Rivers of the Anthropocene?

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The ancient Greek philosopher Heraclitus famously asserted that one can never step into the same river twice, thus providing a physical metaphor for life's constant change. The growth in human population and advances in technology in recent centuries have certainly changed rivers. From a scientific perspective, Heraclitus' dictum has never been more apt than now, at the dawn of the so-called "Anthropocene".

Rivers are exceedingly complex biophysical systems. Observable ecological patterns reflect temporally averaged, spatially distributed, multi-scaled processes arising from watershed controls on precipitation, erosion, and nutrient inputs into river channels. Aquatic and riparian species and communities reflect a long evolutionary history of adaptations to dynamic and heterogeneous environments that are hydrologically connected via channel networks through which movement and gene exchange occur.

Ecological complexity in rivers has been conceptualized scientifically by viewing these systems as existing in a kind of dynamic equilibrium, or balance, defined by prevailing hydro-climatic and watershed controls and by evolutionary species pools. Humans act to disrupt components of this equilibrium, causing "impacts" that are quantified as measurable deviations in riverine biophysical processes and patterns from some unperturbed baseline condition.

Human impacts on rivers are extensive and pervasive. Perhaps nowhere is this better observed than in the case of land-use change (eg urbanization, deforestation) and channel-spanning water infrastructure. Dams dramatically transform rivers by altering the downstream flux of water, sediment, and nutrients, modifying water temperatures, and blocking species movement. They are ubiquitous; in the US alone, there are 75 000 dams exceeding 2 m in height, one on average for every 50 km along mid-sized rivers. Only 42 rivers in the US have undammed reaches greater than 200 km. On a global scale, over 40 000 large dams (>15 m in height) have been built and thousands more are proposed, chiefly in developing countries, to produce so-called "green energy" via hydropower.

There is growing societal interest in "restoring" regulated rivers by deliberately releasing reservoir water from dams to provide more reference-like flow conditions downstream. For example, experimental flow releases in the Colorado River system, such as the recent pulse of water from Arizona's Morelos Dam into the near dry downstream Mexican riverbed (*Science* 2014; **343**: 1301), represent efforts to regain some historical ecosystem function.

There are limits to the effectiveness of such efforts, however. The physical–chemical modifications to systems associated with larger dams, combined with the human-assisted spread and proliferation of non-native species throughout many rivers, can create "novel ecosystems" that are far outside historical equilibrium boundaries and are therefore fundamentally not restorable to reference conditions (Acreman *et al*., this issue).

Rapid climate change and spread of non-native species, along with continuing land-use modification, contribute to shifting baselines in river ecosystems, suggesting we should start viewing rivers as dynamically evolving, not dynamically equilibrial. This change in viewpoint substantially alters how we perceive "natural" conditions and what "impact" means, and raises important new challenges for management. We are rapidly entering an era where restoration interventions will be guided less by statistical deviations from historical reference conditions and more by "process-based" understanding of organism–environment relationships. Linking the ecological performance of species or ecosystem function directly to dynamic environmental variables in a mechanistic fashion will be critical to achieving ecological objectives in our changing world.

A key emerging principle is to manage for resilience against ongoing environmental change. Anticipatory interventions (so-called "adaptation") will be increasingly required to achieve this. Fortunately, existing, well-established scientific insights gleaned from studies of species performance across the dynamic range of historical environmental variation (eg flow, temperature) can inform such adaptation planning, as can new knowledge gained from controlled flow releases below dams.

Freshwater biodiversity is declining rapidly, faster than for any other ecosystem type. The proposed construction of thousands of dams, and the continued clearing of forests and other wildlands to meet human food demands, will further exacerbate this decline. Thus, the future of freshwater biodiversity is inextricably linked to land and water infrastructure management. Efforts beyond planned flow releases below existing dams are needed. The strategic placement and coordinated hydrologic operation of new dams, irrigation canals, etc, across across whole basins, along with intentional conservation of free-flowing river segments, is key to sustaining freshwater biodiversity and desirable ecosystem goods and services in river systems worldwide.

Rivers of the Anthropocene are complex social–ecological systems, where human preferences and actions directly affect the fates of aquatic and riparian ecosystems. From a scientific point of view, rapid global change ensures that Heraclitus' maxim will resonate ever more deeply in the years ahead.