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SPECIAL ISSUE: SCIENTIFIC ADVANCES IN RIVER RESTORATION

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1. INTRODUCTION

In September 2023, the River Restoration Centre (RRC) hosted the inaugural Scientific Advances in River Restoration (SARR) conference in collaboration with the University of Liverpool, UK. As we confront the twin crises of climate change and biodiversity loss, this event underscored the importance of global collaboration among river restoration scientists to help inform evidence-led solutions. Fluvial systems are particularly vulnerable to global climatic pressures, with droughts and floods exacerbating the impacts of human-induced river modifications. River restoration is a crucial tool in addressing these pervasive challenges, capable of benefiting both people (e.g. flood mitigation, community engagement) and nature (e.g. ecological recovery, ecosystem functionality). The SARR conference aimed to unite scientists from various disciplines and countries, foster collaborations, and highlight new advancements to enhance global progress in river restoration science. This river restoration special issue features a diverse selection of papers presented at the SARR conference, showcasing the multidisciplinary nature of contemporary river restoration.

2. THE RRC

The River Restoration Centre (RRC), a UK-based not-for-profit organization, serves as the national expert advice centre for best practice in river restoration, habitat enhancement, and catchment management. It acts as a central hub for the exchange and dissemination of river restoration expertise. The Centre offers site-specific technical advice through its core team of experienced staff and a broader network of river restoration practitioners. The RRC's mission is to actively promote the re-establishment of natural processes, habitat features and biodiversity within river systems. It supports others in achieving these goals by collating information and evidence to generate knowledge, and by sharing best practices across the river management community, which includes regulatory agencies, charities such as Rivers Trusts, volunteers, catchment partnerships, consultancy companies, academics, stakeholders, and residents with an intertest in their local river.

3. WHAT IS RIVER RESTORATION?

Freshwater habitats occupy approximately 0.8% of the total surface of the globe, and make up only 0.01% of Earth's water, yet are home to 9.5% of all known animal species and one third of all vertebrates (Balian et al., 2008; Dudgeon et al., 2006). Since 1970, there has been an 83% decline in freshwater vertebrate species populations (WWF, 2022). In fluvial environments, such declines have been caused by morphological degradation resulting from the construction of dams and weirs, dredging, water abstraction, land use changes, and the reinforcement, reshaping and rerouting of rivers for navigation, industry, drainage, agriculture and flood protection (Palmer & Ruhi, 2019). Humans have modified rivers for thousands of years, but the impacts of human modification have mostly been revealed in the past two centuries – the state of rivers has been substantially impacted since the beginning of the industrial revolution and with rapid expansion of the global population (Wang & He, 2022). Human pressures have adversely affected river ecosystem health, disturbed fluvial processes and in some cases have exacerbated flooding. Globally, human pressures on rivers are expected to increase as urban space expands to accommodate a growing human population (Malmqvist & Rundle, 2002; Wang & He, 2022). River restoration aims to mitigate or reverse morphological damage with a view to promoting more healthy and naturally functioning river environments that can benefit people and wildlife.

For the purpose of this special issue, we will adopt a broad definition of river restoration as: management interventions intended to re-establish natural physical and biological processes, features and habitats in river channels, floodplains and catchments (RRC, 2024). Early river restoration activities tended to be opportunistic and limited in scale and outcome (and in some cases still are). Such efforts were often focused on enhancing or 'mimicking' habitats (Beechie et al., 2010; Sear, 1994;) or managing erosion. This work mostly involved manipulating the physical form of the channel. In recent years, river restoration research and practice has become more holistic and interdisciplinary - spanning geomorphology, ecology, hydrology and social sciences, as well as economics, engineering, geography, and politics. Catchment-scale, process-based river restoration is now widely accepted as the ideal approach and plays a vital role in current international policy and legislative directions (e.g. the European Union's CEN standard on river restoration, which is nearing completion). Rivers are dynamic systems with a remarkable ability to recover once human-induced constraints and controls are removed, although some sections of river do require more active interventions. The overarching aim of river restoration is to assist this recovery and increase resilience (Wohl et al., 2024). A river's resilience (sometimes referred to as 'absorbing capacity') can be defined as its capacity to respond to disturbance and recover; maintaining a characteristic, self-sustaining regime of functions and processes, or sets of feedback loops (Fuller et al., 2019; Wohl et al., 2024).

