations.

Need for ecohydrological science in restoration and evidence-based adaptive management

The purpose of this commentary is not to criticise the principles of rewilding or the catchment-scale restoration of salmon rivers. Indeed, well-designed projects with realistic evidence-based goals and a wide stakeholder buy-in will be important in addressing the biodiversity and climate change crises. More generally, however, restoration and re-wilding projects involving ecohydrological change would significantly benefit from: (a) clear, measurable and evidence-based objectives, (b) thorough assessment of risks through wide consultation, (c) scientifically-robust monitoring of impacts and (d) provision for adaptive management where necessary. It is striking that these components are still absent for most projects, particularly in cases like Scotland where some of Europe's least modified rivers have a high degree of hydrological and geomorphic functionality and Atlantic salmon are only one of several protected freshwater species. Therefore, mechanisms need to be urgently developed to promote the pursuit of clear societal benefits via integrated, interdisciplinary projects.

Assessing the ecohydrological impacts of landscape-scale restoration is often challenging. Whilst the general direction of changes might be predictable, geographical characteristics (e.g. climate, geology, geomorphology, topography, soils, land cover) mean that management interventions may have contrasting effectiveness in different contexts and may not be readily transferable among locations (Falkenmark and Chapman, 1989; Stephens et al., 2021). A lack of data on local hydrological conditions usually mean modelling is also needed to predict potential impacts (Blöschl et al., 2013). However, the uncertainty associated with modelling may be greater than the change associated with the impact, making the outcome of any intervention difficult to predict (Fennell et al., 2023). In addition, the scale of a particular change relative to a particular catchment or river basin will strongly influence the likely impact; the cumulative effects of multiple interventions are also difficult to assess (e.g. Golden and Hoghoohi, 2018). When ecohydrological impacts are a primary component of a restoration scheme, a range of research tools is available allowing interdisciplinary teams of specialists to make qualitative and quantitative assessments with appropriate consideration of uncertainty and risk (e.g. Wohl et al., 2015, 2023; Smith et al., 2021; Luo et al., 2023). Surprisingly, when the focus of restoration is more ecological or species-focused, and carried out by land- or river-management agencies lacking appropriate specialist expertise, ecohydrological assessment may be only cursory and expert evaluation is often lacking. It is important that such projects engage the scientific ecohydrological community in order to provide specialist insights at the outset and opportunities to learn as much as possible from specialist scrutiny of project outcomes.

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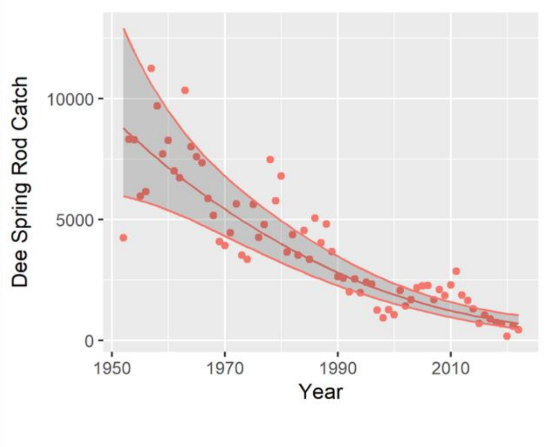
Figure 1 (a) Declining Atlantic salmon angling catches on the Aberdeenshire River Dee, Scotland: Many salmon rivers in Europe and North America show similar declines. (Note spring fish are those that are caught between February and May which mainly spawn in mountain headwater areas). (b) Similar decline in numbers of returning adult female salmon returning to a monitoring site on the Girnock Burn, a tributary of the Aberdeenshire Dee. (After Soulsby et al., 2024).

(a)



(b)

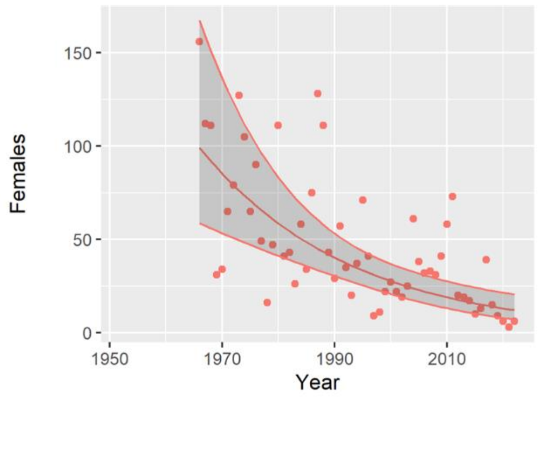


Fig 2 (a) An example of Large Wood Structures being used to "restore" an Atlantic salmon stream of the Aberdeenshire Dee SAC in the Cairngorms National Park, Scotland. In the photo (looking downstream) the root mats of several trees are exposed at the head of a bar feature. Typically, the stream bed or banks are excavated and 5-10m of the tree stem is buried. (b) Large boulders and cobbles are scavenged from the surrounding stream bed to stabilize the feature. In the photo (looking upstream) most large boulders (which provide important natural cover for juvenile salmon) have been removed between the white arrow and the observer including from the gravel bar. The survey pole is 1m long.

a

b

Fig 3 a) A Large Wood Structure installed on a lateral bar in a salmon-bearing stream in the Cairngorms National Park. The exposed root bole is to the centre-right of the image just to the left of the large boulder in the river bank. The excavated area from the heavy plant (visible upstream) is in the foreground. b. Trees located adjacent to stream prior to installation in area of juvenile salmon habitat.

a

b