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A green-gray path to global water security and sustainable infrastructure

Charles J. Vörösmarty [a,b,*], Ben Stewart-Koster [c], Pamela A. Green [a], Edward L. Boone [d], Martina Flörke [e], Günther Fischer [f], David A. Wiberg [g], Stuart E. Bunn [c], Anik Bhaduri [c], Peter B. McIntyre [h], Claudia Sadoff [i], Hongxing Liu [j], David Stifel [g,j]

[a] *Advanced Science Research Center at the Graduate Center, CUNY, New York, NY 10031, USA*
[b] *Department of Civil Engineering, The City College of New York, New York, NY 10031, USA*
[c] *Australian Rivers Institute, Griffith University, Nathan, Queensland 4111, Australia*
[d] *Department of Statistical Sciences and Operations Research, Virginia Commonwealth University, Richmond, VA 23284, USA*
[e] *Institute of Engineering Hydrology and Water Resources Management, Ruhr University Bochum, 44801 Bochum, Germany*
[f] *International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria*
[g] *International Water Management Institute, Colombo, Sri Lanka*
[h] *Department of Natural Resources, Cornell University, Ithaca, NY 14853, USA*
[i] *CGIAR, F-34394 Montpellier, France*
[j] *Department of Economics, Lafayette College, Easton, PA 18042, USA*

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ABSTRACT

Sustainable development demands reliable water resources, yet traditional water management has broadly failed to avoid environmental degradation and contain infrastructure costs. We explore the global-scale feasibility of combining natural capital with engineering-based (green-gray) approaches to meet water security threats over the 21st century. Threats to water resource systems are projected to rise throughout this period, together with a significant expansion in engineering deployments and progressive loss of natural capital. In many parts of the world, strong path dependencies are projected to arise from the legacy of prior environmental degradation that constrains future water management to a heavy reliance on engineering-based approaches. Elsewhere, retaining existing stocks of natural capital creates opportunities to employ blended green-gray water infrastructure. By 2050, annual engineering expenditures are projected to triple to $2.3 trillion, invested mainly in developing economies. In contrast, preserving natural capital for threat suppression represents a potential $3.0 trillion in avoided replacement costs by mid-century. Society pays a premium whenever these nature-based assets are lost, as the engineering costs necessary to achieve an equivalent level of threat management are, on average, twice as expensive. Countries projected to rapidly expand their engineering investments while losing natural capital will be most constrained in realizing green-gray water management. The situation is expected to be most restrictive across the developing world, where the economic, technical, and governance capacities to overcome such challenges remain limited. Our results demonstrate that policies that support blended green-gray approaches offer a pathway to future global water security but will require a strategic commitment to preserving natural capital. Absent such stewardship, the costs of water resource infrastructure and services will likely rise substantially and frustrate efforts to attain universal and sustainable water security.

1. Introduction

Recent studies on human water security reveal globally significant threats from population and economic growth, mismanaged water use, climate extremes and a general failure to effectively protect landscapes and inland waterways (Vörösmarty et al., 2010; Chaplin-Kramer et al., 2019; Harrison et al., 2016; Gleick, 2018; Tickner et al., 2020; Díaz et al., 2019). The prevailing response to these challenges has been the deployment of traditional engineering, featuring centralized water treatment and distribution systems, and prolific, often massive river impoundments and flood protection infrastructure (McKinsey & Company, 2009; Zarfl et al., 2015; Rodriguez et al., 2012). Roughly 85% of humankind relies on freshwater source areas that are moderately to severely threatened as a byproduct of development, and engineered

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* Corresponding author at: Advanced Science Research Center at the Graduate Center and The City College of New York, New York, NY 10031, USA.
E-mail address: cvorosmarty@gc.cuny.edu (C.J. Vörösmarty).

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solutions are routinely applied to substantially reduce the attendant risks (Vörösmarty et al., 2010; Green et al., 2015). Such "gray" engineering is therefore essential in delivering and improving upon the quality of water used by society (HLPW, 2018; OECD, 2012), and underpins an economic sector with annual gross revenues approaching \$0.8 trillion (Ashley and Cashman, 2006; McKinsey & Company, 2009). At the same time, this infrastructure is costly to install and maintain (ASCE, 2011; Foster and Briceño-Garmendia, 2010) and outstrips the technical and institutional capacity of many developing nations (HLPW, 2018; Foster and Briceño-Garmendia, 2010; Wehn de Motalvo and Alaerts, 2013). Persistent shortfalls in funding for traditionally-engineered systems (Rodriguez et al., 2012; ASCE, 2011) and the negative and long-lived impacts they often present to the environment (Vörösmarty et al., 2010; Zarfl et al., 2015; Palmer et al., 2015) illustrate the need for alternatives, like those associated with natural capital (Chaplin-Kramer et al., 2019; Harrison et al., 2016; Palmer et al., 2015; Costanza et al., 2017).

Protected watersheds and aquatic ecosystems are recognized as cost-effective means to improve water security by combining or "blending" nature-based infrastructure with engineered systems to provide services like safe drinking water, waste processing and dilution, erosion control, and flood risk reduction (Palmer et al., 2015; Costanza et al., 2017; McDonald et al., 2016; Huang et al., 2020). Nevertheless, such nature-based solutions have yet to take root more broadly due in part to the absence of comparative economic evaluations (HLPW, 2018; Palmer et al., 2015; Costanza et al., 2017; McDonald et al., 2016; World Bank, 2015), questions regarding their reliability (Muller et al., 2015), and a shortage of technical know-how (HLPW, 2018; Foster and Briceño-Garmendia, 2010; Wehn de Motalvo and Alaerts, 2013; World Bank, 2015). Additionally, the persistent downward trends in global environmental assets, along with underfunded commitments to their protection and rehabilitation, limit the potential contributions of ecosystem services to human water supply (McDonald et al., 2016; McCarthy et al., 2012; Venter et al., 2016; Watson et al., 2014). Given the globally significant public goods and services offered by environmental systems (Costanza et al., 2014; 2016), their diminishment is likely to constrain future economic growth.

Beyond the protection of natural capital, several important calls-to-action on expanding the use of natural systems in water management have materialized across the highest levels of government, business, the multi-lateral banks, and civil society (Browder et al., 2019; HLPW, 2018; WWAP, 2018; OECD, 2019). Designing blended ecosystem and engineered-based management systems could be particularly valuable in regions that retain significant endowments of natural capital that could provide water to sizable numbers of people, but this will require strategic, large-scale stewardship of ecosystem services in terms of both their protection and in many cases rehabilitation (Green et al., 2015; Harrison et al., 2016). Achieving universal water security under the Sustainable Development Goals (SDGs) is motivating serious consideration of such strategies (HLPW, 2018) but requires a coupled framework to assess the global potential for combining green-gray infrastructures.

Here we develop a combined biogeophysical, engineering, and economic framework to assess the global potential for using natural capital (*NC*) and traditional engineering (*TE*) to mitigate contemporary and future threats to human water security. After describing the modeling framework, we explore the mechanisms by which *TE* and *NC* contain contemporary water security threats. We then present global and continental-scale geographies of projected threats to human water security under future scenarios of population growth, economic development, resource use, and climate change. Next, we project and map society's expected response to these growing threats in terms of deploying *TE* and retaining *NC* assets. We then evaluate the contributions of *TE* and *NC* to threat management should present-day approaches to water management persist over the remainder of the century. These contributions are interpreted in terms of opportunities for combining *TE* and *NC* as policy levers in future threat management. We go on to provide the first global estimate of the economic value of *TE* and *NC* in jointly reducing threats to human water security. This portion of the analysis provides an evaluation of replacement costs for services provided by *NC*, enabling us to explore future policy options, identify places where nature-based solutions are most promising, and rank the readiness of individual regions to confront their water security challenges. We also evaluate the relative penalty paid for replacing any lost natural capital with engineering. Throughout, we consider a multi-decade timespan to assess the durability of benefits associated with engineered and nature-based strategies for sustainable water resource development.