4. SARR CONFERENCE 2023

In September 2023, over 150 scientists and practitioners from 26 countries gathered at the SARR conference to share international research and perspectives on river restoration. The conference comprised 60 presentations delivered in plenary or parallel sessions. A poster session provided an opportunity for 18 additional presenters to engage the audience with their research. Themed discussion sessions focused on 'Models and their uses in river restoration' and 'Global perspectives on river restoration policy.' The keynote speakers and additional guest speakers participated in a closing panel discussion, welcoming perspectives and questions from conference delegates to discuss some key scientific topics and advances.

The event featured three keynote speakers who presented diverse perspectives and evidence from around the world.

· Professor Phil Boon (Freshwater Biological Association, UK) provided a historical narrative of river conservation and restoration from an international (largely European) perspective. He acknowledged changes and improvements in the approach to river restoration since a previous conference held by the European Centre for River Restoration in

1996, and highlighted some of the challenges that need to be addressed if progress is to be maintained.

· Professor Kirstie Fryirs (Macquarie University, Australia) reviewed river metamorphosis in eastern New South Wales since European colonization, outlining an approach to identify and measure key geomorphological, vegetative, and hydrological indicators of river recovery. She demonstrated how this understanding can inform management and planning in a future where extreme flood and fire events will become more intense and frequent, threatening riparian ecosystems.

· Professor Ellen Wohl (Colorado State University, USA) offered a North American perspective on the key advances and challenges in river restoration, reviewing fundamental aspects of river form and function, natural regimes of water, sediment, and large wood, and the legacy of human alterations within river corridors and catchments.

Several fundamental questions emerged at the conference, repeatedly addressed by the scientific community across sessions:

· Can restoring rivers help in their adaption to climate change?

· Can river restoration promote greater interaction between people and nature?

· How should we communicate the need for river restoration to policymakers and the general public and work together to implement effective restoration strategies?

· What technology, tools, and techniques can help to improve multi-objective and sustainable river restoration planning, and yield practical outcomes?

A recurring message at the SARR conference was the need for scientists to disseminate knowledge to non-specialists about river forms and processes. Such communication would provide a more accurate understanding of the rivers we live alongside, the pressures rivers face, and attainable and sustainable objectives in river management. Citizen science was highlighted as a key method of engaging communities with their rivers and empowering them with knowledge. The river restoration community has a responsibility to communicate positive messages about the potential to improve the health and resilience of rivers, without being alarmist or sensationalist.

Phil Boon opened the conference with a fitting keynote address titled: “River restoration: Are we there yet?”. This question was revisited during the panel discussion. It was agreed that although there are still gaps in scientific knowledge, enough is known on how to effect changes that will benefit both river systems and society. The greater urgency lies in developing a collective approach for identifying and promoting key messages on river restoration. The SARR conference crystallized many ideas on which the global community seems clear and united, and these are briefly presented here in this Editorial. In addition, we discuss matters that require further debate; some of these are explored in greater depth in the papers of this special issue, and others may be topics for future SARR conferences.

5. RESEARCH THEMES IN THIS RIVER RESTORATION SPECIAL ISSUE

This special issue presents research findings from the fields of ecology, geomorphology, hydrology, social sciences and data sciences, all relevant to the management and restoration of modified and degraded river systems. Although manuscripts are grouped based on their primary focus, we acknowledge that the interdisciplinary nature of river restoration means that much of this work transcends individual topics.

5.1 Ecology Focus

There was wide acceptance at the SARR conference that biology is fundamental to river form and function (Johnson et al., 2020). River restoration science has therefore advanced from the traditional unidirectional viewpoints that only considered abiotic forces as drivers of freshwater ecosystems (Frissell et al., 1986) to a perspective that recognizes complex ecological processes (i.e. metacommunity dynamics) and two-way interactions between biological and geomorphological processes (Palmer & Ruhi, 2019; Johnson et al., 2020; O'Briain et al., 2024).

Studies examining the ecological implications of river restoration in this special issue are wide ranging in the responses assessed and the spatial and temporal scales considered. England et al. (this issue) report taxonomic and functional benefits for macroinvertebrates from a weir removal project that occurred alongside catchment-wide improvements, highlighting the need for scientifically robust post-project appraisals capable of reliably capturing such trends. White et al. (this issue) compared sub-fossilized faunal assemblages collected from a palaeochannel with contemporary communities sampled after its reconnection. This study offers lessons not only from rivers but also from comparable research on lakes that help to characterize the extent of ecosystem degradation and potentially inform reference conditions for restoration.

