Impair-then-Repair: A Brief History & Global-Scale Hypothesis Regarding Human-Water Interactions in the Anthropocene

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Abstract: Water is an essential building block of the Earth system and a nonsubstitutable resource upon which humankind must depend. But a growing body of evidence shows that freshwater faces a pandemic array of challenges. Today we can observe a globally significant but collectively unorganized approach to addressing them. Under modern water management schemes, impairment accumulates with increasing wealth but is then remedied by costly, after-the-fact technological investments. This strategy of treating symptoms rather than underlying causes is practiced widely across rich countries but leaves poor nations and many of the world's freshwater life-forms at risk. The seeds of this modern "impair-then-repair" mentality for water management were planted long ago, yet the wisdom of our "water traditions" may be ill-suited to an increasingly crowded planet. Focusing on rivers, which collectively satisfy the bulk of the world's freshwater needs, this essay explores the past, present, and possible future of human-water interactions. We conclude by presenting the impair-then-repair paradigm as a testable, global-scale hypothesis with the aim of stimulating not only systematic study of the impairment process but also the search for innovative solutions. Such an endeavor must unite and cobalance perspectives from the natural sciences and the humanities.

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Greenhouse warming and potential changes to the hydrologic cycle figure prominently in the climate-change debate, but many other direct anthropogenic factors are today redefining the state of rivers, which supply around 80 percent of renewable freshwater to society.[1] Chief among these are widespread land-use change, urbanization, industrialization, and pollution, all known to stress aquatic ecosystems. The highly positive impacts of a reliable water supply on economic productivity (which requires waterworks like dams, irrigation, and interbasin transfers), means that the water cycle will increasingly be controlled by humans for decades if not centuries to

doi:10.1162/DAED_a_00345

come, a hallmark of the new geological epoch called the Anthropocene.[2] With human control of water also comes the specter of water conflict, an issue emphasized by several high-profile research studies, including the last rounds of the Intergovernmental Panel on Climate Change (IPCC), the U.S. National Climate Assessment, and the National Intelligence Estimate.

Water crises are not restricted to humans alone. Freshwater ecosystems are critical biodiversity hotspots. Occupying less than 1 percent of the Earth's surface, they provide habitat to more than 125,000 cataloged species and one-third of all vertebrates and affiliated taxa.[3] Their restricted spatial extent belies their importance, as they maintain orders of magnitude more species per unit area than their terrestrial or oceanic counterparts. The intimate connection and importance of rivers, lakes, and wetlands to human society, coupled with mismanagement, pollution, and climate change, produces the highest potential loss of species on the planet. By some estimates, between ten and twenty thousand species have been lost to date.[4]

Their current stress notwithstanding, water systems will be relied upon over the next several decades to deliver reliable services in light of anticipated economic development and population growth.[5] We refer here to ecosystem services, the array of public goods and functions that nature conveys and which will in the long term sustain human society. These include provisioning benefits like clean drinking water, navigation, waste dilution, transportation, food, and energy production. Ecosystem services also include important regulatory functions (such as climate control) and supporting functions of the biosphere (such as the cycling of essential nutrients). While the value of all these services is subject to debate, they likely make possible a sizable but poorly quantified fraction of global GDP.[6] Despite their clear importance, a survey of the world's major biomes at the turn of the century shows that in virtually all cases "natural capital" is being actively lost, degraded, or co-opted by humans.[7] It remains an open question how available and capable such services will be to serve the water needs of society over the long haul.[8] The answer concerns an issue no less important than how we humans place the planet's sustainability – and our own water security – in the balance. For freshwater, the preliminary outlook is sobering.

An initial global analysis of risks to river systems presented in 2010 confirmed previous reports that threats to human water security and biodiversity are widespread and pervasive.[9] Nearly five billion people live in close proximity to or directly rely on water systems whose ambient condition is moderately to severely impaired. The study also exposed a previously unrecognized global water management principle under which high levels of incident threat to human water security are allowed to accumulate but are then mitigated through an annual global investment of $0.5 trillion in water technologies and engineering.[10] Because such investments are today directed overwhelmingly toward rich or rapidly emerging economies, this impair-then-repair strategy strands the world's poor in a precarious state. Nonetheless, water security also preoccupies the highly developed countries, as John Briscoe's essay in this issue details.[11]