2. Methods

In the context of human water security (*HWS*), we define natural capital as a type of infrastructure that constitutes a broad category of physical entities (e.g., upland watersheds, floodplains, lakes, rivers), collectively representing terrestrial and aquatic ecosystems that are intimately connected to the hydrologic cycle. This nature-based infrastructure is functionally analogous to traditionally engineered/built capital infrastructure (e.g., water and wastewater treatment plants, hydraulic conveyances, etc.). Both types of infrastructure can be harnessed to realize improvements in *HWS* through the services they provide to society. *NC* has an affiliated portfolio of ecosystem services that can provide clean, reliable drinking water from well-managed upland ecosystems, instream water pollution control, flood protection by wetlands, and a vital source of protein through inland fisheries (Browder et al., 2019; McIntyre et al., 2016; USACE EWN, 2020; Vörösmarty et al., 2018; Stewart-Koster and Bunn, 2016). *TE* services include public and private water delivery and treatment systems, water storage, and management services. *NC* can be combined with *TE* to produce "blended systems" across this broad spectrum of service benefits. Here, we consider *NC* operating in tandem with *TE*, evaluating their regional-to-continental scale geographies and importance, going well beyond both the notion and domain of green infrastructure as currently embraced by urban planners (e.g., green roofs, rain gardens) (Brown, 2013). Natural capital and its affiliated services have also collectively been termed nature-based solutions (Cohen-Shacham et al., 2016; WWAP, 2018). As we explain below, and throughout this study, we inventory and map *NC* and *TE* as physical infrastructures. We also derive measures of their affiliated services to society, which we sometimes refer to as their function, but concentrate specifically on their capacity to control threats to *HWS*. Both *NC* and *TE* can gain functionality by investments in maintenance and protection but can lose it by allowing these assets to depreciate over time, through impairment or poor management.

We modified and extended an existing approach that focused on estimating contemporary ambient environmental conditions, how they impose incident threat (T) on *HWS,* and how such threat is remediated through engineering systems alone (Vörösmarty et al., 2010). The new formulation allows us to: (a) present the global spatial distribution of T and maximum incident threat (T_{max}) should *NC* be lost; (b) evaluate the contributions that *NC* and *TE* make in preventing and reducing these threats (TR_{nat} and TR_{eng}, respectively); (c) project future T, TR_{nat}, and TR_{eng}; and (d) estimate the future investment expenditures required for threat-reducing *TE* and the avoided replacement costs associated with threat prevented by existing *NC* and its affiliated ecosystem services. This new framework enables us to evaluate, on a common scale, the individual as well as joint roles of *TE* and *NC* in mitigating or offsetting projected threat to *HWS*. We make calculations on 46,517 grid cells (30′ lat/long), comprising the continental land mass across which rivers actively flow. Future projections are run for a 30-year duration, +/- 15 years of 2005, 2030, 2050 and 2080.

Within our computational framework (see Supplementary Material, Fig. S1), *HWS* ultimately rests on the combination of economic development; water availability, condition, and use; and, the capacity of *NC* and *TE* to reduce *HWS* threat. Our estimated levels of threat to renewable freshwater resources are embedded within the runoff and river corridor flows that serve the vast majority of human population (Harrison et al., 2016; Green et al., 2015), and are therefore intimately connected to the ecosystem services provided by natural capital, specifically upstream contributing areas that serve downstream human beneficiaries and water-dependent ecosystems. As shown in our conceptual framework (Figs. 1 and 2), levels of incident threat in a given grid cell (*i*) will rise in response to poor environmental management but will simultaneously reflect the countervailing impacts of natural capital and ecosystem services, which reduce otherwise higher levels of incident threat in that grid cell (T_i). This threat reduction by natural capital, $TR_{nat,i}$, essentially goes unobserved, but can be computed, mapped, and compared to $TR_{eng,i}$ using the common biogeophysical and economic units provided by our framework. Should all *NC* be eliminated at a given location, we can estimate what would be its potential maximum incident threat ($T_{max,i}$). T_i is therefore a net quantity, representing the balance between human pressures that tend to increase incident threat and its concurrent suppression by existing *NC*. T_i at any location is further reduced to a residual (remaining threat, $T_{rem,i}$) through engineered management ($TR_{eng,i}$).

In order to project future threats to *HWS*, we apply advanced geostatistical models, configured over digital river networks, that relate T_i to a set of drivers associated with economic development and with well-established negative impacts on water systems (e.g., population, GDP, water use, agricultural activities) (OECD, 2012; Venter et al., 2016; Orubu and Omotor, 2011, Tables S1-S3). As we show in the Supplementary Material, these models reproduce well the contemporary spatial patterns of T_i from a previous study (Vörösmarty et al., 2010) that used a much larger set of drivers but that have no future analogues. With these new drivers, we use the geostatistical models to project contemporary and future T_i, and then estimate $TR_{nat,i}$ and $TR_{eng,i}$ using statistical models based on these projections of T_i (see S1 and S3 for detailed calculations).

We estimate and project contemporary and future expenditures on threat-reducing *TE* using observed patterns of spending on engineering relative to GDP per capita across different countries. By assuming that financial resources are allocated efficiently within countries, we estimate total expenditures on *TE* for each pixel ($\$TR_{eng,i}$) (S1.3.1). We then use similar projections to estimate $\$TR_{nat,i}$ as the expenditures on *TE* that would be needed to replace the existing *NC* if it were to be lost. We allow these *avoided replacement costs* of preserving current *NC* to vary depending on our assumptions about the substitutability between *TE* and *NC* (corresponding to the concepts of strong and weak sustainability and serving to illustrate an uncertainty envelope) (S1.3.2). We quantify the benefits of preserving *NC* at the country level with an "avoided penalty" index, which shows the extra efficiency loss if countries were to replace the current *NC* ecosystem services entirely with threat reduction from *TE* (S1.3.2). Lastly, we calculate the lower-bound cost of reducing the *HWS* threat that remains after threat reduction from both existing *NC* and *TE* ($\$T_{rem,i}$) by assuming that all of the remaining threat can be reduced with *TE* (S1.3.2).

A complete description of the modelling protocol, including variable nomenclature, equations, key assumptions, each input data set, and measures of model performance is given in the Supplementary Material (S1, Figs. S1–S4). Table S1 lists the seven surrogates and their relation to the larger set of drivers from the original threat mapping (Vörösmarty et al., 2010). Table S2 defines all variables used in this study, with units and a corresponding calculation or reference to an equation described in the Supplementary Material. A worked numerical example is given in Table S3.

3. Results and discussion

3.1. Increasing threat to human water security and corresponding changes in TE and NC

We simulated three scenarios depicting alternate climatic and socio-economic development pathways, but report mainly on business-as-usual (*BAU*) projections (*IPCC RCP6.0/SSP2;* van Vuuren, 2014; O'Neill et al., 2014 [see Supplementary Material Table S5]), featuring a rising global middle class (Fig. 3). Our *BAU* projections provide a convenient means to reveal likely trends in T_i and to explore the limits and opportunities of engineered and nature-based threat management. Under these projections, *T* grows throughout the 21st century, fueled by rising population density, industrialization, and food production (Fig. 4). This result is consistent with historical trends (Venter et al.,

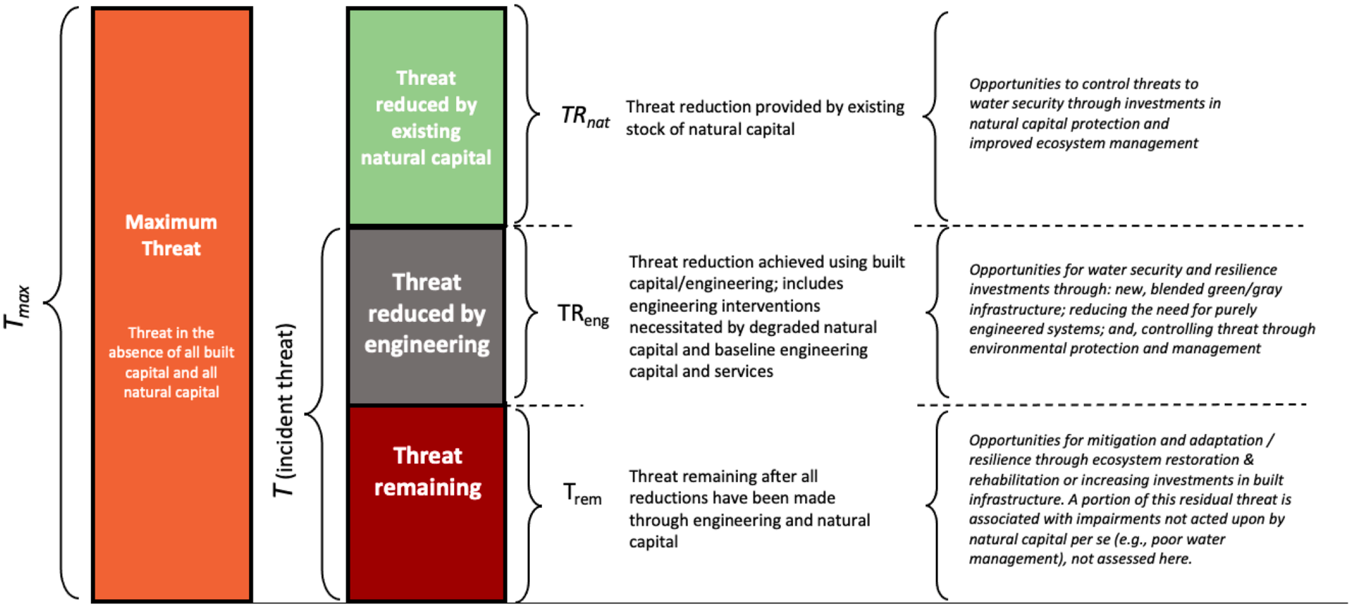

Fig. 1. Conceptual framework and key water security threat nomenclature. Threat is apportioned in terms of its control by natural capital (*NC*) and traditional engineering (*TE*), plus any residual impairment. A parallel set of variables for replacement cost estimates (not shown for brevity) can be found in Table S2. The variables shown are computed on a grid-cell basis and denoted by *i* elsewhere in the text. Additional nomenclature, intermediate steps and specific equations, input data, and assumptions are described in the Supplementary Material.