Other studies in this special issue statistically explored ecological responses to abiotic controls in a river restoration context. Noone et al. (this issue) investigated the effects of restoration schemes on habitat diversity, water temperature heterogeneity and aquatic macroinvertebrate taxon richness in Whychus Creek, Oregon, USA. Their results support the view that floodplain restoration creates diverse thermal conditions and richer macroinvertebrate communities.

Human activities have also affected river water quality, a reality that has received attention in the mainstream media worldwide. Exton et al. (2024), in their study of undesirable river biofilms (sewage fungus), highlight the need for a more holistic approach that considers pollution in the wider context of river functioning (e.g. flow velocity, substrate type, artificial structures, riparian zone shading) and climate change. Hons et al. (this issue) investigated the impact of meander reconnection on various physico-chemical parameters (e.g. dissolved oxygen, macronutrient concentrations) and reported promising, but variable, findings on how reconnected channels mitigated phosphorus and carbon levels.

On a markedly different scale, Wilkes et al. (this issue) statistically modelled the responses of a suite of macroinvertebrate species to prospective restoration interventions across England. This type of 'big data' approach will be a critical tool for spatially prioritising restoration measures and predicting the ecological implications of different interventions.

5.2 Geomorphology Focus

There was agreement at SARR that terms such as 'river corridor' or 'riverscape' (Fausch et al., 2002) should be used more widely to dispel the myth that a river is only as wide as its channel and as deep as its bed. Similarly, river restoration science supports the view that reach-scale opportunism should be replaced with strategic catchment-scale restoration, because river corridors exist within catchments and reflect the catchment processes that create fluxes of water, solutes, sediment, and organic matter throughout a river network (Wohl et al., 2024). Robins et al. (this issue) stress the importance of evidence-based decision-making at catchment scale to prioritize measures that will reverse the decline of biological communities. Their review of more than 230 catchment plans from the UK indicates that most plans do not clearly link empirical data to decision-making, and there is no common approach to catchment planning. They present a framework that encourages evidence-based assessment of pressures and impacts to help practitioners identify and prioritize river restoration options.

A clear message at the SARR conference was the agreement that simple, uniform rivers should not be the goal - messy rivers are healthy rivers (Wohl, 2016) and are associated with many ecological benefits (Everall et al., 2012). Rivers exhibit flow, sediment, and wood regimes, and river systems require all three to increase both geomorphological and ecological integrity (Wohl et al., 2019). Resilient rivers respond to fluxes of water and sediment supplied by their catchment and are characterized by constant, or at least repeated, adjustment (Fuller et al., 2019).

Restoring river health also means giving rivers space and freedom to flood and adjust their channels (Skidmore & Wheaton, 2022), working with river processes to develop sustainable management and restoration strategies (Grabowski et al., 2014). The most resilient rivers are expected to be those that are the least impacted by people and most connected to their floodplain and catchment – industrialized anthropogenic alteration has suppressed river resilience (Fuller et al., 2019; Wohl et al., 2024). The importance of the lateral, longitudinal, and vertical dimension of the river, is now increasingly recognized (Boulton, 2007; Wohl, 2017; Wood et al., 2012) (see also stage zero below). Despite this, there is still a need to reduce erosive pressure on river banks in critical locations, with an increasing trend towards nature-based solutions, in some cases replacing the traditional structural engineering approach. For example, Leblois et al. (this issue) investigate the reasons behind the failure of willow fascines. Using a review of French case studies as well as complementary laboratory experiments, the authors show that these structures are susceptible to erosion and deposition at specific locations, leading to recommendations for more robust design standards.

Where floodplains have been urbanized or developed for agriculture, industry or settlement, engineering structures are often already in place. These alter flow and sediment transport patterns and adversely affect biodiversity, especially in highly mobile rivers that experience extreme flow variability. Tolentino et al. (this issue) investigated the impact of existing flood structures in a tropical wandering gravel-bed river in the Philippines to screen opportunities for structure removal and channel reconnection as a natural flood management strategy. The study area is already prone to tropical cyclones and storms and the magnitude and frequency of storms is expected to increase with climate change, increasing the risk of flooding in a region where there is also rapid urbanization and a high population density. The authors recommend using hydraulic models alongside high-resolution topographic mapping and multi-criteria analysis to appraise opportunities for river reconnection and inform nature-based flood management plans in other tropical wandering gravel-bed rivers facing similar conditions.

