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Global threats to human water security and river biodiversity

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Protecting the world's freshwater resources requires diagnosing threats over a broad range of scales, from global to local. Here we present the first worldwide synthesis to jointly consider human and biodiversity perspectives on water security using a spatial framework that quantifies multiple stressors and accounts for downstream impacts. We find that nearly 80% of the world's population is exposed to high levels of threat to water security. Massive investment in water technology enables rich nations to offset high stressor levels without remedying their underlying causes, whereas less wealthy nations remain vulnerable. A similar lack of precautionary investment jeopardizes biodiversity, with habitats associated with 65% of continental discharge classified as moderately to highly threatened. The cumulative threat framework offers a tool for prioritizing policy and management responses to this crisis, and underscores the necessity of limiting threats at their source instead of through costly remediation of symptoms in order to assure global water security for both humans and freshwater biodiversity.

Water is widely regarded as the most essential of natural resources, yet freshwater systems are directly threatened by human activities[1–3] and stand to be further affected by anthropogenic climate change[4]. Water systems are transformed through widespread land cover change, urbanization, industrialization and engineering schemes like reservoirs, irrigation and interbasin transfers that maximize human access to water[1,5]. The benefits of water provision to economic productivity[2,6] are often accompanied by impairment to ecosystems and biodiversity, with potentially serious but unquantified costs[3,7,8]. Devising interventions to reverse these trends, including conventions[9] and scientific assessments[10] to protect aquatic biodiversity and ensure the sustainability of water delivery systems[11], requires frameworks to diagnose the primary threats to water security at a range of spatial scales from local to global.

Water issues feature prominently in assessments of economic development[6], ecosystem services[3], and their combination[12–14]. However, worldwide assessments of water resources[2] rely heavily on fragmented data often expressed as country-level statistics, seriously limiting efforts to prioritize their protection and rehabilitation[15]. High-resolution spatial analyses have taken understanding of the human impact on the world's oceans[16,17] and the human footprint on land[18] to a new level, but have yet to be applied to the formal assessment process for freshwater resources[2] despite a recognized need[19,20].

The success of integrated water management strategies depends on striking a balance between human resource use and ecosystem protection[2,9,10,21]. To test the degree to which this objective has been advanced globally, and to assess its potential value in the future, requires systematic accounting. An important first step is to develop a spatial picture of contemporary incident threats to human water security and biodiversity, where the term 'incident' refers to exposure to a diverse array of stressors at a given location. Many stressors threaten human water security and biodiversity through similar pathways, as for pollution, but they also influence water systems in distinct ways. Reservoirs, for example, convey few negative effects on human water supply, but substantially impact on aquatic biodiversity by impeding the movement of organisms, changing flow regimes and altering habitat. Similarly, non-native species threaten biodiversity but are typically inconsequential to human water security.

Here we report the results of a global-scale analysis of threats to fresh water that, for the first time, considers human water security and biodiversity perspectives simultaneously within a spatial accounting framework. Our focus is on rivers, which serve as the chief source of renewable water supply for humans and freshwater ecosystems[2,3]. We use river networks to redistribute the distinctive impacts of stressors on human water security and biodiversity along a continuum from headwaters to ocean, capturing spatial legacy effects ignored by earlier studies. Our framework incorporates all major classes of anthropogenic drivers of stress and enables an assessment of their aggregate impact under often divergent value systems for biodiversity and human water security. Enhancing the spatial resolution by orders-of-magnitude over previous studies (using 30′ latitude/longitude grids) allows us to more rigorously test previous assertions on the state of the world's rivers and to identify key sources of threat at sub-national spatial scales that are useful for environmental management. Finally, we make the first spatial assessment of the benefits accrued from technological investments aimed at reducing threats to human water security, revealing previously unrecognized, global-scale consequences of local water management practices that are used extensively worldwide.