The impair-then-repair approach also distorts public perception of water challenges and contributes to our collective tolerance of the status quo and resistance to change, which is endemic even in rich countries with the technical wherewithal and mature environmental regulations to institute otherwise sensible conservation measures (see also Jerald Schnoor's essay in this volume).[12] In rich countries, an expensive technological curtain separates us from a generally impaired ambient water environment and the clean, reliable water supplies we draw from the tap. A series of surveys published in 2008 and 2010 shows that two-thirds of the American public believes the nation is stable or making progress on environmental pollution whereas two-thirds of the Chinese public believes that water pollution is a "moderately big" or "very big" problem.[13] The mapping study showed very similar levels of threat to water resources in the United States and China, directly at odds with the U.S. public's perception.[14]

The state of water and water management today did not materialize spontaneously. It is more accurate to consider the contemporary setting as but an instant in historical time, conditioned on decades if not centuries of past human behavior (and, as Michael Witzel argues in this volume, belief systems).[15] How, why, and when did such a globally pervasive management strategy emerge? And where is it likely to take us in the future? Using examples from the historical literature, we address this subject in the next sections.

While our interactions with natural and engineered water systems have been part and parcel of human history since the dawn of civilization, the more recent evolution of human-water systems in the Northeastern United States is instructive, as the region moved from a nearly pristine state under indigenous management to today's post-industrial condition in only a few hundred years.[16] The impair-and-repair pattern is clearly evident in seventeenth- and eighteenth-century urban development. Soon after arriving in Boston in 1630, settlers began tapping groundwaters; by 1678 there were so many wells that city streets periodically flooded.[17] In New York, where seawater and sewage periodically fouled wells, the Common Council issued municipal bonds to construct a steam-powered waterworks, holding pond, and network of wooden pipes in 1774, only to have the project derailed by the Revolutionary War.[18] By the mid-1700s, Philadelphia also had a system of public wells. Responding to a yellow fever outbreak believed to be linked to tainted water, Philadelphians began piping water into the city by 1801, creating one of the largest and most advanced urban water systems in the world at the time.[19]

With continued urbanization in the nineteenth century, municipalities faced growing pollution problems. In 1833, Boston announced plans to pipe water into the city because the local supply had become "highly impregnated with the deleterious contents of cesspools and drains."[20] In response, a greatly expanded municipal water system transferred water from Cochituate Lake nearly twenty miles into Boston "to provide for the health, security, cleanliness and comfort of the city."[21] Similarly, Baltimore, Philadelphia, and New York enacted measures to protect water supplies from contamination. With breakthroughs in the germ theory of disease in the 1880s, bacteriologists identified the pathogens responsible for cholera and typhoid. In response, sanitation engineers began experimenting with sand filters, which twenty cities had installed by 1900. By 1910 cities began disinfecting their water with chlorine as a remediation measure.[22]

The ease with which water could be drawn from the tap led Boston authorities to criticize the citizenry's increasingly wasteful ways. Appalled that Bostonians were using nearly one hundred gallons per person per day (compared to the three to five gallons typically drawn from pumped wells), the local water board exclaimed in 1860 that the city consumed water at "an amount believed to be without parallel in the civilized world."[23] In response, Boston annexed several neighboring communities and extended pipes and aqueducts through them to secure new water supplies.[24] Similarly, New York expanded its waterworks, constructing a reservoir in Central Park in 1862 and building a new larger Croton Aqueduct and Dam, which at 1,600 feet long and 240 feet high was the largest masonry dam in the world upon its completion in 1906.[25] By the beginning of the twentieth century, there were more than 3,100 waterworks piping water into urban households across the United States. Heavily engineered water systems had become the norm.[26]