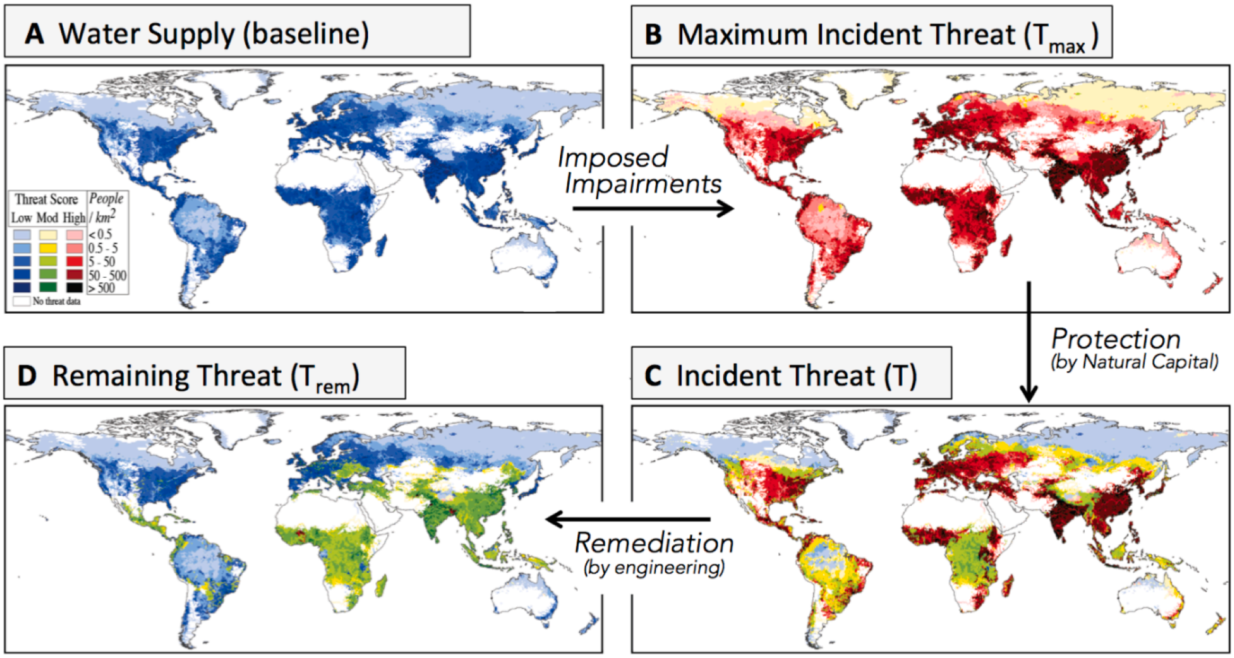

Fig. 2. Features of water security threat and its control. (**A**) Water supply conveyed to downstream populations in the absence of human impacts. (**B**) Environmental stressors produce a maximum potential incident threat; T_{max} represents the endpoint of complete removal of natural capital and its associated threat suppression. (**C**) Natural capital reduces the maximum to incident threat, the level observed and acted upon by engineered remediation. (**D**) A residual threat remains after engineered interventions.

2016) and present-day geographical patterns (Vörösmarty et al., 2010) that generally favor threat intensification over its spatial expansion. By 2080, population-weighted global mean T_i increases by 10% over 2005 levels, with much of the change focused on rapidly developing countries. The rising middle class in China, India, and other non-OECD countries drives these increases, while the OECD remains generally stable (Fig. 3C).

Through mid-century, our projections in Fig. 5 show rich nations reducing much of their incident threat to water resources using *TE*, while poor countries only partially offset T_i in this way, due to their limited investment capacity (Fig. S2A,B). The overall control of contemporary incident threat by *TE* (T_i reduced to $T_{rem,i}$) is substantial. Across the OECD countries, this mean reduction (in population-weighted terms) is 58%, while for non-OECD countries it is 49%. *NC* contributes corresponding levels of 20% and 16% to threat containment that ultimately avoids $T_{max,i}$ and benefits downstream populations, making natural capital an important global-scale asset in *HWS* management.

By 2050, the projected geographic differences between *TE* and *NC* are striking, although engineered approaches are expected to continue to grow strongly under *BAU* (Fig. 6). Our projections regarding the essential role of *TE* is corroborated by ongoing construction of massive engineering works with multi-decade planning horizons (Zarfl et al., 2015; Ashley & Cashman, 2006) and the common assumption of their necessity in attaining *SDG* water targets (HLPW, 2018; OECD, 2019). By 2050, as a result of rapid economic growth and wealth creation, some river basins show significant new deployments of *TE* (e.g., Niger, Ganges, Changjiang). However, their high levels of threat drivers make it difficult to achieve more than a modest alleviation of T_i, even after major engineering investments (Fig. 2). Elsewhere in the developing world, and despite the rapid rise of *TE* in relative terms, low levels of remaining threat are projected to remain elusive due to limitations in estimated future engineering deployments in absolute terms (e.g., sub-Saharan Africa, Central America, most of Asia and Oceania). Consistent with the general observation that environmental impairment accompanies economic expansion (Vörösmarty et al., 2010; Tickner et al., 2018; Díaz et al., 2019; OECD, 2012; Venter et al., 2016; Orubu and Omotor, 2011), our modeling projects widespread losses of *NC* under *BAU*. Losses of ecosystem services are particularly obvious across densely populated or rapidly developing regions (Fig. 6B), precisely those areas requiring the highest levels of threat control (Fig. 4).

3.2. Blended systems and pathways to future threat control

Well-designed combinations of natural capital and built infrastructure can boost the performance and reduce the costs of engineered solutions (Browder et al., 2019; Palmer et al., 2015; Vörösmarty et al., 2018; WWAP, 2018), with many successful "worked examples" like wetlands functioning alongside massive flood control infrastructure (UNEP-DHI, 2014), healthy catchments purifying urban water supplies (McDonald et al., 2016; Dudley and Stolton, 2003), and wetlands providing effluent treatment in urban water systems (World Bank, 2015). Blended systems could therefore play an important role in future *HWS*, but only in regions that retain significant endowments of natural capital. To safeguard that potential, strategic stewardship of ecosystem services will be needed, encompassing regional if not continental-scale perspectives (Harrison et al., 2016; Green et al., 2015).

We projected the capacity of *TE*, *NC*, and their combination to deliver water services using river network topologies that quantify downstream populations dependent on upstream water source areas and their corresponding levels of incident threat (Harrison et al., 2016; Green et al., 2015) (Fig. 7). The relative roles of *TE* and *NC* shift dramatically across the decades and reveal strong path dependencies. Through 2050, our projections show upward trajectories in *TE*-centered threat management, accompanied by declines in the potential for *NC*-based threat control. Europe and broad areas of South and East Asia have already lost or will imminently lose *NC* to the point where higher *TE* becomes the only viable option for threat control. In these regions, the population-weighted mean threat reduction by engineering (TR_{eng}) rises from 0.55 to 0.62 and 0.33 to 0.53, respectively, between 2005 and 2050. Over the same period, South and East Asia is projected to experience an overall net loss in threat suppression by *NC*, with population-weighted average