Global patterns of incident threat

Using a global geospatial framework[22], we merged a broad suite of individual stressors to produce two cumulative incident threat indices, one for human water security and one for biodiversity. The resulting

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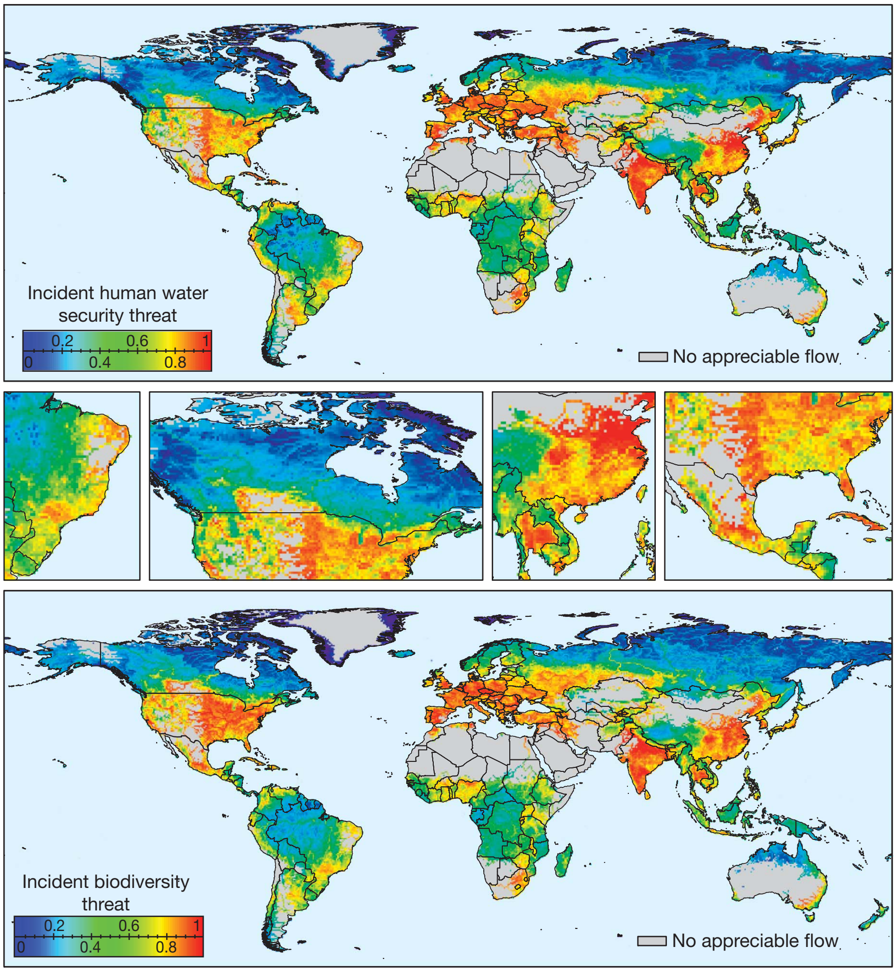

Figure 1 | Global geography of incident threat to human water security and biodiversity. The maps demonstrate pandemic impacts on both human water security and biodiversity and are highly coherent, although not identical (biodiversity threat = 0.964 × human water security threat + 0.018; $r = 0.97$, $P < 0.001$). Spatial correlations among input drivers (stressors) varied, but were generally moderate (mean $|r| = 0.34$; $n = 253$ comparisons). Regional maps exemplify main classes of human water security threat (see main text and Supplementary Fig. 4). Spatial patterns proved robust in a variety of sensitivity tests (Supplementary Methods and Supplementary Discussion). Threat indices are relative and normalized over discharging landmass.

maps reflect the central role of hydrology in spatially configuring environmental impacts, with local stressor loads routed downstream through digital river networks[23] and adjusted for new sources and dilution (Supplementary Methods and Supplementary Fig. 1). Similar to an approach used for marine systems[16,17], multiple stressors were combined using relative weights to derive cumulative threat indices. Stressors were expressed as 23 geospatial drivers organized under four themes (catchment disturbance, pollution, water resource development and biotic factors). Expert assessment of stressor impacts on human water security and biodiversity produced two distinct weighting sets, which in turn yielded separate maps of incident threat reflecting each perspective.

We find that nearly 80% (4.8 billion) of the world's population (for 2000) lives in areas where either incident human water security or biodiversity threat exceeds the 75th percentile. Regions of intensive agriculture and dense settlement show high incident threat (Fig. 1), as exemplified by much of the United States, virtually all of Europe (excluding Scandinavia and northern Russia), and large portions of central Asia, the Middle East, the Indian subcontinent and eastern China. Smaller contiguous areas of high incident threat appear in central Mexico, Cuba, North Africa, Nigeria, South Africa, Korea and Japan. The impact of water scarcity accentuates threat to drylands, as is apparent in the desert belt transition zones across all continents (for example, Argentina, Sahel, Central Asia, Australian Murray–Darling basin).