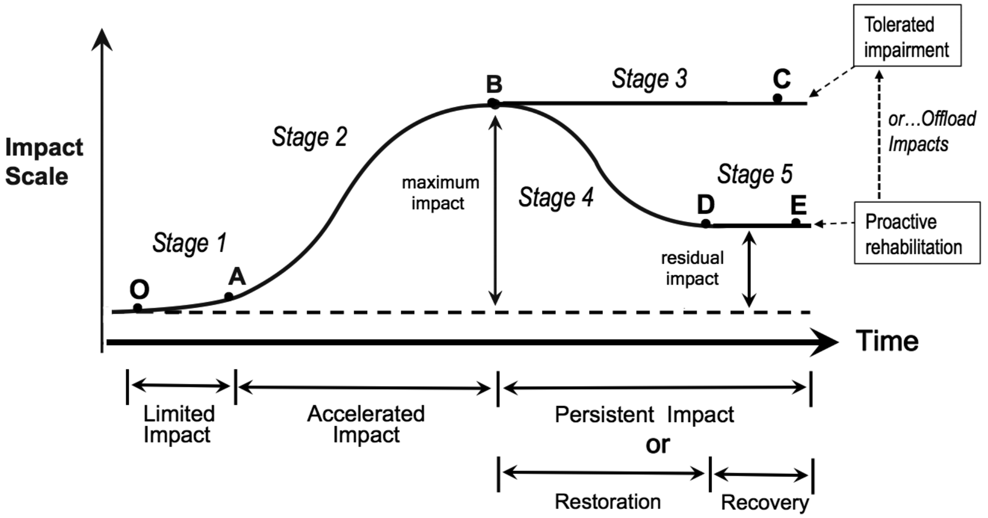
Industrialization further reshaped the ways humans interacted with their water systems. Increasingly, a river's value lay in its capacity to be modified for human use.[27] Human dominance of water, even if later revealed to be impairing water systems, became a potent symbol of progress. It was far better to use, abuse, and later mend (or ignore) a river than to neglect its development potential. Thus, early solutions lay in new water infrastructure and technology, a fortuitous development as the region ran out of undeveloped land and the pristine water associated with it. A time-honored tradition of fouling and then fixing waterways became an economic necessity.

By their very nature, rivers are important conduits for materials recruited from upland watersheds, transported downstream, and processed through river corridors leading to the sea. By their very nature, humans both accelerate and decelerate this transport of material. One example is the widespread increase of field erosion due to poor land management paired with widespread reservoir construction that intercepts and settles riverborne sediment in the quiet holding waters behind engineered dams. Globally, reservoirs have ultimately won out, with one estimate indicating that only two-thirds of all continental sediment destined for the world's oceans makes it there,[28] placing at risk coastal systems that depend on riverborne sediment to prevent coastal erosion. This includes river deltas, a coastal landform inhabited by a half-billion people.[29] Clearly, what happens upstream does not stay upstream.

These hydrologically mediated "teleconnections" are augmented by economically driven ones whose impacts extend well beyond any local drainage basin. In early stages of development, human impact on water systems is limited to the river basin where the water is actually used. But with urban growth and industrialization, impacts easily spill over into the hinterlands that sustain human populations living in the city.[30] In Paris during the early 1800s, food supply systems serving the city were limited to the Seine basin.[31] But a century later, animal products traveled an average of about 300 kilometers to market. These distances have continued to increase; the travel distance for meat and milk has doubled, while the distance for fruit increased eight-fold. Today, Paris, a megacity of ten million, obtains its grain, meat, and vegetables from an enormous swath of real estate extending from the Seine and other French watersheds to Brazil and Argentina.

Such teleconnections thus affect rivers thousands of kilometers from the centers of demand. While Parisians enjoy world-class cuisine, rivers draining croplands in South America bear the brunt of the pollution and other impacts associated with industrial agriculture. The damming of the James Bay rivers in Northern Quebec to supply New England cities with electricity has resulted in a major impact on regional water resources, the environment, and society far from the point of consumption.[32] Cotton and wheat production in the Aral Sea basin, begun in the 1950s by the Soviets and still expanding, places Central Asian countries today at the forefront of water consumption on a per capita basis world-

Figure 1
A Heuristic Model or Typology of Water System Impacts and Societal Response to Water-Related Environmental Stress



This typology represents a time series of development for a particular region or country (such as for Europe or the United States historically, or a developing region currently or in the future). It can also depict the status of regions or countries at different levels of economic development (poor countries to the left, rich to the right). In addition to investments in environmental protection, local-scale impacts can be reduced by employing the global economy to outsource threat-producing activities. Source: Image prepared by authors.

wide.[33] The cotton worn throughout the world demonstrates how the water demands of a globalized consumer economy can yield one of the world's most catastrophic environmental disasters: the death of the Aral Sea.

As with the many other impair-then-repair examples, these far-reaching impacts are nothing new. Silver extraction by the Spanish in Peru over the course of five hundred years has required the continuous import and then release of enormous quantities of mercury (100,000 tons in total from two European mines in Slovenia and Spain).[34] The impacts of mercury extraction in all three countries over the *longue durée* illustrate the capacity of globalization to reconfigure the geography of water-resource systems.