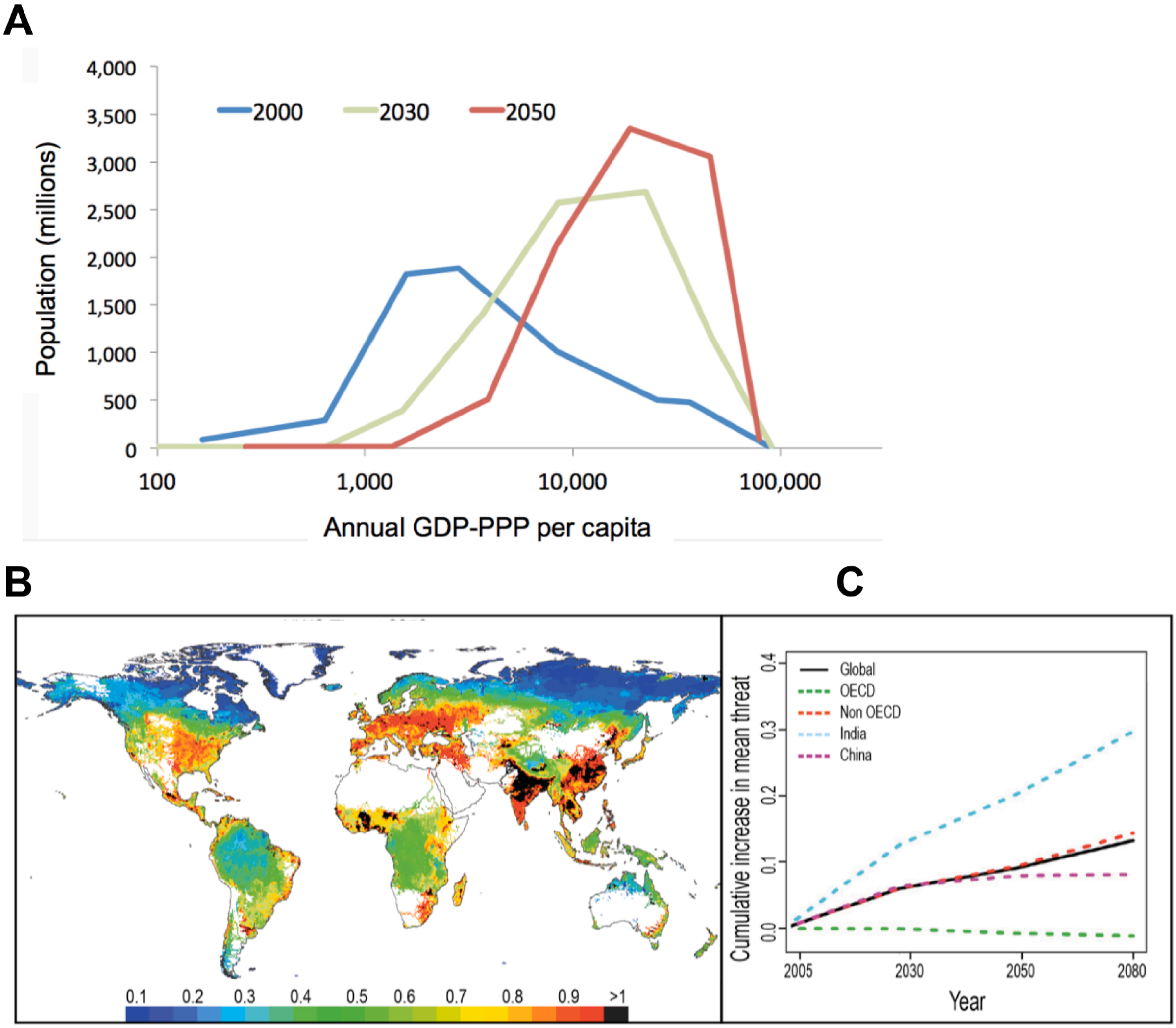

Fig. 3. Growth and re-distribution of global income and the affiliated rise in incident threat. (**A**) The impact of anticipated global economic development moves overall population distributions to the right, reflecting the rise of the global middle class. Estimates are derived from the *IPCC-AR5*, *SSP* database (SSP, 2016). All values are in GDP-PPP/capita (2000 \$). (**B**) Future distributions of *T* (for 2050) are similar to those of the present, stabilized across the United States and Europe, but accelerating across Western Africa, South and East Asia. (**C**) Mean population-weighted trajectories for major economic blocks reflect rapid demographic and economic growth and agricultural intensification followed by slowing and stabilization. Pixels reported at 30′ lat/long; non-discharging landmass shown in white.

TR_{nat} declining from 0.17 to 0.13, due to rapid intensification of threat drivers. In contrast, *NC* threat suppression is projected to remain stable but low (~0.2) across much of Europe, reflecting its mature economies and agricultural systems.

While we found similar patterns under each *RCP/IPCC* scenario, a more aggressive transition to *NC*-based threat control is plausible, insofar as we tabulate nearly 2.5 billion people today living downstream of high *NC* assets that could augment the more prevalent *TE*-based approaches. Broad-scale application of blended green-gray systems would reposition some countries toward a high *NC*-high *TE* state (upper right quadrant, Fig. 7 inset). Such a transition is most plausible for South America. Africa also maintains high *NC*-based potential, but projections of its limited capacity to invest in *TE* through 2050 means that it will likely fall far short of the combined *NC-TE* endpoint. Similar shortfalls in *TE* will continue to hinder the transition to blended green-gray systems across much of the developing world. Our projections show that several countries could still be significantly supported by nature-based threat management, with remaining $TR_{nat,i}$ values in 2050 at least equaling, if not exceeding, their accumulated reductions to that year (e.g., Congo [CG & COG], Sudan, Tanzania, Brazil, Bolivia, Peru) (Table S4).

3.3. An economic perspective

The potential benefits of blended green-gray systems can also be evaluated in economic terms. Recognizing that economic valuation of natural resources is fraught with technical and philosophical issues around sustainability, substitutability, and irreversibility (NRC, 1994), our straightforward approach provides first-order estimates of the threat-reducing economic value of *TE* and *NC*, and how they can be jointly used in future water management, by way of estimating avoided replacement costs of *NC*. While a more complete economic assessment of tradeoffs, opportunity costs, and synergistic cost-savings by green-gray systems is left to future study, important policy-relevant results nonetheless emerge from this initial accounting.

Under *BAU*, growing financial investments in *TE* aimed at reducing threat accompany increases in per capita income (Fig. S2A) and are projected to reinforce a heavy reliance on engineering over the remainder of the century (Table 1). With economic expansion and population growth, annual global expenditures on *TE* infrastructure and operations triple from \$0.7 to \$2.3 trillion (2020 PPP) from 2005 to 2050. Relative increases are expected to be most rapid in the developing world (Fig. 6A) with its expanding middle class. For China, India, and

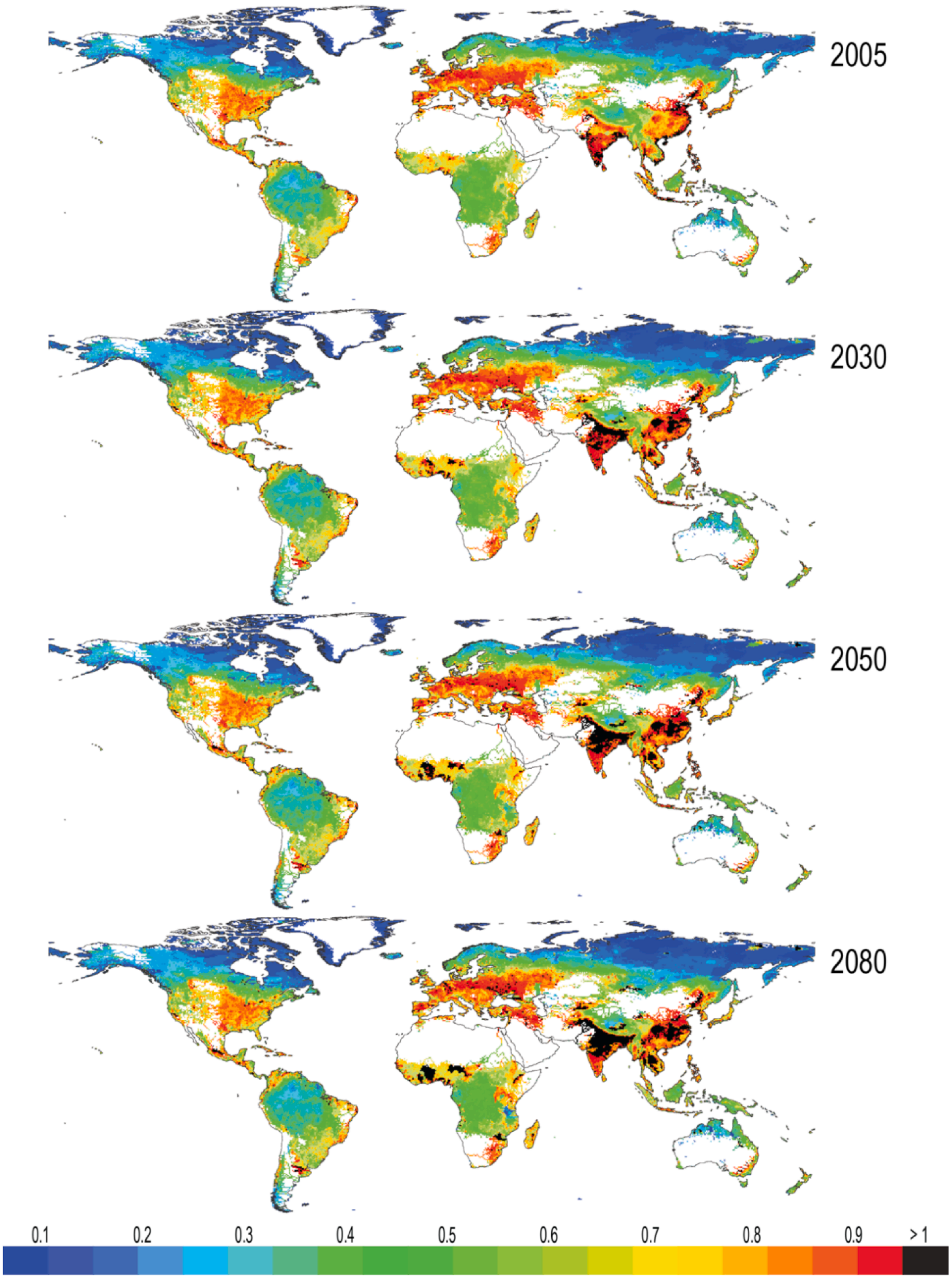

Fig. 4. Projections of future incident threat *T* under the business-as-usual (*BAU*) scenario. The estimates are based on IPCC (*RCP* 6.0/*SSP2* combination [SSP, 2016]) reflecting the spatial distribution of regional development determined by macro-economic trends and population growth. Throughout the simulation timeframe, threat generally intensifies over previously threatened areas, in lieu of a broadening, or extensification, of the spatial domain of *T*.

the non-OECD states, collective annual investments rise between 2005 and 2050, comprising 94% of the total $1.6 trillion increase seen worldwide.