Spatial differentiation of incident threat also arises from the interaction of multiple factors. China's arid western provinces would be expected to show high threat due to minimal dilution potential, but sparse population and limited economic activity combine to keep indices low. In contrast, heavily populated and developed eastern China shows substantially higher threat, despite greater rainfall and dilution capacity, especially within the Yangtze basin. Other large rivers are incapable of fully attenuating the impacts of concentrated development. Over 30 of the 47 largest rivers, which collectively discharge half of global runoff to the oceans, show at least moderate threat levels (>0.5) at river mouth, with eight rivers (for human water security) and fourteen (for biodiversity) showing very high threat (>0.75).

A strikingly small fraction of the world's rivers remain unaffected by humans. Remote areas of the world including the high north (Siberia, Canada, Alaska) and unsettled parts of the tropical zone (Amazonia, northern Australia) show the lowest threat levels. Across remote areas (Fig. 1), incident threat arises largely from trans-boundary atmospheric pollution. A mere 0.16% of the Earth's area experiences low scores for every contributing stressor (that is, lowest decile globally).

Upstream–downstream transects of incident threat yield signatures of human water security or biodiversity conditions unique to each river that arise from the action of hydrology and networked flow paths (Fig. 2). Such transects highlight the diversity of stressors in river

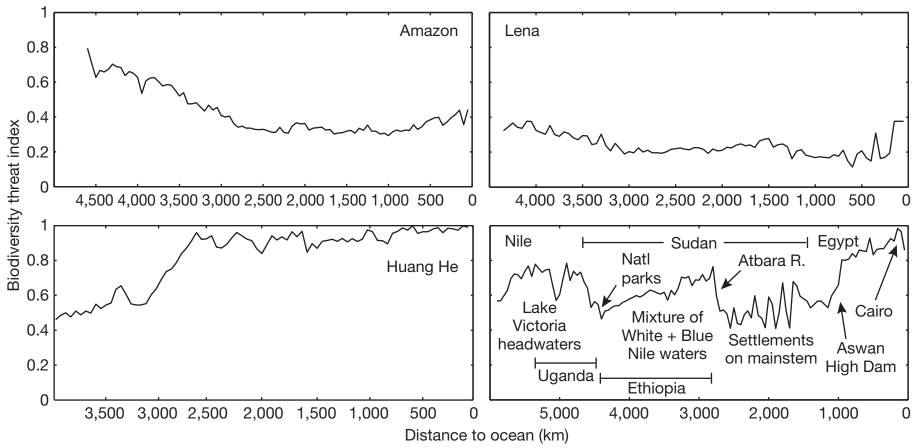

Figure 2 | Incident biodiversity threat transects from headwaters to ocean. Distinctive patterns characterize each river system resulting from complex spatial patterns of stressor loadings across the catchment plus mixing of higher and lower concentration tributary waters through river networks. Transects represent the collective impact of stressors operating within particular development settings, and thus serve to diagnose the chief factors giving rise to threat or to identify critical areas at risk, as shown for the Nile (Natl, National). Threat indices depict conditions over the full basin at set distances from river mouth, but can be reconfigured to track individual reaches or tributary sub-basins.

systems, combining the accumulation of diffuse non-point source pollutants with dilution by less impacted tributaries, often punctuated by point sources from large urbanized areas. Levels of threat often grow in the downstream direction (for example, the Huang He and Nile rivers), indicating the accumulation of residual stressor impacts generated upstream and augmented by dense development along major river corridors. The Amazon shows the reverse, with impacts from human-dominated source areas in Peru and Bolivia persisting but progressively diluted downstream. Even sparsely settled basins like the Lena in Siberia with generally low threat can show the impact of development near the river mouth. The proliferation of densely settled areas in the coastal zone including mega-cities means that its many rivers show high threat over virtually their entire length (for example, Paraíba do Sul (São Paulo state), Pasig (Manila), Ogun (Lagos)).

Our results agree with recent field surveys, underscoring the dire state of river health. Recent sampling of rivers across the United States showed impairment across 750,000 km (50%) of sampled river length and demonstrated the coincidence of multiple stressors, with agricultural factors predominant[24]. In China, 45% of major river reaches surveyed in 2008 were moderately to badly polluted[25]. Reviews of global pollution based on water monitoring[26] and modelling studies[27] have shown broadly similar patterns to our threat maps. Our results are also congruent with previous threat assessments conducted at the coarser catchment and ecoregional scales[7,28] (Supplementary Discussion), yet provide the much greater levels of spatial detail needed for environmental planning and management.