Based on these many documented narratives, we present here a multistage typology of river development as a time series of human-water interactions in a particular river basin or region. Alternatively, the typology can be regarded as a contemporary snapshot of rivers distributed along a global gradient of impairment. Examples from Europe and the United States are emphasized, given their well-documented histories across each of the stages.

Stage 1 (O – A; Figure 1) rivers are basically intact but also show the early impact of humans. Rivers provide basic goods (such as food) and services (such as floodplain agriculture, river transport), and societies adapt well to their dynamics (as had the ancient Egyptians, whose culture, sustenance, and economies were wellmatched to the rise and fall of the Nile's annual floods).[35] Both water use and pollution from physiological wastes (organic carbon and nutrients in human and livestock excrement) are more or less directly proportional to population. Deterioration of water quality is mainly from bacterial pathogens and lowered dissolved oxygen, conditions arising from the release of domestic and agricultural waste that overwhelms the dilution and self-purification capacity of receiving waters.

In traditional or early development cultures, Stage 1 impacts accumulate gradually over decades or centuries to reveal the fingerprint of human activity. A good example is the physical disruption of small-stream diversions for fish and mill ponds in Europe starting in the early Middle Ages. The mills ultimately proliferated to the point that peasants had rarely to travel more than 5 kilometers to process their products.[36] Records of sedimentation in European lake cores also show medieval deforestation increasing natural soil erosion and sediment transfers by factors of ten to one hundred.[37] Early mining and metal use in Western Europe produced the earliest evidence of environmental pollution as recorded in sediments and peat deposits. In Spain's Rio Tinto, the first Early Bronze Age gold mines (c. 2500 BC) increased lead, mercury, and gold levels on river particles by one-hundredfold over natural background levels.[38]

Some Stage 1 systems can completely modify land and waterscapes for human benefit without necessarily impairing their function. This is true for traditional Asian rice cultivation and was the case for the irrigation systems of Egypt until the mid-twentieth century. In Stage 1, major engineering works are absent or very limited and there is no real impact on aquatic life forms or fish diversity. Nevertheless, these early technical innovations could be truly impressive and greatly outlast the societies that commissioned them, as with the Cloaca Maxima, a stone-lined canal constructed c. 600 BC that served as the main sewer in Rome until the twentieth century.[39]

Before 1800, Stage 1 could easily be found on all continents, even in heavily populated Europe where high levels of impact were mainly concentrated downstream of major cities.[40] Today, Stage 1 can be found wherever large river systems are outside the reach of significant numbers of humans and thus nearly pristine (for example, in Amazonia, Eastern Siberia, Alaska, Northern Canada, New Guinea, and Patagonia). Yet the byproducts of modern society extend to the far corners of the Earth (via transboundary air pollution, for instance), and virtually no location is without evidence of the Anthropocene.[41]

Stage 2 (A – B; Figure 1) shows accelerated environmental degradation, typically linked to urbanization, with pollution increasing faster than population.[42] It arises when traditional recycling systems are abandoned in favor of those that use and release large quantities of imported materials, as when manufactured fertilizers replace domestic wastes in agriculture that then leach into rivers.[43] In Western Europe, urban waste collection began in the mid-1800s after the London epidemics and was generally available after 1875 in some big cities (Paris, Berlin).[44] Best practices for sewage treatment then were rudimentary and emphasized land disposal of wastes collected from cities. In the suburbs, individual waste disposal was the general rule, leading to frequent leaks and major degradation of groundwaters (those within and around Paris were still loaded with excessive nitrates in 1900). Land disposal lasted nearly one hundred years for Berlin. During this period, sewage connections expanded at faster rates than did treatment capacities, thus creating "sacrificed" rivers whose natural dilution and assimilation capacities were overwhelmed.[45]

Impacts of Stage 2 management strategies were largely unknown before the 1950s and, even if demonstrated (such as when oxygen deficits were discovered in the Ohio River in the 1920s), they were accepted as a necessary price to pay for development. After World War II, proliferation of wastewater treatment plants gradually outpaced the rise in sewage collection, which yielded some improvement. Maximum degradation (B; Figure 1) was reached soon after World War II and associated with the loss of most fish downstream of Brussels, Milan, and Paris, with only a few resistant and invasive species surviving.[46] Health impacts were generally left unaddressed, as were ecological consequences.

