The Pace of Human-induced Change in Large Rivers: Stresses, Resilience and Vulnerability to Extreme Events

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The world's great rivers are threatened by a range of anthropogenic stresses - climate change being just one – that decrease resilience and increase vulnerability to extreme events. Future governance must recognise both the rate of change associated with these stressors, and the potential for extreme events to transgress sustainability thresholds.

The World's changing large rivers

The World's large rivers are changing fast. As home to over 3 billion people, and harbouring some of the planet's most diverse ecosystems, large rivers are hot spots of resources, agriculture, trade and energy production. Many large rivers flow through developing nations where much of the population is vulnerable to environmental and ecological stresses. Especially in areas near the poverty boundary, both subsistence and cash elements of the economy tend to rely disproportionately on the ecosystem services associated with the water and nutrient fluxes delivered by large rivers to floodplains and deltas. However, the demands posed by burgeoning population growth are placing unprecedented stresses on the world's great rivers[1]; without urgent interventions, some face ecosystem collapse in the coming decades[2]. These anthropogenic stressors operate on a range of timescales, and we argue that their effects potentially amplify the risks posed by extreme climate events[3], thereby increasing the likelihood of key resilience thresholds being crossed. Moreover, the strong link between ecosystem services and livelihoods, associated with the unifying nexus of water, energy and food security[4], means that, along many large rivers such as the Ganges, Mekong and Nile, these stressors are inhibiting efforts to meet United Nations Sustainable Development Goals (SDGs) by 2030.

Rivers respond to disturbances, such as changes in water or sediment flux, through self-adjusting processes of erosion and sedimentation. These responses typically involve feedbacks that impart some resilience, allowing rivers to absorb a degree of change. Climate change, as manifested through a complex global pattern of future floods and droughts[5], presents a background stress that is increasing through time (Figure 1A). However, river resilience can also be lowered due to a range of other anthropogenic stressors that may present slow ongoing changes, or extreme events that operate over short timescales (Figure 1A; labels E1 and E2, Figure 1B). For example, the ways in which river channels are engineered[6] may cause increased extremes in floods and droughts. This reduction in resilience makes river systems more vulnerable to the increasing magnitude and frequency of floods/droughts, potentially crossing the tipping point for system resilience (Figure 1A). Such changes can have immediate consequences, expressed through river responses such as hazardous river bank erosion, which damages infrastructure and threatens lives, but may also impose a legacy of change that persists for centuries. For example, eroded sediment can, over time, be transported downstream where it accumulates, reducing the capacity of the channel to convey flows and increasing flood risk.

Timescales of threats & the effects of extreme events

The array of anthropogenic stressors, beyond climate change, that threaten big rivers[1] differ in both the rapidity of their effects (Figure 1B) and the extent to which they leave a legacy as river responses to disturbance translate up and/or downstream.

Changing river flows also modulate the movement of sediment to floodplains and deltas. Timescales of effects for climate-related changes in river flows, and their extremes, range from decades to hundreds of years. In addition, land use changes, such as deforestation or reforestation of catchment hillslopes and floodplains, can modify the quantity of water and sediment entering rivers through soil and bank erosion, over timescales of decades to centuries (Figure 1B).

The construction of mega-dams, for hydropower, flood control, irrigation and water supply, is booming, with some 3700 dams planned or under construction that would, if fully implemented, decrease the number of remaining free-flowing rivers by 21%[7] . Dams trap sediment, alter flow regimes, trigger river bed incision and bank instability and, in tropical regions, cause substantial release of the potent greenhouse gas methane[1], due to vegetation decay. Such effects are compounded by water diversions and interlinking of rivers within, and between, river basins[1]. Such schemes take decades to plan and construct (Figure 1B), but once built, their consequences on riverine ecology (e.g. fish and mammal migration once a reservoir begins to fill) can be rapid (months-years). Where the world's great rivers enter the oceans, they form deltas that are home to over half a billion people, often in sprawling megacities, but support a rich and essential agriculture. These deltas are not only prone to longer term sea-level rise linked to greenhouse-gas induced warming, but also to stressors such as sediment starvation due to upstream sediment trapping and extraction, and subsidence that is often enhanced by groundwater extraction[8] that act on shorter timescales (several years-decade; Figure 1B).