Despite the variety of stressors that we considered, our study and all previous assessments[7,28] of anthropogenic impacts are conservative owing to insufficient information on pharmaceutical and other synthetic compounds, mining, interbasin water transfers, and other commonplace stressors[1,3]. Our current inability to account for in-stream transformations, stressor synergies[21], concentrated impacts during low flow periods, and threats to smaller streams (≤Strahler order 5; 1:62,500 scale)[23] are additional limitations. Finally, uncertainties in stressor data are inevitable, but our standardization procedures limited their influence on our results (Supplementary Information).

Chief determinants of global threat

Globally, the catchment disturbance, pollution, and water resource development themes are spatially well correlated ($r \geq 0.75$ for human water security, $P < 0.001$; $r \geq 0.62$ for biodiversity, $P < 0.001$; $n = 46{,}517$ grid cells), reflecting congruent gradients of human activities and their impacts (Supplementary Table 3). Biotic factors are less strongly correlated with other themes ($r \leq 0.37$ for human water security, $P < 0.001$; $r \leq 0.44$ for biodiversity, $P < 0.001$), reflecting the spatial decoupling of fish species introductions from human population density (Supplementary Table 3) and the broad distribution of inland fisheries. Incident threats to human water security and biodiversity are themselves well correlated (Fig. 1), with the highest levels in heavily settled regions.

In areas of high incident threat (>0.75), water resource development and pollution are dominant contributing themes for both human water security and biodiversity (Fig. 3), and they typically occur together. Their combined importance derives from the waterborne nature of the stressors: water pollution distributed throughout the world's rivers is broadly coincident with the widespread presence of engineering works that enable the overuse and mismanagement of water in many locations. Catchment disturbance and biotic factors have a secondary role in high incident threat areas as their stressors often represent more localized effects.

High levels of incident human water security and biodiversity threat emerge only from the spatial concordance of high scores for many stressors (Fig. 3). Stressors within the catchment disturbance and pollution themes generally act in unison across human water security and biodiversity, highlighting shared sources of impact, with cropland the predominant catchment stressor and nutrient, pesticide and organic loads dominating pollution sources. For the remaining themes, stressors act more independently, reflecting distinctions between human water security and biodiversity perspectives. Stressors associated with impoundments and flow depletion are the clearest sources of biodiversity threat by directly degrading habitat, while negligibly affecting human water security. These results highlight the diverse and unique sets of stressor impacts confronting rehabilitation efforts in high impact areas, and argue for replacing current fragmentary approaches to management with integrative strategies that deliberately alleviate multiple sources of threat[29].

Reducing threats to human water security

Our incident threat maps do not reflect technological investments that can improve human water security. To capture this effect, we derived an 'investment benefits factor', depicting supply stabilization, improved water services and access to waterways, then used it to calculate an 'adjusted human water security threat'. Comparison of incident and adjusted human water security threats reveals that technological investments produce globally significant, positive impacts on human water security and substantially reconfigure exposure to threat (Fig. 4 and Supplementary Information). Highly developed

