Freshwater science - Perspectives from the Royal Society Global Environmental Research Committee

This paper is an output of a discussion on freshwater science at a Royal Society Global Environment Research Committee (GERC) meeting (see 'context' on page 3). It seeks to highlight science issues of potential interest to researchers, funders and government.

Executive summary

GERC identified four key areas where further research or investment is important and a further three thematic challenges that cut across a range of science questions.

Key priorities for study are: (1) Understanding how water moves and is stored in the soil to enable better interventions, for example to reduce flood risk; (2) Developing integrated models across meteorology and hydrology able to predict catchment responses to better understand, for example the interaction of climate change with land use change; (3) Developing earlier warnings from freshwater natural hazard forecasts to ensure better preparedness; and (4) Addressing fragmentation in freshwater research to fully quantify catchment impacts on nutrient and contaminant fluxes along the aquatic continuum from land to ocean.

Multidisciplinary themes identified include: (1) Building a resilience framework to account for global-scale water manipulations such as river diversions and abstractions; (2) developing a systems-based approach to capture the multi-stressors on freshwaters; (3) integrating the diverse data streams underpinning freshwater research.

Introduction

Freshwater is fundamental to life but its availability is limited as it comprises only about 2.5% of all water on Earth. The water or hydrological cycle affects biogeochemical cycling and consequently freshwater ecosystem health, as well as being critical to human survival. Parts of the water cycle – notably the terrestrial water cycle - remain poorly quantified. Delivering a theoretical framework that includes both flow and the age distribution of these flowing and stored waters has been described by some as a wicked problem. Without this framework, interventions that seek to address direct human impact on the water cycle, such as over abstraction or the impact of human-induced climate change, may fail. Global warming is expected to intensify the water cycle, shift its regional patterns and in some instances alter its seasonality, yet evidence of changing baselines for freshwater systems (e.g. river discharge) is limited and we lack predictive capability to say how change will impact the system.

The UK has a rich history in freshwater science that is well-grounded in process understanding derived from experiment and observation. National modelling efforts strive to be realistic about the level of complexity that can be modelled given available data while attempting to consider and quantify unavoidable uncertainties. The interdisciplinary nature of dynamic interactions and feedbacks between water and people – a field termed socio-hydrology – is challenging understanding but is some way from informing the needs of decision-makers. The UK National Flood Resilience Review, for example, called for an end-to-end risk modelling framework to address the propagation of uncertainty down the *whole* value chain.

Past research programmes, such as NERC's £10m Changing Water Cycle (2007-12), advanced understanding of particular aspects of the hydrological cycle, as has the underpinning monitoring and data analytics undertaken by NERC Institutes (notably CEH and BGS). Long-term government investment in observation (e.g. Environment Agency, SEPA), and forecasting (e.g. UK Met Office and the Flood Forecasting Centre) contribute to UK expertise and the assessment of any future change. There is very

significant interest in freshwater science from policy and regulation in the UK (e.g. Defra's 25-Year Environment Plan; the Cabinet Office flood resilience initiative, the UK Hydrological Outlook) and internationally (e.g. IPBES Global Assessment Report on Biodiversity and Ecosystem Services, 2019).

This paper seeks to highlight some specific areas of freshwater science of potential interest to researchers, funders and government.

Science issues

The GERC discussion identified four key areas for freshwater research (not in priority order):

1. **We do not fully understand the interactions between different parts of the (vegetation-soil-geology) terrestrial cycle and how long water is stored in them.** Without knowledge of rates of flow and soil moisture residence times, we cannot make informed water management interventions (for example whether afforestation/deforestation increases or decreases flooding). Advances in techniques like isotopic tracking can inform an understanding of these processes under different environmental conditions, but we are some way from the integrated understanding of storage, connectivity and flow that would allow better predictions of water travel and residence times.

2. **Better understand the hydrological cycle through advances in observational capacity and Earth system modelling**. We want models to be able to predict catchment responses to particular types of external forcing, such as changes in the spatial/temporal rainfall distribution under climate change or land use change. Whilst the physical laws governing water movement at small scales have been understood for decades, we are only just understanding how to apply these physical laws to systems that are complex, heterogeneous on all scales, and poorly characterised by direct measurement. Coupling advances in quantifying hydrologic behaviour at the catchment or hillslope scale with UK-led improvements in hyper-resolution global hydrological models (1km^2 or finer c.100m) should help address pressing questions. These include: is the hydrological cycle regionally accelerating /decelerating under climate and environmental change? And, are there thresholds at which irreversible changes occur?

3. **Developing earlier warnings from freshwater natural hazard forecasts to ensure greater preparedness.** Improvements in understanding connections at large distances within hydrological cycles and medium range (3-15 days) forecasts could now enable this advance but need to be developed so they can support diverse users (e.g. policymakers). Further, we need to better understand the consequences of freshwater natural hazards in dirty water systems: most floodwater is sediment-laden with associated contaminant transfers, including sewage, plastics and synthetic chemicals. Such transfers may have lasting ecological impact.