Other anthropogenic stressors act on even shorter timescales of just months to years (Figure 1B). Sand and gravel mining are destroying river beds across the globe as the demand for concrete and silica escalates[9], and have been linked to severe ecosystem degradation, illegal mining/organised crime and social injustice. The introduction of non-native species – such as fish, invertebrates and vegetation - can have almost immediate ecological effects and economic consequences, potentially compounded by river interlinking. Studies of the River Rhine reveal dispersal rates for some non-native aquatic species of up to 461 km per year, whilst costs to combat the spread of Asian Carp within the Mississippi River and US Great Lakes have been speculated as up to $1.5 billion USD over the next decade. Pollution, from industrial, domestic and agricultural sources, may pose a near instantaneous threat. Alarming new research has revealed the extent of riverine antibiotic pollution[10], introduced into watercourses through human and animal waste, and leaks from wastewater treatment plants and chemical factories. Such potent antibiotic pollution is present worldwide, and aids development of antimicrobial resistance[10].

All of these anthropogenically-induced stresses must be viewed in the light of shocks generated by political, social and economic extremes. The current COVID-19 pandemic is already influencing regulatory frameworks: the US government has eased its enforcement of pollution monitoring, enabling polluters to avoid penalties if they argue violations are related to the COVID-19 crisis[11]. Political and societal shocks, such as that imposed by the first Gulf war, had major consequences for river pollution and water resources in the Tigris-Euphrates river basin, a situation compounded by upstream damming in Turkey.

The Mekong River: a river under extreme stress

Identified by the IPCC as one of the three most vulnerable deltas in the world, the Mekong is home to 60 million people, most of whom are highly reliant on agriculture for their livelihoods, and is an exemplar of the challenges faced by many large rivers (Figure 2). In particular, the processes contributing to delta drowning and salinity intrusion are complex, multi-faceted, and rapid, and a suite of more pressing anthropogenic stressors, besides climate change, are those that demand immediate attention. Specifically, land subsidence, caused by groundwater pumping, has in the last 25 years exceeded rates of greenhouse gas-driven sea-level rise by an order of magnitude[12]. Indeed, projections[13] indicate that, if unmitigated, this process alone will submerge the delta below current sea-level by the end of the 21st century (Figure 2B). Groundwater-induced subsidence has also led to arsenic pollution[12], with arsenic mobility further enhanced by seasonal wetting/drying and saltwater intrusion.

A further key stressor is sediment starvation as a result of declining river sediment loads caused by: (i) the changing frequency of extreme events (tropical cyclones; Figure 2 main panel)[14]; (ii) sediment trapping behind dams (Figure 2C) [1,2,15], and (iii) large-scale mining of river sand (Figure 2, main panel)[16]. The combined impacts are so large that river bed-levels have lowered by *c.* 2 to 3m in only the last decade, destabilising river banks[16] and enabling saltwater incursion, at high tide, to propagate some 10km further inland, posing a severe threat to agricultural production. The near-instantaneous impact of sediment starvation is thus an order of magnitude more significant as a driver of saline intrusion than ongoing, climate-driven, sea-level rise.

The contribution of climate-change to the processes of delta 'drowning' and saline water intrusion is thus best viewed as a slow onset hazard that progressively increases system risk

(Figure 1A). Meanwhile, multiple other anthropogenic stressors (Figure 2) reduce the resilience threshold of the river and delta, increasing the likelihood of extreme events crossing this critical state (T1, Figure 1A). It is thus imperative to consider the timescale and magnitude of these stressors that, when combined with long-term, progressive, reductions in resilience, threaten to force the Mekong delta into a new state, as reflected in rapid (~1M people in the last decade) rates of human migration from the region. These challenges are exemplified currently by severe drought in the delta region, with record low water levels. This drought is undoubtedly partly driven by below average levels of precipitation in the Lower Mekong Basin, but it has also been speculated that extreme levels of water storage behind dams in the Upper Basin in China have amplified the impacts[17]. One estimate suggests that the drought has caused the fish catch from the Tonlé Sap Lake in Cambodia, on which 3 million people depend for their main source of protein, to decline by 90%.