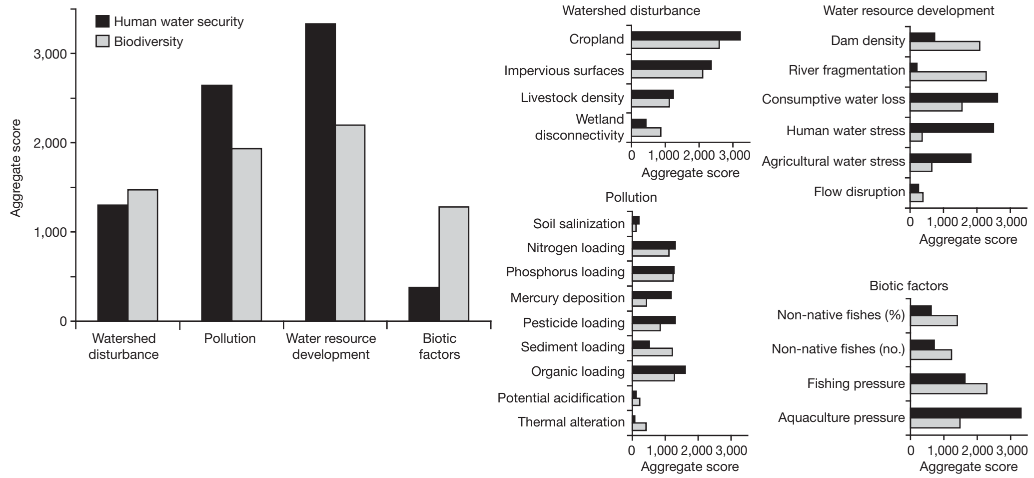

Figure 3 | Theme and driver contributions in areas where incident threat exceeds the 75th percentile. High incident threat typically arises from the spatial coincidence of multiple themes and/or drivers of stress acting in concert. Each aggregate score represents the number of grid cells exceeding the 75th percentile for each individual theme or driver over the high incident threat areas. Influence of each of the four themes (left) is relative to its contribution to overall incident threat. For the individual drivers (right), scores are relative to other drivers in the same theme. Bars summarize results over the entire discharging landmass.

regions with high incident threat (for example, United States, Western Europe) often show much lower adjusted threat indices, gaining benefit from massive investments in water infrastructure, the total value of which is in the trillions of US dollars[2,3,30]. Investments by high-income countries benefit 850 million people, lowering their exposure to high incident threat by 95%, with corresponding values for upper middle-income countries of 140 million and 23% (Table 1). Minimal investment in developing countries means that their vulnerability remains high, with 3.4 billion people in these regions residing in areas showing the highest adjusted threat category.

Our analysis is a spatial expression of the many water security challenges facing the world's poor, as identified in case studies, documentary evidence and global, although fragmentary, data[2,6,12] (Fig. 4). Most of Africa, large areas in central Asia and countries including China, India, Peru, or Bolivia struggle with establishing basic water services like clean drinking water and sanitation[31], and emerge here as regions of greatest adjusted human water security threat. Lack of water infrastructure yields direct economic impacts. Drought- and famine-prone Ethiopia, for example, has 150 times less reservoir storage per capita than North America[32] and its climate and hydrological

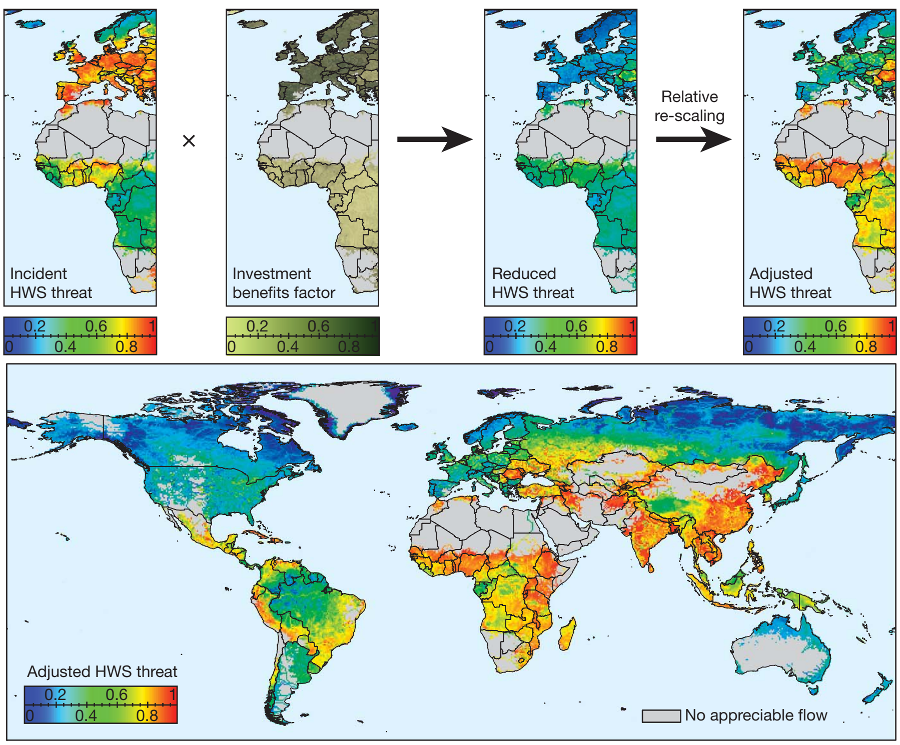

Figure 4 | Shifts in spatial patterns of relative human water security threat after accounting for water technology benefits. Inset maps illustrate the analytical approach and net impact of investment over a north–south transect (top). Incident human water security (HWS) threat is converted to reduced threat (inset maps), which is then globally re-scaled into adjusted human water security threat. The final map shows relative units: areas with substantial technology investments have effectively limited exposure to threat whereas regions with little or no investment become the most vulnerable in a global context. Colour spectra depict three measures of threat (increasing, blue to red) and investment benefits (increasing, light to dark).