We find two important features of *NC*-based threat control in current and future *HWS*-related cost projections (Table 1). First is its role in suppressing T_i, which otherwise would reach $T_{max,i}$. The global replacement cost of this *NC*-based threat prevention ($\$TR_{nat,i}$) is estimated at $1.4 trillion worldwide in 2005, expanding to $3.0 trillion by 2050. To put this in perspective, existing *NC* accounts for 67% and 56% of all prevention and reduction of threat to *HWS* in 2005 and 2050, respectively. While the biogeophysical importance of *NC*-based threat prevention is on par with *TE*-activated threat reduction across many regions (Fig. 5), our estimates show that it is, in fact, greater in aggregate economic terms at the global scale.

The second dimension of $TR_{nat,i}$ is associated with the avoided penalties related to the economic inefficiencies incurred should *TE* expenditures be used to replace lost ecosystem services. A strongly increasing cost burden falls onto *TE* wherever there is diminished or degraded *NC* and where the functionality of this *NC* needs to be replaced (Fig. 8, S4). We see this most dramatically in the projection for India, and to a lesser

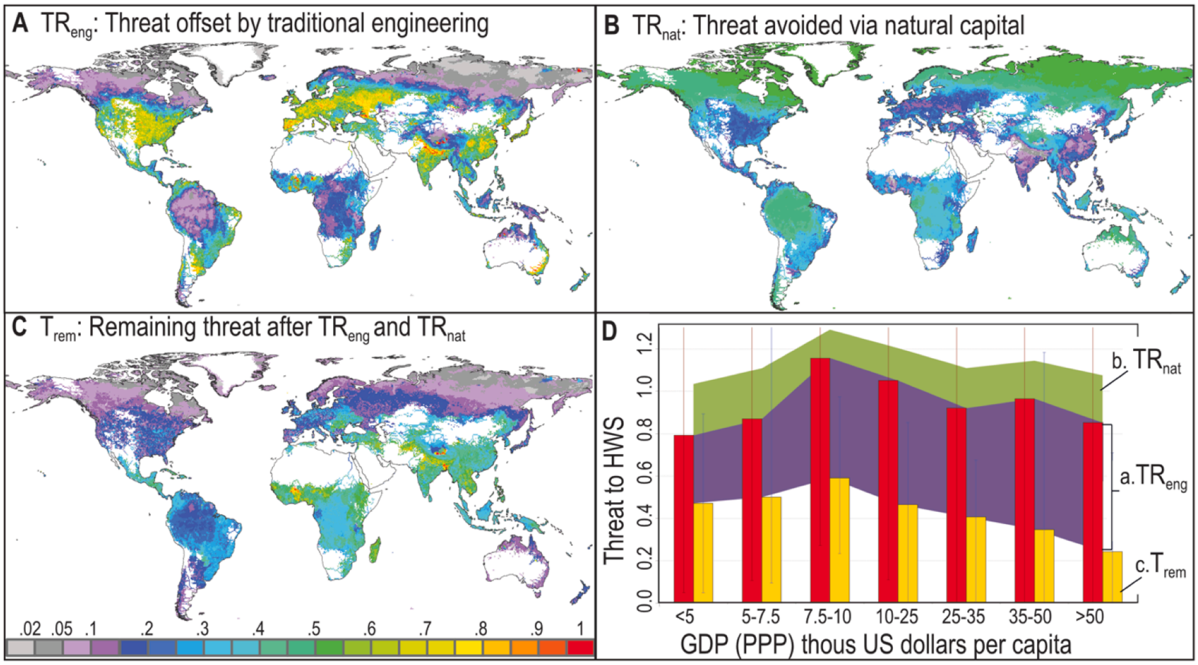

Fig. 5. Components of incident threat containment and final threat remaining ($T_{rem,i}$) in 2050. (**A**) Engineering-remediated threat reduction ($TR_{eng,i}$) at point-of-service prevails in middle-to-high income countries. (**B**) $TR_{nat,i}$ limits otherwise higher T and is generally inversely related to proximity to human population and economic activity. (**C**) $T_{rem,i}$ represents T_i after *TE* interventions and accounts for the effect of *NC* threat reduction. (**D**) Mean values of threat components for countries grouped by income; non-linear trajectories exist in both T_i and its remediation by $TR_{eng,i}$ with rising income, a pattern consistent with present-day tendencies (*1*). Total threat attenuated by engineering and natural capital is the sum of panel values in (**A**) and (**B**) (purple and green, respectively in panel **D**), in turn giving the remaining threat ($T_{rem,i}$). T_i and $TR_{eng,i}$ means are weighted by local population, $TR_{nat,i}$ by downstream river corridor population. $TR_{nat,i}$ maximum is 0.53, representing theoretically pristine water source areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

extent in France, where most pixels have low levels of threat reduction by existing *NC*. For India and France, the remaining scarce *NC* is at a premium and for each unit of *NC* lost on an areal basis these countries would pay penalties of 160% and 115% (a more than doubling), respectively, should that *NC* be lost and then replaced by *TE* (P_{av} in Fig. 8). Much flatter replacement cost curves are apparent for Brazil and Tanzania, reflecting the beneficial effect of their higher stocks of existing *NC*. While P_{av} is more modest for these countries, they would still pay a substantial premium (a 60–70% higher cost) on the use of engineering to replace the same level of threat control represented by any lost *NC*. Such penalties amount to a "tax" on human water security from poor environmental management, with the population-weighted global average P_{av} growing from 100% to more than 110% after 2030 (Table 1) and corresponding to the general decline in natural capital (Fig. 6B).

Despite these important investments, there is substantial remaining threat, $T_{rem,i}$, which could be ameliorated by still larger expenditures in *TE* (Eq. S19). From 2005 to 2050, we estimate these costs to more than double to over $2.0 trillion. They represent "stranded" threats or impacts from damages to *NC* that fail to be addressed. These represent in 2005 about 150% of *TE* outlays, diminishing to 90% in 2050, a reflection of the growing reliance on and effectiveness of *TE* globally.

Despite differences in system definition and methodology, other work corroborates the direction and general magnitude of our estimates (Costanza et al., 2017; McDonald et al., 2016). For example, global economic penalties for the loss of all terrestrial, freshwater-related ecosystem services were previously tabulated (Costanza et al., 2014) as growing at ~ 2% per year between 1997 and 2011. If we assume this to be analogous to the sum of our $\$TR_{eng,i}$ and $\$T_{rem,i}$, we get a growth rate of 2.7% annually between 2005 and 2030, a comparable finding considering that a portion of our projected growth rate will be dedicated to investments purely in baseline engineering expansion (i.e., exclusive of compensating for *NC*-associated impairments), which were not isolated within our calculation scheme. Our projections also seem reasonable given the more rapid growth in the future economy (Fig. 3A). At the same time, the projections of avoided penalties are likely to be underestimated, since they fail to consider any associated human health or biodiversity impacts.

3.4. Protecting natural capital for water security

To what practical degree could the positive benefits of *NC* shown in Table 1 be relied upon and integrated with *TE*? Natural capital is already used widely by cities across the development spectrum, with one-third of the 100 largest urban areas served by protected forests (Dudley and Stolton, 2003). Expanding the role of protected natural areas in principle could be significant, insofar as designated reserves constitute only 13% of the landmass (Watson et al., 2014) yet serve as water provisioning areas for 80% of the world's population (Harrison et al., 2016). However, protected areas are often positioned where incident threat is moderate-to-high, due to stressors originating outside their boundaries and difficult to control (Harrison et al., 2016). Even ostensibly protected source areas for urban water supply have historically shown substantial degradation (McDonald et al., 2016).