The end of Stage 2 (B; Figure 1) represents a "moment of truth" for environmental stewardship and a turning point between tolerating persistent impairment and commencing rehabilitation. Even with active investment in remediation, a plateau can persist (B – C; Figure 1), reflecting the collective inertia of impaired biological and physical processes.[47] Depending on the particular issue at hand, Stage 3 may last for decades, as was the case for the organic pollution and fecal contamination across Europe – most clearly exemplified by the Seine downstream of Paris (which was contaminated from 1880 to 1990) or the Zenne River in Brussels (which was totally devoid of oxygen from 1900 to 2005).[48] Chloride pollution in the Rhine persists, with France now facing a severe salinity problem on its major Alsace aquifer that could last for more than three hundred years in some places.[49] In the United States, remediation of toxic and even radioactive chemical pollution is addressed at several Superfund sites,[50] yet legacies can affect densely settled areas and aquatic environments for decades or more.[51] Impair-then-repair is a long and costly process.

The alternative represented by Stage 4 (B – D; Figure 1) sees the fruits of a proactive response to environmental degradation even in light of continued economic growth. Environmental laws are assertively formulated and enforced. A gradual improvement in water quality takes place, typically beginning with reductions in organic and bacterial pollution that increase oxygen levels, then control of eutrophication, acidification, metal contamination, and organic micropollutants. Sewage and industrial treatment outpaces the mere collection and transport of waste streams, and per-capita water use and consumption of pollution-generating products begin to stabilize and decline.

Stage 4 rehabilitation can be rapid in light of aggressive regulation. Signs of environmental recovery emerged not long after the ban of DDT and PCBs, two organochlorinated products synthesized before World War II and largely used in the United States and Western Europe from 1945 to 1970. Sediment cores taken from the Mississippi Delta in the mid-1980s revealed a sharp decline in these chemicals and in lead particulate – a clear indication of how political willpower, financial investment, and technology can be combined to create environmental benefits.[52]

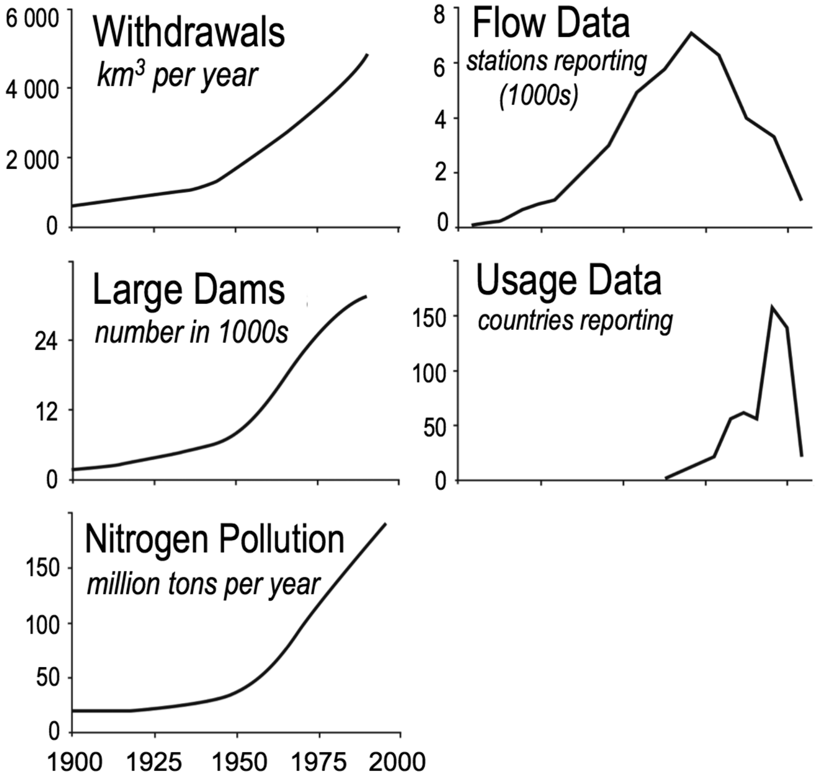
Rehabilitation in Stage 4 also reflects the broad currents of economic development and technology. In the Seine, for example, metal contamination began to ease in the 1960s, a full two decades before any EU regulations. This can be attributed to industrial efficiency gains such as metal recycling in plating industries and to the economically motivated relocation of most pollution-producing industries outside of Paris in the 1950s, then outside of the Seine basin in the 1970s, and finally outside the country.[53] Environmental improvements are also linked to major political change. After the collapse of the Berlin Wall, water quality in the Elbe River improved markedly due to the closure of many industries.[54] More broadly, global redistribution of manufacturing processes – many generating dangerous byproducts like toxins and heavy metals – represents an opportunity to offload environmental threats from the developed countries to rapidly developing parts of the world like China and India.