Table 1 | Reconfiguring global exposure to incident human water security threat through technology investments

Income level*	GDP (PPP)† (10^3 US dollars per capita)	Global population by income level‡ (%)	Fraction of population within each income level‡ where HWS threat >0.75	
			Incident HWS threat (%)	Adjusted HWS threat (%)
Low	<1	7	43	96
Lower middle	1–5	61	85	88
Upper middle	5–10	14	79	61
High	>10	18	90	5

Percentages were determined by summing populations within national-scale designations of income that were exposed initially to high levels of incident human water security (HWS) threat and then residual adjusted human water security threat, after benefits were tabulated and results re-scaled globally. Differences in the last two columns indicate a major global-scale realignment of relative risk, with human water security most assured for wealthy nations and least so for the world's poor. Investments are represented by existing infrastructure comprising water supply, use and delivery services, plus access to waterways (specific driver data sets and calculation procedures used are given in Supplementary Methods 'Overview').
* Approximated from World Bank categories[50].
† Classifications are for 2008[50].
‡ Computed over the discharging landmass.

variability takes a 38% toll on gross domestic product (GDP)[2]. The number of people under chronically high water scarcity, many of whom are poor, is 1.7 billion or more globally[2,3,15], with 1.0 billion of these living in areas with high adjusted human water security threat (>0.75).

Contrasts between incident and adjusted human water security threat are striking when considered relative to national wealth. Incident human water security threat is a rising but saturating function of per capita GDP, whereas adjusted human water security threat declines sharply in affluent countries in response to technological investments (Fig. 5). The latter constitutes a unique expression of the environmental Kuznets curve[33], which describes rising ambient stressor loads during early-to-middle stages of economic growth followed by reduced loading through environmental controls instituted as development proceeds. The concept applies well to air pollutants that directly expose humans to health risks, and which can be regulated at their source[33]. The global investment strategy for human water security shows a distinctly different pattern. Rich countries tolerate relatively high levels of ambient stressors, then reduce their negative impacts by treating symptoms instead of underlying causes of incident threat.

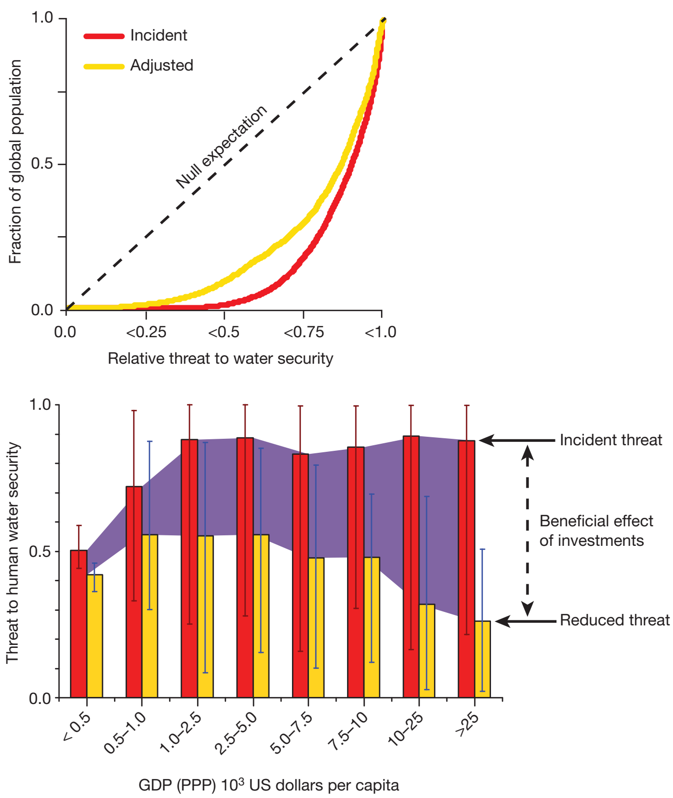

Figure 5 | Globally aggregated human water security threat indices linked to population and level of economic development. Investments in engineering infrastructure and services improve water security, with their value expressed here in reduced threat units. Net benefits accrue to only a fraction of global population (top). Technology investments greatly benefit wealthy nations, shifting them from most to least threatened (bottom). The fraction of global population is over the discharging landmass. GDP (PPP) refers to annual gross domestic product in 2008 at purchasing power parity exchange[50], with associated grid-cell means of incident human water security threat (red bars) and reduced threat (yellow; see Fig. 4). Vertical lines represent ranges.