4. **Considering the aquatic continuum from land to ocean**. Climate change, combined with human-driven alterations to catchment systems, impacts nutrient and contaminant fluxes along the aquatic continuum from to land to ocean, with consequences for freshwater and coastal ecosystems and for human health (e.g. drinking water quality). To make progress, observation and modelling capabilities need to be joined up. The fragmentation of freshwater science - soil water, surface water and groundwater - restricts our ability to build integrated assessment models for water like that for climate. We currently use proxies to bridge these gaps and we lack data. Whilst access to data sets has improved, we still lack the integrated datasets available in countries like the US. The principles of open data applied to freshwater sciences could significantly advance our understanding – especially in the socio-hydrological sciences.

The GERC discussion also raised three thematic challenges that apply to several areas of freshwater science:

1. **Large-scale water manipulations reduce system resilience**. Many major rivers now often no longer make it to the sea owing to water abstractions and/or diversion (e.g. Colorado, Indus). In the UK, we have yet to fully understand the ecological impacts of natural flood management. Accounting for and managing water can be difficult because water becomes virtually embedded in goods such as food or manufactured products; so called, "virtual water". Transfers of virtual water are an inevitable consequence of global trade, with the UK and Europe being net importers of virtual water to the tune of 100-300 Gm^3/yr (waterfootprint.org). Building a resilience framework to quantify and address water stress (both quantity and quality) and its consequences for freshwater biodiversity is a global priority.
2. **People impact freshwater ecosystems**. Freshwater species are going extinct more rapidly than terrestrial or marine species (IUCN). The IPBES Global Assessment 2019 places land use as the major driver of change. UK science is world-leading in characterising biodiversity and habitat loss. Academic interest focuses on describing and understanding individual issues such as neonicotinoids or plastics and more recently, on understanding the multi-stressors impacting freshwater ecology especially with respect to the impacts of climate change. However, a systems-based approach is required to bring all research strands together, using appropriate models to address what-if scenarios such as land use change in a world that constantly evolves. This would help our regulatory frameworks focus both on preventing impacts and on predicting solutions.
3. **Complex socio-hydrology challenges require multidisciplinary approaches**. The need to integrate freshwater science in the UK is no exception. Yet, as a country, we don't generally do long-term, large scale multi-stakeholder experiments or capitalise on effort undertaken by others, for example, water companies. This is in part the challenge of open data (see earlier), yet other countries have invested in integrated platforms, for example the German TERENO network or US NSF National Ecological Observatory Network. These are used to observe hydrological cycles at relevant scales; drive innovation in measurement; undertake meta-analyses of the available data (including those that are not publicly available), and foster an integrated framing of the science from multiple perspectives. Integration of the diverse data streams, including governmental, academic, satellite, and industrial has the potential to drive a step change in understanding the freshwater system in the UK.

The context for Global Environmental Research Committee reports

The Royal Society's Global Environment Research Committee (GERC) is charged with advising the Royal Society, and with interacting with research councils, the environmental science community, and other bodies. To do this, it is undertaking a rolling series of reviews of areas of science within its remit. The areas it has identified are (in alphabetical order): air quality, biodiversity, carbon and other biogeochemical cycles, climate, natural resources (including land use) and food, oceans, polar science, and freshwater. In each area, GERC uses its own expertise, and that of a small number of invited experts to consider the questions:

1. What are the hot research topics in this area at present?
2. What is the status of UK science within this area?
3. What are the most pressing research needs in the next 5-10 years?
4. Are there specific areas where UK science should be focused to meet these needs?
5. How should priority topics be incorporated into multidisciplinary issues that Future Earth and its UK committee should consider?

This paper results from the discussion about freshwater science, held in May 2019. In addition to contributions from its regular and co-opted members, the committee was advised in person by **Prof Hannah Cloke (Reading University), Prof Joe Holden (Leeds University), Prof Lorraine Maltby (Sheffield University), Prof Thorsten Wagener (Bristol University) and Prof Susan Waldron (Glasgow University).** In addition, **Prof Rick Battarbee FRS** attended, **Prof Keith Beven FRS** provided written input from the British Hydrological Society, and **Prof Julia Slingo FRS** provided feedback on the draft report.

This paper does not seek to represent the views of the Royal Society or to produce a comprehensive overview of freshwater science, but instead to highlight some specific areas of potential interest to researchers, funders and government. Exclusion of a topic from this document does not negate its importance, and many areas that are already under intense research are not highlighted here.

Membership of GERC (including co-opted members) at the time this topic was discussed (May 2019) was: **Prof Gideon Henderson FRS (Chair), Dr Kirsti Ashworth, Prof Mike Bentley, Prof Harry Bryden FRS, Dr Maria Dornelas, Prof Pierre Friedlingstein, Prof Joanna Haigh FRS, Prof Roy Harrison FRS, Prof Sue Hartley, Dr Ruth Kelman, Prof Louise Heathwaite, Prof Peter Smith FRS and Prof Martin Solan.** Hélène Margue acted as Secretary.