The significant potential replacement costs and penalties of using *TE* to substitute for existing *NC* ($\$TR_{nat,i}$), which totals $3 trillion annually by 2050 (Table 1), provides a strong economic incentive for environmental protection. And, while this stewardship would undoubtedly encompass large tracts of land, recent research demonstrates how targeting critical sub-domains (e.g. riparian wetland restoration for non-point pollution control) (Sheldon et al., 2012) and areas of greatest human need (Chaplin-Kramer et al., 2019; Harrison et al., 2016; Green et al., 2015) would make *NC* protection more tractable.

The avoided penalties (P_{av}) presented in section 3.3, Table 1, and Fig. S4 provide further justification for green-gray blending in future

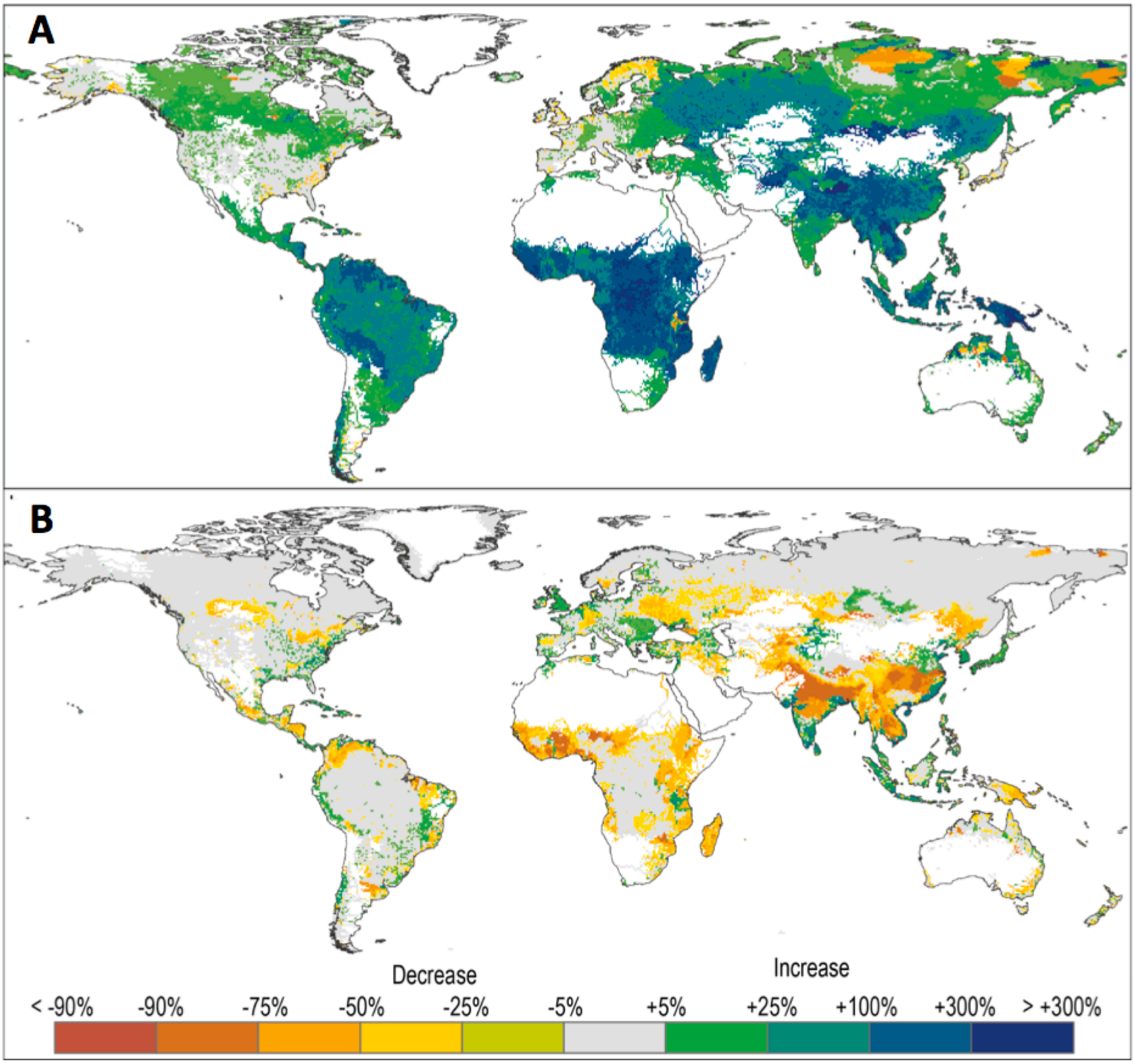

Fig. 6. Threat control by traditional engineering and natural capital in year 2050, relative to 2005. (**A**) Threat reduction by engineering (TR_{eng}) and (**B**) natural capital (TR_{nat}). The business-as-usual case shows growing emphasis on *TE* globally. Despite rapid growth in relative terms, many developing world regions (e.g. sub-Saharan Africa) have limited *TE* systems by mid-century in absolute terms. *NC* losses are a byproduct of development, limited environmental protection, and some *TE* interventions themselves (e.g., sewerage works with poor treatment; excessive dam construction).

water infrastructure investment. Our avoided economic penalty estimates show that given the current cost-effectiveness of *TE*, countries can avoid a penalty that on average, would double the cost to maintain the same level of threat reduction simply by preserving existing *NC* (Table 1). The sources of such penalties are important to recognize. On the one hand, because the marginal cost of replacing threat reduction from *NC* increases at an increasing rate as the stock of *NC* declines (Fig. S4), avoided penalties will increase as *NC* decreases, directly supporting the argument for natural asset protection. On the other hand, for countries with similar levels of *NC*, those with less cost-effective *TE* will suffer from higher penalties. Therefore, the avoided penalties highlight the need for a complementarity in approaches to water security that capitalize on best practices in technical innovation, environmental stewardship, and promoting improved cost-effectiveness and economic incentives. These are management levers that could be controlled by decision makers, after fully understanding the tradeoffs, benefits, beneficiaries, and downsides of any specific plans to combine green-gray water infrastructure (e.g., McCartney et al. 2019, Hurford et al. 2020).

In contrast to the immediate advantages inherent in natural capital protection, post hoc restoration often proves expensive, often spectacularly so, and many case studies point to the wisdom of damage prevention over rehabilitation. For example, $80 billion was expended over multiple decades to rehabilitate the 1,000 km^2 Yamatogawa River in Japan (Tsuzuki & Yoneda, 2012). Organic pollution was controlled, but at a cost of $65 billion in the Rhine (Wilken, 2006). In the U.S., the many tens of thousands of rehabilitation projects for riverine ecosystems (Bernhardt et al., 2005) is a testament to the scope of the problem, supporting a sector with annual revenues of $25 billion that employs more than 200,000 (BenDor et al., 2015). While we have not explicitly evaluated the global costs of either protecting or rehabilitating watersheds and waterways, the endpoint of such interventions could save trillions of dollars in engineering costs that otherwise would be necessary to replace lost *NC* threat reduction services (Table 1).

4. Conclusion

Our unified framework linking natural capital to traditional engineering enables us to determine how the ongoing loss of well-