The challenges faced by the Mekong River, a transboundary river crossing through six countries (Figure 2), and its delta are further compounded by issues of governance, in particular a lack of international and inter-provincial coordination over water use. Decision-making is complicated further because of diverse interests amongst, and between, provinces as to which sectors and farming practices to pursue. This includes competition for water between shrimp farming and agriculture, diverse rice farming practices, and a lack of communication between policy-making and community levels, resulting in frequent implementation problems, particularly concerning drought and flood policies.

What is needed?

Consideration of anthropogenic stressors and extreme events tells us three things about the future of the world's large rivers.

First, the timescales over which stressors exert an effect must be recognised and incorporated into management responses. Although climate change poses considerable risks by changing the global patterns and scale of flood and drought, other stressors act far more quickly, and pose a more immediate threat to the integrity of many riverine ecosystems.

Secondly, although such stressors can act in isolation, they are frequently compounded, making it more likely that resilience thresholds are approached or crossed. In particular, the probability of thresholds being exceeded by extreme events is significantly enhanced when resilience is reduced by compound stressors (Figure 1A).

Lastly, the changes to some large rivers as a result of non-climate related pressures are now so great and so rapid that there is a clear danger of imminent, and irreparable, environmental change. Ironically, this affords some grounds for optimism. Just as river response to some anthropogenic disturbances is rapid, when effective interventions are made, a return to a safer trajectory can be commensurately swift. For example, a range of measures along the Chang Jiang (Yangtze) River, including dredging plastic, relocating factories, and banning waste discharge and single-use plastic goods, is having major effects[18], potentially reducing plastics pollution into the oceans.

Any strategy to enhance resilience, and safeguard the critical services that large rivers provide, must recognise the specific characteristics and challenges posed in their management. Often - but not always - these rivers flow through multiple jurisdictions. Sometimes - but not always – they are in developing nations. The different time lags in river response, and their legacy over individual and generational timespans, demand integrated governance as an essential pre-requisite in any effort to sustain rivers.

How is this to be achieved? Effective international institutions must provide a channel for scientific advice, and help support and enable the capability and capacity of local, national and transnational river management organisations. Centrally, river governance (Figure 1) must include local stakeholders, and incorporate issues of social equity, inclusivity and gender. The 2011 Vienna Declaration on the 'Status and Future of the World's Large Rivers' called for such a UNESCO-led initiative, but thus far effective progress has been slow. Much as the IPCC was created by the UN to assess the state of knowledge on climate change, its social and economic impacts and potential response strategies, it is overdue that a similar *UN International Panel for the Worlds Large Rivers* (IPWLR), is established and charged with a similar holistic brief. Indeed, the effectiveness of IPCC recommendations will be limited for billions of people living within large-river basins unless the presence, timescales of effect and nature of other anthropogenic stressors and extremes are incorporated into policy. Creative financial instruments are also essential to deliver the investment necessary to fund restoration, protection and management. Carbon credits have, not without controversy, created incentives for polluters to reduce or offset their carbon emissions. Analogous schemes could, over time, create a significant market to fund river restoration and protection efforts worldwide.

Some of the world's largest and most productive rivers are now at a critical juncture. It is our choice, and entirely within our control, as to whether sustainable futures - and the essential riverine contributions to achieving UN Sustainable Development Goals - will be attained or foregone. The effects of these stressors, and critically their timescales, must be incorporated into planning. Progress towards environmental sustainability and food security within these regions hinges on our response over the next decade. If we fail to recognise the timescales of change, incorporate the effects of extremes and implement an appropriate international response, in 50 years' time our despondent descendants will be baffled as to why.