The biodiversity dilemma

We find that 65% of global river discharge, and the aquatic habitat supported by this water, is under moderate to high threat (>0.5). Yet, we were unable to compute a globally meaningful estimate of adjusted biodiversity threat due to the paucity of relevant data but also the reality that much less comprehensive investment has been directed to biodiversity conservation than to human water security[34,35]. Limited global investment in environmental protection and rehabilitation means that stresses on biodiversity for many locations go unabated. In addition, the substantial reductions in incident human water security threat through point-of-service strategies emphasizing water supply stabilization and delivery incorporate some of the very factors that negatively impact biodiversity through flow distortion and habitat loss. This helps to explain why environmental Kuznets curve benefits that typically rise with increasing levels of affluence do not necessarily hold for fish biodiversity[36] or water quality[33], and why river restoration efforts often fail[29]. Indeed, Europe still suffers significant biodiversity threat despite concerted, high-level efforts aimed at achieving the contrary[35,37].

The worldwide pattern of river threats documented here offers the most comprehensive explanation so far of why freshwater biodiversity is considered to be in a state of crisis[38–41]. Estimates suggest that at least 10,000–20,000 freshwater species are extinct or at risk[8,42], with loss rates rivalling those of previous transitions between geological epochs like the Pleistocene-to-Holocene[43]. Although we have not established causality, our results establish a precursor to future studies that could link the role of stressors to biodiversity loss more directly.

Rising to a dual challenge

Given escalating trends in species extinction, human population, climate change, water use and development pressures[44], freshwater systems will remain under threat well into the future. Without major policy and financial commitments, stark contrasts in human water security will continue to separate rich from poor. We remain off-pace for meeting the Millennium Development Goals for basic sanitation services[31], a testament to the lack of societal resolve, when one considers that a century of engineering know-how is available and returns on investment in facilities are high[2]. For Organisation for Economic Co-operation and Development (OECD) and BRIC (Brazil, Russia, India and China) countries alone, 800 billion US dollars per year will be required in 2015 to cover investments in water infrastructure, a target likely to go unmet[30]. The situation is even more daunting for biodiversity. International goals for its protection lag well behind

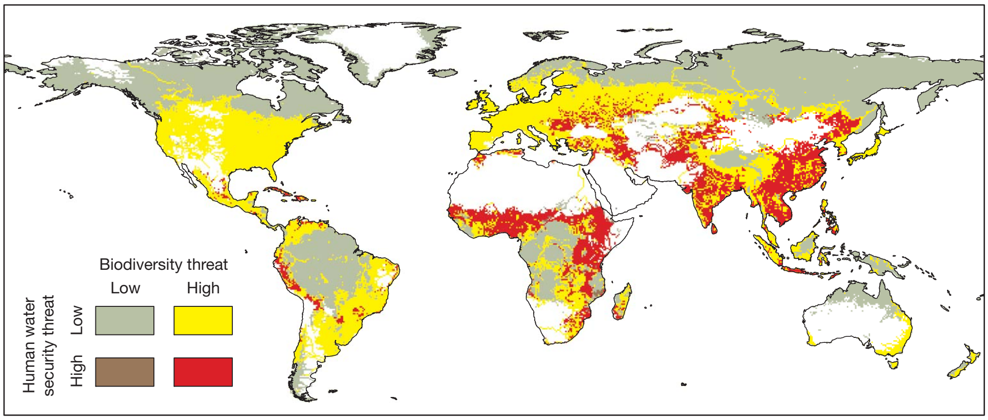

Figure 6 | Prevailing patterns of threat to human water security and biodiversity. Adjusted human water security threat is contrasted against incident biodiversity threat. Much of the developed world faces the challenge of reducing biodiversity threat and protecting biodiversity, while maintaining established water services. The developing world shows tandem threats to human water security and biodiversity, posing an arguably more significant challenge. Large, contiguous areas of low threat to biodiversity and human water security remain where dense population and agriculture are absent. These contrasts help to identify target regions and investment strategies to enhance water stewardship and biodiversity protection[34,45]. In this Figure, a breakpoint of 0.5 delineates low from high threat.

expectation and global investments are poorly enumerated but likely to be orders of magnitude lower than those for human water security[35,45], leaving at risk animal and plant populations, critical habitat and ecosystem services that directly underpin the livelihoods of many of the world's poor[46]. Left unaddressed, these linked human water security–biodiversity water challenges are forecast to generate social instability of growing concern to civil and military planners[47].