Stage 5 (D – E; Figure 1) represents rehabilitation and sustained recovery when river waters are managed to maintain the previously won gains in environmental integrity. River systems are purposefully engineered to sustain an array of benefits to society and aquatic biota alike, recognizing the legitimate needs of both humans and nature for water and promoting well-designed co-use strategies. Even among the success stories, rehabilitation can last one to two generations and bear extreme costs. In the Yamato-gawa River draining Osaka, Japan it took forty years and $80 billion to rehabilitate this relatively modest basin (one hundred times smaller than the Mississippi).[55] It took twenty-five years to overcome the organic pollution problem in the Rhine with a total expenditure of $65 billion, or $50 per capita per year.[56] Legacy effects, including loss of habitat, biodiversity, and the integrity of surrounding landscapes, mean that the system may never return to its predevelopment state.[57] Singapore is a rare example of a development trajectory moving directly from Stage 1 to Stage 5 without major impairment. Another example is Switzerland, which addressed eutrophication of its water bodies in 1985 through early detergent bans. Swiss rivers display the benefits of taking a proactive stance, as they never reached the level of degradation observed in other European rivers.

Some rehabilitation strategies are both conceptually simple and cost-effective. In the Danube River Project between Vienna and Bratislava, restoration focuses on reconnecting the riparian forest to the river.[58] The aim is to re-establish hydraulic links between the river, groundwaters, and lowland forests that constitute critical habitat and nursery grounds for aquatic life as well as natural flood and water quality protection. For a relatively modest "reconnection fee" of approximately $100 million annually, this large and economically essential river can still be navigated by huge barges and boats crossing Europe from the Black to the North Sea and yet limit the negative environmental impacts historically linked to human use.[59] These reestablished hydraulic links and "green infrastructure" strategies are now recognized as standard procedure by a new generation of environmental engineers, who often train at the same schools that earlier created "hard-path" engineering in the form of massive dams, locks, and river channelization schemes throughout the twentieth century.

What might the future hold? Worldwide, it is safe to say that rivers have evolved much faster in the past fifty years than in the previous five thousand due to the rapid rise in human use and abuse of this strategic resource. The countless human decisions made each day about water that are executed at the local (and indeed at the individual business or household) level should not obscure the fact that their cumulative impact gives rise to a global-scale syndrome.[60] Figure 2 shows a century-scale trajectory of some key variables, each with well-known and negative impacts on rivers.[61] Humans have stumbled into many of the same pitfalls throughout history, and we see little reason to expect that the social, technological, and economic inertia represented by these curves will be reversed quickly or easily. The figure also shows that our willingness or capacity to monitor the changing state of affairs is completely out of step with the realities of intensifying water stress and concerns about water as the "oil of the twenty-first century." Thus we see a long future for impair-then-repair stewardship.

Figure 2
Human Use and Pressures on Freshwater Resources and Ecosystems



Century-scale inertia on climate progress can be seen in the graphs on the left. At the same time, available monitoring data at UN-designated repositories (right) are in severe decline due to funding cutbacks, commercialization, intellectual property rights restrictions, and delays in data analysis. Source: Data from David L. Strayer and David Dudgeon, "Freshwater Biodiversity Conservation: Recent Progress and Future Challenges," *Journal of the North American Benthological Society* 29 (2010): 344–358, doi:10.1899/08-171.1; Global Runoff Data Centre (GRDC), *Global Runoff Data Base – Statistics 2012*, http://www.bafg.de/GRDC/EN/01_grdc/13_dtbse/db_stat.html?nn=762018; and Food and Agriculture Organization of the United Nations (FAO), Aquastat, http://www.fao.org/nr/water/aquastat/main/index.stm.