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FIGURES

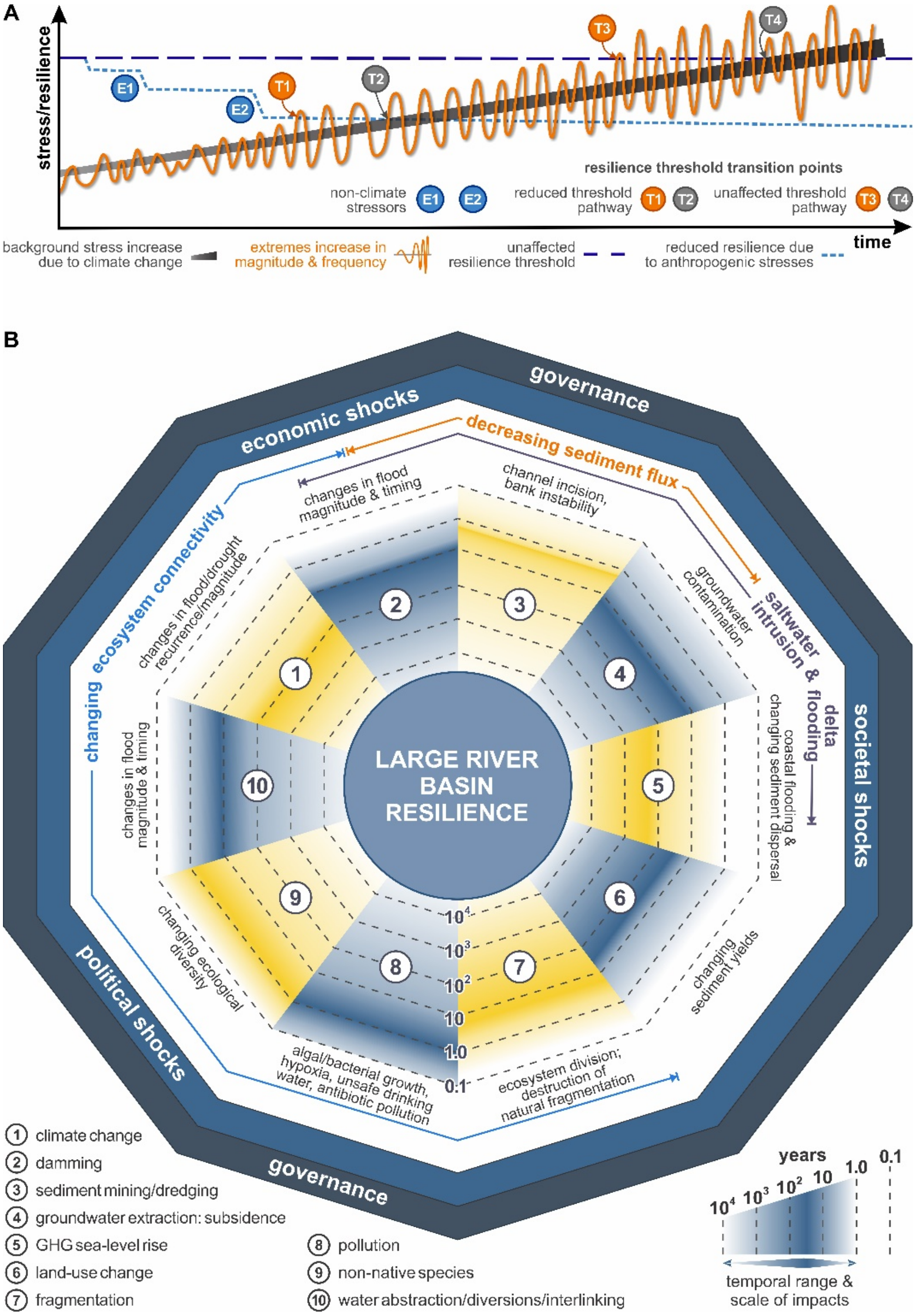

Figure 1. Anthropogenic stresses on the world's large rivers

A) Schematic showing influence of progressive climate change and decreasing resilience due to other stressors (E1 and E2, such as damming and sediment mining) that may cause resilience thresholds to be crossed under the presence of increasing extreme events (T1 and T3), as well as the slower background stress of climate change (T2 and T4).

B) Anthropogenic stresses (numbered), showing indicative timescales of effect (dotted lines, in years) and some of their principal consequences. Text with arrows denotes some effects of compound stressors. All stressors are affected by societal, economic and political shocks, and must be managed within a framework of inclusive governance.