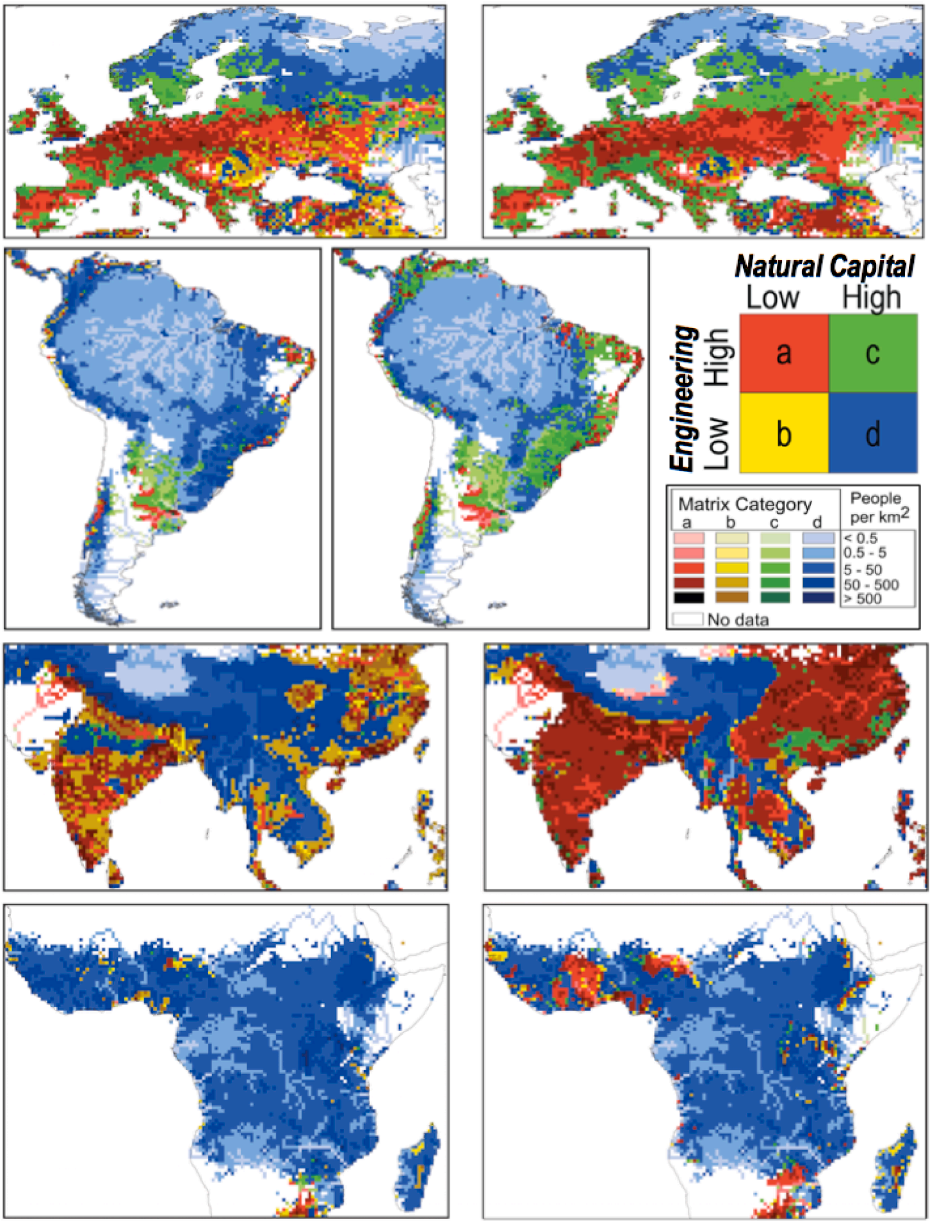

Fig. 7. Geography of traditional engineering and natural capital in threat management in 2005 (*left*) and 2050 (*right*). Mapped color densities represent downstream populations served by water source areas. Business-as-usual trends in the growth of incident threat and societal response (Figs. 3, 4) mean that nearly all areas improve their engineered water services and will reside in the High-*TE*/High-*NC* (green color) or High *TE* / Low-*NC* (red) category by 2050. Red areas suggest strong path dependencies in future threat management, requiring a nearly exclusive reliance on *TE*; green indicates the potential for blending *NC-TE* approaches. High-to-Low thresholds determined from population-weighted global mean threat containment in 2005 ($TR_{eng} = 0.38$; $TR_{nat} = 0.20$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

functioning ecosystems and the subsequent replacement of their affiliated environmental services through engineering strengthens or compromises water security over regions and continents. These findings support, for the first time at the global scale and in the domain of water resources, some key tenets as first proposed in the early ecosystem services literature (Odum 1973). Chief among these is the concept that environmental services typically go unrecognized until they are compromised, creating economic hardship when society elects to replace them or abandon them to environmental degradation. While there are inherent uncertainties in our projections, our assessment of threat reduction by natural capital (TR_{nat}) demonstrates the value of such hidden ecosystem services, which substantially dampen otherwise higher human water security threat. They are functionally of the same order globally as services deployed through engineering, but in economic terms they substantially exceed the value of engineered water management. Should the otherwise free public subsidies conveyed by the environment be lost, we calculate that their replacement cost will be at a substantial penalty—at least twice the cost, on average, for each equivalent unit of water security services provided by engineering. Mounting losses of natural capital as the global economy continues to expand translates into substantially higher costs and inefficiencies for achieving water security in the future. Cost-containment and sustainable water resource development can be achieved by preserving natural capital and incorporating it wisely into a next generation of water management systems.

These findings bear important policy implications; but, before any strategic shift to green-gray approaches in water security can be realized, several pressing, practical challenges must be confronted. Global investments in protected areas and their maintenance amounts to $< 3\%$ of water sector expenditures, with chronic shortfalls totaling tens of billions of dollars annually (McCarthy et al., 2012). Moreover, investments aimed at rehabilitating and/or protecting water-critical ecosystems amounted to only \$12.3 billion worldwide in 2013 (Bennett & Carroll, 2014), while monitoring networks to track the status of water systems continue their general decline (Lawford et al., 2013; Fekete et al. 2015).

Fig. 9 shows the shifting worldwide pattern of country-level investments in *TE* as well as in the burden of *NC* replacement costs through

Table 1
Global estimates of rising expenditures in traditional engineering (*TE*), natural capital (*NC*) benefits expressed as avoided replacement costs, and the penalties incurred should NC be lost and replaced by *TE*. Allocations for *TE* infrastructure accommodate expanding water demands and loss of *NC* over time. The costs to remediate remaining threat, unrecovered by this *TE,* are also substantial, exceeding *TE* expenditures in the early part of the century until TE expenditures accelerate. Intact *NC* dampens otherwise higher levels of threat and greatly exceeds the value of *TE* threat mitigation. Relative contributions of *NC* decline over time due to degraded ecosystem services and expanding reliance on *TE*. All values in the first three rows are in billions of US $ 2020 PPP[a]; for *NC* these represent *TE*-based avoided replacement cost equivalents.

	2005	2030	2050	2080
Threat Reduction by *TE* [b]	690	1,610	2,300	3,400
Threat Prevention by Existing *NC* [c]	1,380 (1,020–1,880)	2,330 (1,690–3,230)	2,950 (2,160–4,140)	3,900 (2,850–5,450)
Remaining Threat [d]	1,000	1,700	2,060	2,510
Relative Contribution of *NC* [e]	67%	59%	56%	54%
Avoided Penalty [f]	100%	111%	114%	114%

[a] Converted from US $ 2005 to 2020 PPP (purchasing power parity) using BLS (2020).

[b] $\$TR_{eng,i}$, total *TE*-based threat remediation ($Spend_{eng}$, Eq. S11 for countries); Eq. S12 for individual pixels. Includes the net cost of capital, operations, and maintenance.

[c] $\$TR_{nat,i}$, threat prevention considered as avoided costs. The range in parentheses shows the upper and lower limits from the power function used in Eqs. S14, S15, and S16.

[d] $\$T_{rem,i}$, the cost to remediate remaining incident threat calculated as a residual based on Eq. S19.

[e] Calculated relative to the sum of the value of threat reduction by *TE* and threat prevention by *NC*.

[f] Population-weighted avoided penalty, P_{av} (Eq. S18).

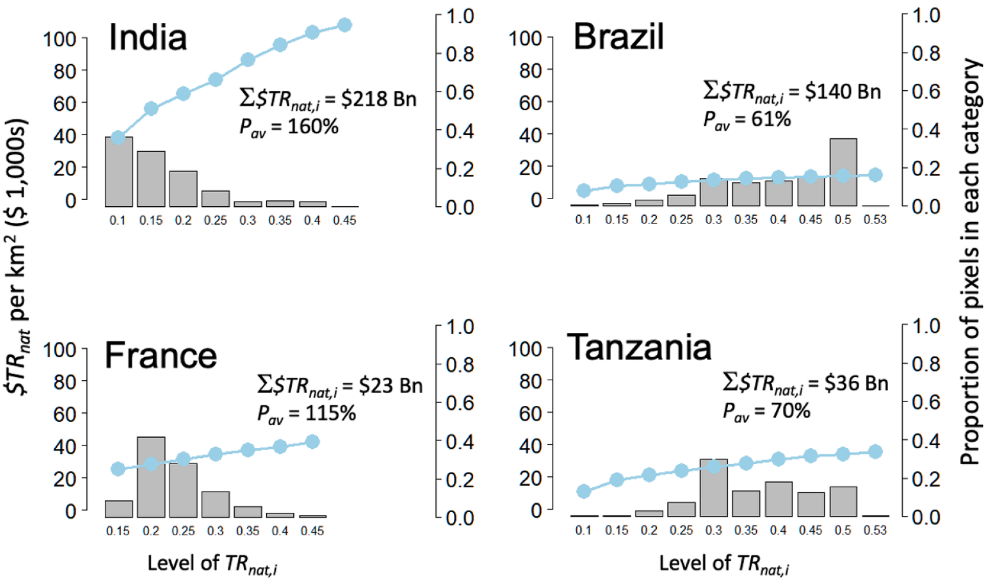

Fig. 8. Annual replacement costs per unit area for existing natural capital ($\$TR_{nat,i}$) through traditional engineering in 2050 in four different countries. Grey bars represent the proportion of pixels in each country with each level of $TR_{nat,i}$ on the horizontal axis. The blue curves represent the per square km cost to replace the existing natural capital in the pixels in each bin. Country-level specificity arises from differences in the cost effectiveness of engineered management of threat across the globe (Eqs. S13 & S14). Total replacement cost ($\Sigma\$TR_{nat,i}$) and avoided penalty ($P_{av}$) are at the national level (percent and US $ 2020 PPP, respectively). Fig. S4 gives the general response function. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mid-century. A commitment to the protection of nature-based assets would yield broad global benefits. For developing countries with an accelerating rise in both *TE* investments and *NC* replacement costs, preserving *NC* would arguably be at a still higher premium. Yet, these are the countries that are least able financially to accommodate the rapid installation of *TE* and simultaneous losses in *NC*, exacerbated by a raft of additional institutional, technical, and human capital obstacles (Cornell University et al., 2020; HLPW, 2018; Vörösmarty et al., 2018; Wehn de Motalvo and Alaerts, 2013). Sub-Saharan Africa is emblematic of these challenges (e.g., Nigeria, DR Congo, Ethiopia, Sudan), given its rapidly rising demands for water services, limited *TE* investment potential, and poor track record in maintaining its current infrastructure (Foster and Briceño-Garmendia, 2010). Yet, much of the continent could benefit from protecting a relatively abundant stock of *NC* over the next decades (Fig. 7), and successful demonstrations of green-gray water management there are already in place (e.g., World Bank, 2015).