The effects of nature-friendly farming methods on ecology and hydrology were also discussed at the conference. Using catchment based approaches, rivers should be managed in conjunction with the land that surrounds them. Agricultural land (grazing and cropland) occupies approximately 37% of ice-free land globally – the rate of land use change greatly accelerating in the last 300 years with human population growth (Kopittke et al., 2019). In approximately the last 80 years, however, increases in food production have been achieved largely through intensification of agriculture; practises which result in soil erosion (and loss of soil nutrients) and lead to increased fertilizer use, to great economic and ecological cost (Kopittke et al., 2019). Flooding, fine sediment loss and pollution of watercourses by nutrients and pesticides can all be reduced by the use of more appropriate land management practices (Boardman, 2013; Wiltshire et al., 2024). Shtull-Trauring et al. (this issue) studied a stream impacted by intensive agricultural activity in the eastern Mediterranean which is prone to water scarcity, seasonal rainfall and streamflow variation. The Nahalal stream has been historically modified so that it functions as a drainage channel, with the original intention to protect farmland from flooding and maximize the area of cultivated land. Disconnected from its floodplain, the stream has poor ecological health and low resilience. Using their water quality results, the authors conclude that the groundwater which feeds the baseflow of the stream has been contaminated by treated waste water (used to irrigate the crops) and excess fertilizer that has leached through the soil. The authors also attributed low water quality to soil erosion, leading them to suggest that the region adopts soil conservation practices such as no or reduced tillage in cultivated areas and riparian buffer strip establishment. Practices that retain ground cover and plant roots all year improve soil structure and increase water infiltration rates, both reducing soil erosion and holding water back (Basche & DeLonge, 2019). Healthy soils also act as a sink for atmospheric carbon whereas soils in agricultural ecosystems can become depleted of organic carbon, with those prone to erosion by water and wind becoming depleted the most quickly (Lal et al., 2021). Soil health indices derived from soil surveys can help identify land where soils are degraded and where alternative management practices would be recommended (Stott, 2023).

5.3 Stage Zero Restoration Focus

'Stage zero' is a concept that describes the initial, pre-disturbance condition of a river (Cluer & Thorne, 2014. Rivers are keystone components of the biomes within which they exist (Dodds et al., 2014), but the reality is that few pristine biomes remain (Johnson et al., 2020), so we rely on evidence from the past. There is growing evidence showing that before human disturbance, watercourses in low-gradient depositional reaches flowed through multiple, low-banked anabranching or anastomosing channels that were hydrologically connected to wet woodland or wet grassland (Brown et al., 2018; Fleming, this issue; Flitcroft et al., 2022; Marcinkowski et al., 2017).

The philosophy of stage zero restoration is to work with the natural processes of the river to rehabilitate modified and incised or aggrading channel networks and restore connection to the floodplain and hyporheic aquifer. Stage zero aims to lift water back up into the landscape. This may include active infilling of incised or degraded channels and drainage ditches, and passive infilling by the reintroduction of beavers, construction of beaver dam analogues, and placement of large wood. Clarke (this issue) provides a comprehensive review of the stage zero restoration approach, the historical and geographical context from which it emerged, and the many practical considerations associated with expanding the use of stage zero across temperate regions.

Fleming (this issue) used new, accessible unmanned aerial vehicle technology and 3D photogrammetric models to provide evidence for historical reference conditions in lowland rivers where early human modification has reduced floodplain connectivity and promoted single-threaded river configurations. The author's techniques reconstructed past planforms and reveal a mosaic palaeolandscape consisting of multiple anabranching channels, providing a template for future stage zero river restoration.

With the re-creation of these past landscapes, one of the challenges is deciding how to assess the impacts on biodiversity, climate resilience, flood attenuation and water resources, given the significant transformation from single-threaded to multi-threaded channels. Traditional monitoring strategies that target single-thread channels are inadequate for capturing differences between pre- and post-project site conditions (Flitcroft et al., 2022). Hinshaw et al. (2022) have proposed a geomorphological monitoring protocol based on randomly located sampling plots to assess changes in canopy cover, wood volume, flow depth, flow velocity, area covered by coarse and fine organic material, and substrate size.