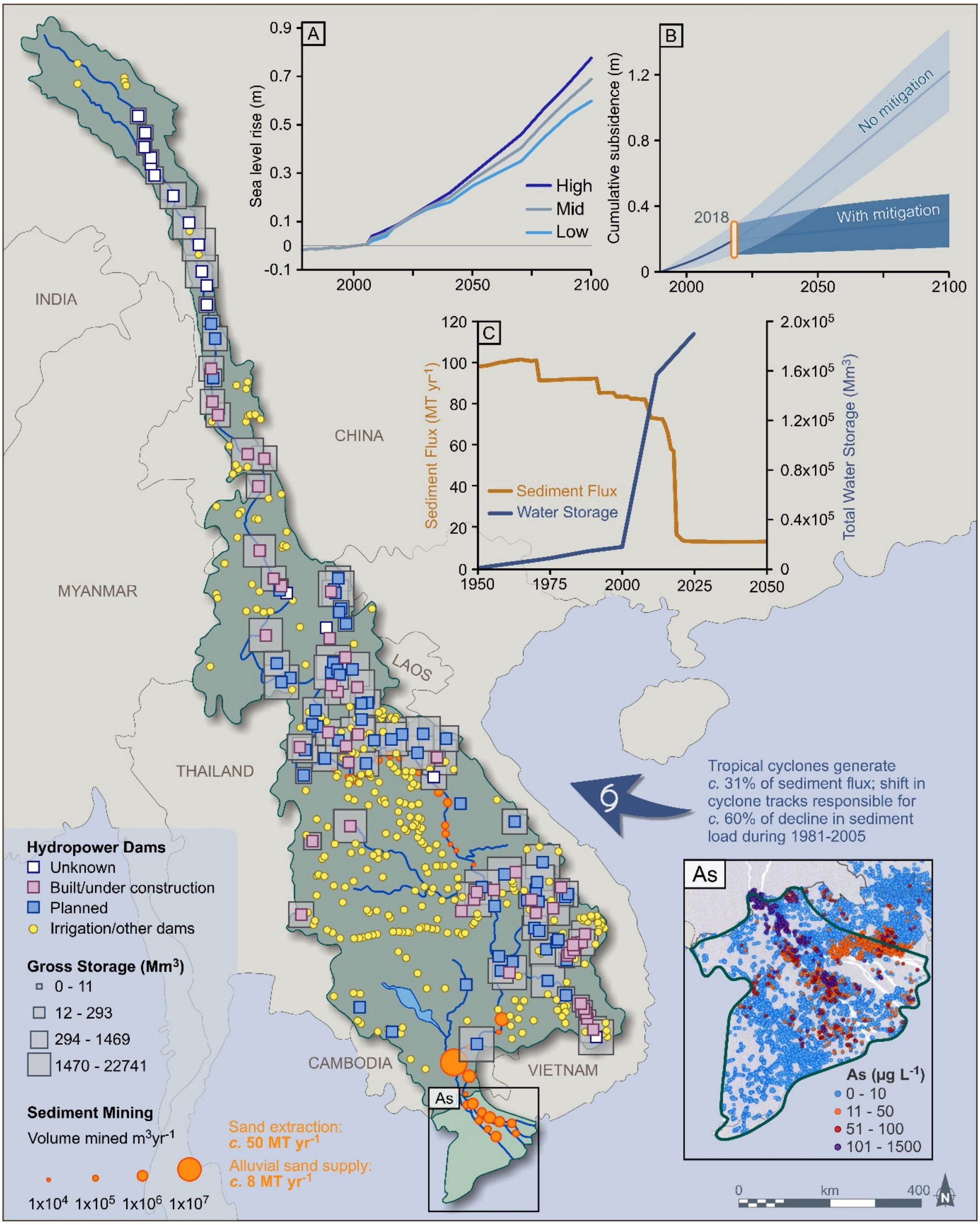

Figure 2. Anthropogenic stresses and extreme rates of change in the Mekong River Basin

The Mekong Delta is at risk of drowning in the coming decades due to a combination of climate-driven sea-level rise[19] (A), anthropogenic subsidence[13] (B) and sediment starvation[2,15] (C), which prevents sediment deposition offsetting rising sea-level. Sediment starvation is driven by shifts in climate extremes (tropical cyclone tracks[14], main panel) along with a combination of sediment trapping[2,15] behind hydropower dams (squares, main panel and inset C for timeline) and intense sand mining[16,20] (orange circles, main panel). Groundwater pumping is also linked to arsenic contamination in the delta's aquifers[12] (see inset As; 10µg L^{-1} is the World Health Organisation drinking water standard[12]).