While the expanding global middle class spells success for poverty alleviation under SDG-1, we have shown that *BAU* approaches to water resource management will embody costly negative impacts on freshwater resources under SDG-6. This is a prime example of incongruities inherent within the SDG framework (International Council for Science ICSU, 2017), and suggests the wisdom of pursuing cross-sectoral synergies. Cost-effective greening of water management represents an important opportunity to liberate financial resources and benefit other aspects of the sustainable development agenda, given water's preeminent role in human enterprise and among global economic risks (World Economic Forum WEF, 2020). A redesign of business-as-usual practices is also timely given insufficient financial commitments to *TE*-based water resource development (Rodriguez et al., 2012; HLPW, 2018). This important constraint is not confined to the developing world. In the U.S., an annual $55 billion shortfall in capital investment for water engineering means that only 40% of today's needs are satisfied, with underfunding slated to rise to $144 billion in 2040 (ASCE, 2011), unless pending legislation begins to reverse this trend (The White House, 2021).

Given the global economic significance of investments in water resources that is apparent throughout the century, we see wisdom in pursuing a strategic transition to water management systems that are inherently more cost-effective and sustainable (Gleick, 2018, Liu et al. 2013), and capable of reliably serving large numbers of people (Chaplin-Kramer et al., 2019; Harrison et al., 2016; Green et al., 2015). An improved alliance between natural capital and traditionally-engineered

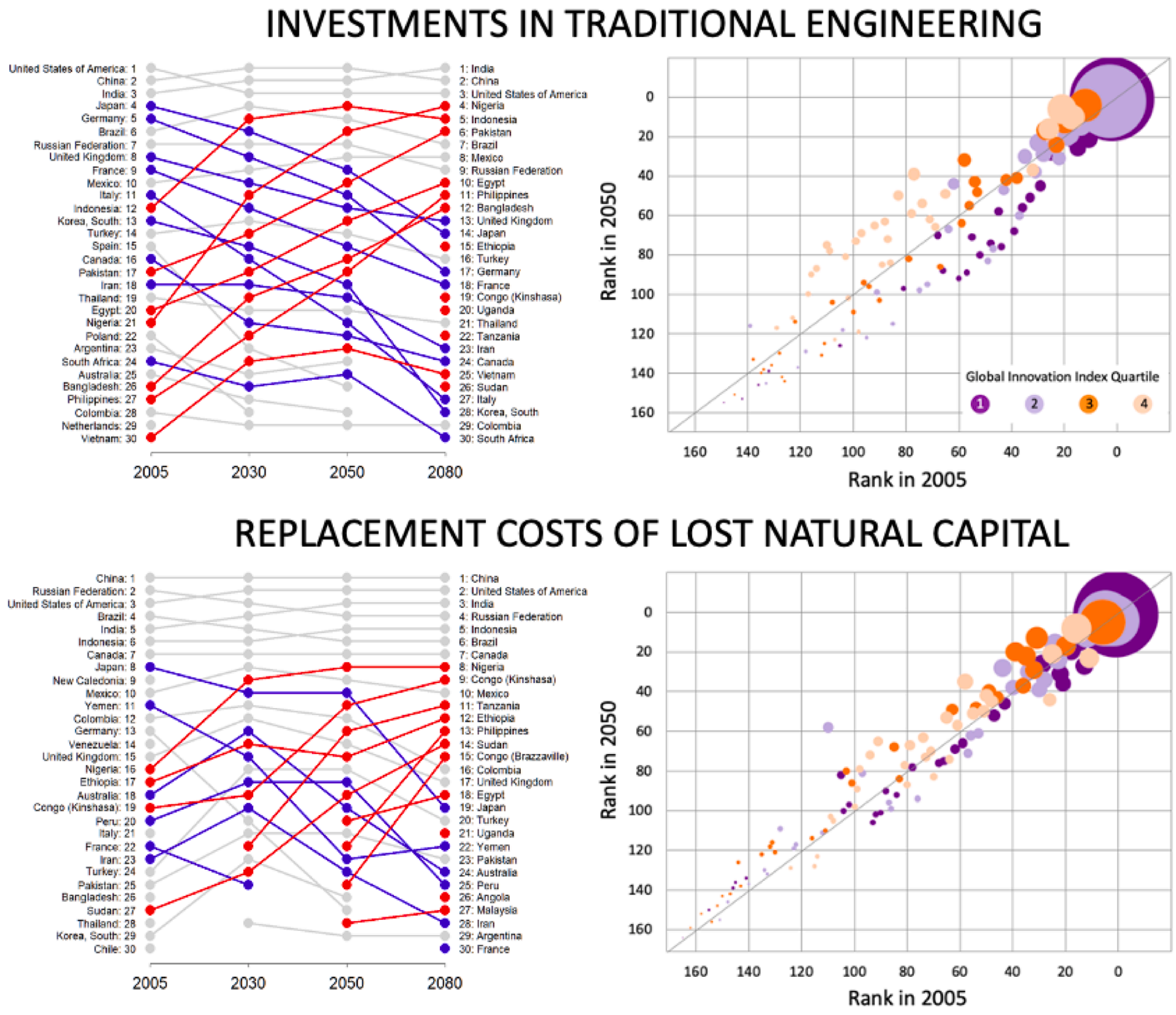

Fig. 9. Nations ranked by projected expenditures on *TE* investments and replacement cost of *NC*. (*left panels*) Countries labeled in red experience the most rapid relative increases in required *TE* expansion ($\$TR_{eng}$), while also incurring increased cost to replace *NC* ($\$TR_{nat}$). These tend to be poor countries. Countries with general declines in both variables (labeled blue) are typically richer. (*right panels*) Rankings (1 = highest) in 2050 versus 2005, with colors reflecting quartiles of a 2017 index of institutional capacity, technology, and human capital (Cornell University et al., 2020) (highest index score [purple] = 1, typically more wealthy countries); sizes indicate expenditure levels. Countries above 1:1 line move to higher rank in required expenditures/penalties. Relative to rich countries, the developing world faces the dual challenge of financing more rapid deployment of traditional water engineering while simultaneously coping with degraded natural capital, which itself increases the costs of water resource systems. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

infrastructure researchers and practitioners, starting with the training of our next generation workforce to co-manage issues going well beyond engineering alone (e.g., social and environmental equity) (Kelly, 2008), should go far towards achieving these objectives. In doing so, society will also benefit from the non-economic value of sustainably managed natural capital (Tickner et al., 2018; Díaz et al., 2019), including its biodiversity and essential earth system support services like climate stabilization. Traditional engineering is a necessary part of the solution, but it is neither economically nor environmentally feasible as the sole approach to sustainable water development.

CRediT authorship contribution statement

Charles J. Vörösmarty: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Ben Stewart-Koster:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Pamela A. Green:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Edward L. Boone:** Conceptualization, Formal analysis, Methodology, Validation. **Martina Flörke:** Conceptualization, Formal analysis. **Günther Fischer:** Conceptualization, Formal analysis. **David A. Wiberg:** Conceptualization, Writing – review & editing. **Stuart E. Bunn:** Conceptualization, Writing – review & editing. **Anik Bhaduri:** Conceptualization, Writing – review & editing. **Peter B. McIntyre:** Conceptualization, Writing – review & editing. **Claudia Sadoff:** Conceptualization. **Hongxing Liu:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **David Stifel:** Conceptualization, Formal analysis, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data and materials availability

Background material, images, and all of the data used in our study (both input data and model results) are available for download at https://www.water-sustainable-infrastructure.com/. The complete set of computer codes to reproduce our results is also included.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102344.

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