Our threat maps enable spatial planning to enhance water security for humans and nature[16]. Although our intent is not to develop formal priorities to mitigate risk, we present a final analysis that is instructive in considering options. Comparing adjusted human water security to incident biodiversity threats highlights regions where either human water security or biodiversity challenges, or their conjunction, predominate (Fig. 6). Such patterns are important to identify because the main stressors determining human water security and biodiversity threat are sometimes distinct, thus requiring different and potentially conflicting management solutions (Fig. 3).

In remote areas with low indices of both human water security and biodiversity threat, preserving critical habitat and ecosystem processes may be the single best strategy to contain future risk, yet the issue of who will pay for such protection is unresolved[34,45]. Solutions for densely settled regions will be more elusive. Although there may be easy consensus on controlling factors that lead to both human water security and biodiversity threat (for example, pollution), the decision to construct large-scale dams is a prime example of how development pressure is often at odds with biodiversity conservation and thus more contentious[11,48]. In populated regions of the developed world, existing human water security infrastructure will require re-engineering to protect biodiversity while retaining human water services. Across the developing world, establishing human water security for the first time while preserving biodiversity constitutes a dual challenge, best met through integrated water resource management[2] that expressly balances the needs of humans and nature. Although our results offer prima facie evidence that society has failed to institute this principle broadly, there are promising, cost-effective approaches to preserve and rehabilitate ecosystems[29]. Engineers, for instance, can re-work dam operating rules to maintain economic benefits while simultaneously conveying adaptive environmental flows for biodiversity[49]. Protecting catchments reduces costs for drinking water treatment, whereas preserving river floodplains sustains valuable flood protection and rural livelihoods[3]. Such options offer developing nations the opportunity to avoid the high environmental, economic and social costs that heavily engineered water development systems have produced elsewhere[11].

The need to mobilize financial resources to support integrated approaches remains urgent, lest further deterioration of fresh water becomes the accepted norm[2,34]. Habitat monitoring[24–26] and spatially explicit species inventories[7] are essential in evaluating the success of investments[31,34] and detecting the emergence of new challenges. Trade-offs and difficult choices involving competing stakeholders are already commonplace[2,3,48] and resolving these dilemmas more effectively requires high-resolution spatial approaches that engage policymakers and water managers at scales relevant to their decisions, including sub-national administrative units, river basins and individual stream reaches. Uniting our current approach with ocean-based assessments[16,17] will identify areas where improved freshwater and land management would benefit the world's impaired coastal zones. If climate mitigation is any guide, a generational timeframe may be necessary to stimulate sufficient political willpower to address the global river health challenge. In the meantime, a substantial fraction of the world's population and countless freshwater species remain imperilled.

METHODS SUMMARY

Maps of incident threat to river systems were based on spatially explicit data depicting 23 stressors (drivers), grouped into four major themes representing environmental impact. We chose drivers based on their documented role in degrading river systems and the availability of global-scale information with sufficient fidelity and spatial resolution. Conceptual and computational details are given in Supplementary Methods. Briefly, impacts of individual drivers originated from the spatial distribution of loadings onto 30′ (latitude × longitude) grid cells covering the actively discharging portion of global landmass bearing local runoff or major river corridor flow (46,517 cells representing 99.2 million km^2). Driver loadings were routed down digital river networks[23], accounting for new stressor inputs, and dilution or concentration from tributary mixing, based on spatial changes in river discharge determined from net precipitation and abstraction, where appropriate. Global, high-resolution maps of each driver were then standardized using a cumulative density function that ranked all grid cells, yielding final driver scores between 0 and 1 that reflect the relative stressor level on each cell across the globe. The re-scaled driver scores were combined into overall incident threat indices using a two-tiered relative weight matrix derived from expert opinion (first among drivers within each theme, then among themes). We used separate weights to capture differences between human water security and biodiversity perspectives on each driver and theme (Supplementary Table 1). Separately, we applied the same procedure to an additional set of five drivers to derive an index of the beneficial effects of water-related capital and engineering investments[2,3,6,31] in alleviating threats to human water security. By applying this investment benefits factor to the incident human water security threat index and re-scaling the global results, we produced the map of relative adjusted human water security threat (Fig. 4). There is insufficient information to map corresponding adjustments to incident biodiversity threat.

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