Some of the impetus for this management approach is undoubtedly rooted in the economic incentives perceived by an industrial water sector slated to gross more than $1 trillion in annual revenues over the next ten years.[62] In the case of a much-cited water-sector blueprint for the future, there is no single mention of the word *biodiversity* and only one formal use of the phrase *ecosystem services*; other high-profile syntheses advance similarly anthropocentric perspectives.[63] We see this human-nature dichotomy as artificial and as a limit to our ability to meaningfully define future risks to freshwater. Not surprisingly, some of the very threats to aquatic biodiversity – combined effects of poor land management, overuse of water, or even our inability to accurately assess nonpoint pollution[64] – pose a high risk to human water systems. But threats to one do not universally mean threats to the other, as is the case with dams and reservoirs, which negatively impact aquatic biodiversity by disrupting essential flow and temperature regimes and blocking fish migration, yet provide important benefits to society in terms of water supply and flood control. Artificial reservoirs have a pandemic and negative impact on aquatic ecosystems, but their benefits to human water security now total in the trillions of USD. This contrast sets the stage for a major decision point for humankind as it contemplates the nature of sustainable development.[65]

As a result of the unending quest for reliable water supplies – whether pursued though engineered solutions or more haphazardly in the course of development – we run the risk of systematically destroying the free natural subsidies conveyed by well-functioning ecosystems.[66] Losses can be irretrievable, like extinct species, or costly to replace, like natural floodplains that are destroyed and then replaced by massive flood-control infrastructure. This need not be the case, as ecological engineering and "green" alternatives, which emphasize preservation and prevention, are maturing.[67] Yet only $10 billion is spent annually on all protected landscapes and watersheds: a mere 2 percent of current water-sector income.[68]

The necessary socioeconomic and policy conditions for river restoration have taken more than a century to coalesce across the West during a time when scientific and technical know-how was still very limited. We understand far more today about how rivers function and how they can be protected. So in some sense, there is no excuse for inaction. While we can cite individual success stories, we see little evidence of a broad-scale adoption of integrated water resource management, the commonly accepted gold standard for environmental protection of water resources.[69] It will take time, money, water-literacy, and proactive problem avoidance to effect meaningful change.[70] Clear lines of communication between scientists and policy-makers are also essential (see Katharine Jacobs and Lester Snow's essay in this volume).[71]

The world's rapidly emerging economies provide a unique opportunity space for instituting more sustainable, cost-effective, and prevention-oriented approaches to water development, but new market dynamics and incentives harmonized with natural variability in the hydrologic cycle will be necessary (see Terry Anderson in this volume). Developing economies need not repeat the costly mistakes made by rich countries in the past and be relegated to a perpetual reliance on capital- and debt-intensive solutions. Exporting the developed world's impair-then-repair model thus has serious implications for human rights and environmental justice – especially among the poor, who are increasingly impacted by fundamental changes to the world's hydrosystems. Given the emergence of a global middle class in the next two decades, the window of opportunity for meaningful change will be short.[72] The need for innovative solutions, particularly when densely populated regions face absolute scarcity, has never been clearer.

We do not take issue with the countless well-recognized benefits that water infrastructure and engineering systems convey to society, but at some point the world must ask itself: *At what price?* And: *Are there workable alternatives to the current approaches?* Our collective capacity to design sustainable solutions for the future (like those proposed by Richard Luthy and David Sedlak in this issue) that protect valuable water resources in the context of growing environmental and climate stress, dwindling energy resources, and (quite likely) shrinking investment capital, remains an open question. Indeed, when it comes to breaking with the deep historical roots that bind us to the status quo, we face more a crisis of confidence or willpower than a lack of sensible ecosystem-based alternatives or the scientific and technical means to bring them to fruition.

In conclusion, we issue a call-to-research: to systematically test our hypothesis that the impair-then-repair model has guided human-water interactions throughout the Anthropocene and has in the process accumulated globally significant century-scale impacts. This challenge requires a fundamentally new type of collaboration, which must simultaneously explore the biogeophysical, social, and economic forces that shape an increasingly human-dominated global hydrologic system. It will require dissolving the distinctions between the natural sciences and the humanities and between the traditions of scholarship that emphasize quantitative information and those that emphasize narrative approaches. We see equal value in assessing information derived from numerical models and engineering analyses as from indigenous knowledge, cultural anthropology, and historical records. If our hypothesis holds, it will represent an important step toward raising awareness that the impacts of water management easily reverberate far beyond the local domain and ultimately generate global-scale impacts and multigenerational legacies. We see such self-awareness as a necessary precursor to reversing the many deeply entrenched habits that continue to undermine an essential strategic resource.

ENDNOTES

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