Stage zero restoration falls within the emerging concept of ‘Biomic River Restoration’ (Johnson et al., 2020) which shifts the focus of river restoration from traditional natural fluvial process drivers (e.g., hydrology, in-channel sediment processes) to considering the role of biology and landscape in driving stream form and function. This approach reconnects streams to their biomes and resets the baseline level for river formation (Johnson et al., 2020).

5.4 Social and Policy Focus

A socio-political perspective is fundamental to river restoration, with assessments of international policy now focusing on the societal transformations needed to support nature recovery. Gittins et al. (this issue) state that it is necessary to view rivers as social-ecological systems to include feedback between human systems and river ecosystems, and provide insight into how transformative change can be leveraged to support river restoration. Within this, they consider the different models of interaction between people and the environment – for example ‘nature for humans’ versus ‘nature and humans’. The latter, where people are connected to the river and the river is respected as an entity in its own right, is also illuminated by the Māori concept ‘I am the river and the river is me’ (Fuller, 2023) and in ‘Te Awa Tupua’ (the Whanganui River Claims Settlement Act 2017). To communicate this message most powerfully to non-scientific audiences, can we use artistic outlets, such as images, designs, and visually descriptive or figurative language?

Important questions arose in the conversations at the SARR conference that flowed around this subject. Is there tension between the paradigms we are promoting - do rivers matter and deserve to be restored solely for the good of nature, or for the good of humans? How can we demonstrate that restored rivers represent real societal value while simultaneously avoiding their monetization? How much should science be guided by current government policy? Traditionally, policy makers have looked to science to provide evidence upon which their decisions are made, yet increasingly research questions are framed with a specific policy focus. Perhaps this is unsurprising given the urgency of the joint climate and biodiversity crises. For example, Wilkes et al. (this issue) prioritize river restoration actions that would be most likely to deliver specific species abundance targets in England by 2030 and 2042.

There is also a growing field of research that is best described as the ‘science of policy’, in which analyses of policy documents can reveal underlying priorities, values and deficiencies in the rapidly advancing area of environmental policy making. For example, Liu et al. (this issue) examine China’s River Chief policy, finding that there is limited appreciation of ecosystem services provided by rivers, and a restricted focus on who is responsible for river management, which may hinder attempts at holistic river restoration. Interviews and other observations conducted with river restoration practitioners in Quebec, Canada, by Gariépy-Girouard et al. (this issue) suggest that expertise and funding are key drivers behind the objectives of river restoration projects, and these may either promote or restrict the inclusion of scientific principles in the decision-making process. The authors argue for regulation that is better informed by scientific knowledge, better adapted for realistic project timeframes, and which calls upon more diverse expertise (from both academic researchers and stakeholders).

6. LOOKING TO THE FUTURE

In some countries restoration efforts in rivers have been under way for over 40 years, gaining momentum in response to the pressing need for resilient river systems. However, the legacy of human impact is extensive, and rapid climate change represents a moving target. We are often out of touch with the true ‘reference’ conditions that we strive towards (Grabowski, 2014). Is this why we are shocked by headlines about rivers ‘bursting their banks’ when river channels have intermittently occupied their floodplains for millennia (a question posed by Professor Boon in his keynote address)? Recovery may not be about returning rivers to a previous state, but rather about enhancing the biogeomorphological condition of rivers, recognizing that rivers are dynamic and that new evolutionary trajectories are being created for which there are no reference conditions or analogues (Dufour & Piégay, 2009; Fryirs, 2024).

Questions remain to be answered, and we include these here to inspire future research. These include:

- How can forecasting future scenarios and predicting the level of resilience within river systems be improved?
- What should the target condition of a restored river look like in an ever-changing world, and what methods should be used to assess the extent to which rivers have been altered or improved following restoration?
- In the face of a changing climate, should there be a focus on the ecological potential of a river for recovery?
- What role can river restoration play alongside other river management interventions such as environmental flows and water quality improvement schemes?

With climate change and an ever-increasing human population, there is a growing need to accelerate work on protecting freshwaters and ensuring that river systems function sustainably (Fryirs, 2024). Despite the challenges rivers face, the river restoration community strives to show an alternative and achievable future. As the famous quote attributed to Archbishop Desmond Tutu goes, ‘Hope is being able to see that there is light despite all of the darkness,’ (BBC, 2018).

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Editorial: Scientific advances in river restoration

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