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Global threats to human water security and river biodiversity

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Rivers in Crisis: Global Water Insecurity for Humans and Biodiversity

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SUMMARY

Protecting the world's surface water resources requires a diagnosis of threat over a broad range of scales, from global to local. We present the first global synthesis to unite human and biodiversity perspectives on water security using a spatial framework that quantifies multiple stressors and accounts for downstream impacts. We find nearly 80% of world population is exposed to high threat. Huge investments in water technology enable wealthy nations to offset high stressor levels but without remedying their underlying causes and leaving the poor vulnerable. A similar lack of precautionary investment jeopardises biodiversity, with habitats representing 65% of continental discharge classified as moderately to highly threatened. The cumulative threat framework offers a tool for prioritising policy and management responses to this crisis, and demonstrates that limiting threats at their source rather than through costly remediation is an effective strategy to assure global water security for both humans and aquatic biodiversity.

Water is widely regarded as the world's most essential natural resource, yet freshwater systems are directly threatened by human activities[1,2,3] and stand to be further impacted by anthropogenic climate change[4]. Direct stressors include widespread land cover change, urbanisation, industrialisation, and engineering schemes like reservoirs, irrigation, and interbasin transfers that maximise human access to water[1,5]. The benefits of water provision on economic productivity[2,6] are often accompanied by impairment to ecosystems and biodiversity, with potentially grave but unquantified costs[3,7,8]. Devising interventions to reverse these trends, such as conventions to protect aquatic biodiversity[9,10] 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 figure prominently in assessments of the state of human development[6], ecosystem services[3], and their combination[12,13,14]. Yet global assessments of water resources[2] are fragmented and generally confined to country-level statistics, seriously limiting efforts to prioritise their protection and rehabilitation[15]. Spatially explicit analyses have taken understanding of human impacts 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 despite a recognised 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 whether this objective can be advanced globally, we map *Incident Threats* to human water security (*HWS*) and biodiversity (*BD*), where the term *Incident* refers to the exposure to a diverse array of stressors at a given location. Many stressors threaten *HWS* and *BD* 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 aquatic biodiversity by impeding faunal migration and changing flow regimes. Similarly, non-native species threaten *BD* but are typically inconsequential to *HWS*.

We report here on a global-scale analysis of threats to freshwater 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 distinctive *HWS* and *BD* stressors 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 net impact under alternative value systems for *BD* and *HWS*. Enhancing the spatial resolution by orders-of-magnitude over prior studies (using 30' latitude/longitude grids) allows us to rigorously test prior assertions on the state of world rivers and to identify key sources of threat at sub-national spatial scales that are relevant to environmental management. Finally, we make the first spatial assessment of the global benefits accrued from technological investments aimed at reducing threats to *HWS*, revealing previously unrecognized consequences on people and biodiversity associated with traditional water management approaches that are employed extensively over the global domain.

Global Patterns of Incident Threat

Using a global geospatial framework[22], we aggregated the relative strength of individual stressors to produce a cumulative *Incident Threat* index. The resulting 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, SI Figure 1)**. Similar to the approach of Halpern et al.[16,17] for marine systems, multiple stressors (expressed as 23 geospatial drivers under four themes) were combined with relative weights to determine cumulative threat indices. Expert assessment of stressor impacts on *HWS* and *BD* produced two distinct weighting sets, which in turn yielded separate maps of *Incident Threat* reflecting each perspective.

We find that nearly 80% (4.8Bn) of the world's population lives in areas where either *Incident HWS* or *BD Threat* exceeds the 75th percentile. Regions of intensive agriculture and dense settlement show high *Incident Threat* (**Figure 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 (*e.g.,* Argentina, Sahel, Central Asia, Australian Murray-Darling basin). Within the broad regions separating intensively settled basins and remote areas, as in North America and northern Asia (**Figure 1**), *Incident Threat* arises largely from transboundary atmospheric pollution.

Spatial differentiation of *Incident Threat* also arises from the interplay 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 of the world are incapable of attenuating the impacts of concentrated development. Over 30 of the 47 largest rivers that collectively discharge half of global runoff to the oceans show at least moderate *Threat* levels (>0.5) at river mouth, with from eight (for *HWS*) to fourteen (*BD*) showing very high *Threat* (>0.75).

In contrast, a strikingly small fraction of the world's rivers remain unaffected by humans. Remote areas of the globe, including the high north (Siberia, Canada, Alaska) and unsettled parts of the tropical zone (Amazonia, northern Australia), show the lowest *Threat* levels. A mere 0.16% of Earth's area experiences low scores for every contributing stressor (*i.e.,* lowest decile globally).

Upstream-downstream transects of *Incident Threat* yield signatures of *HWS* or *BD* conditions unique to each river and that arise from the action of hydrology and networked flow paths (**Figure 2**). Such transects highlight the diversity of stressors in river 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* generally grow with river size (e.g., Huang He and Nile), 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 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 river mouth. The proliferation of densely settled areas including mega-cities means that many rivers of the coastal zone show high *Threat* over virtually their entire length (*e.g.,* Paraíba do Sul [São Paulo], Pasig [Manila], Ogun [Lagos]).

Our results are supported by field surveys of river health. Recent sampling of rivers across the United States showed impairment in 750,000 km or 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]. Global reviews based on water monitoring[26] and modelling studies[27] have shown broadly similar patterns to the *Threat* maps, but only considering pollution. Our results are also congruent with previous threat assessments conducted at the coarser drainage basin 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 we considered, our study and all prior assessments[7,28] of anthropogenic impacts are conservative due to insufficient information on xenobiotic 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 ($\leq$ Strahler Order 5; 1:62,500 scale)[23] are additional limitations. Finally, uncertainties in stressor data are inevitable, but our standardisation procedures limited their influence on our results (**Supplementary Information**).

Chief Determinants of Global Threat

Globally, the *Watershed Disturbance, Pollution,* and *Water Resource Development* themes are spatially well-correlated ($r \geq 0.75$ for *HWS*, $p<0.001$; $r \geq 0.62$ for *BD*, $p<0.001$; $n=46517$), reflecting the collective impacts of anthropogenic activity in densely populated basins (**Supplementary Table 3**). *Biotic Factors* are less strongly correlated with other themes ($r \leq 0.37$ for *HWS*, $p<0.001$; $r \leq 0.44$ for *BD*, $p<0.001$), reflecting the long reach of inland fisheries, and the introduction and dispersal of non-native fish species beyond populated areas (**Supplementary Table 3**). *Incident Threats* to *HWS* and *BD* are themselves well-correlated (**Figure 1**), with the highest levels in heavily settled regions.

In high *Incident Threat* (>0.75) regions, *Water Resource Development* and *Pollution* are dominant contributing themes for both *HWS* and *BD* (**Figure 3**), and they typically occur together. Their importance derives from the waterborne nature of the stressors; water pollution is distributed throughout the world's rivers that coincidentally accompany widespread water engineering and use. *Watershed Disturbance* and *Biotic Factors* play a secondary role in high *Incident Threat* areas as their stressors often represent more localised effects.

High levels of *Incident HWS* and *BD Threat* emerge only from the spatial concordance of high scores for many stressors (**Figure 3**). Stressors within the *Watershed Disturbance* and *Pollution* themes generally act in unison across *HWS* and *BD*, highlighting shared sources of impact, with cropland the predominant watershed stressor and nutrient, pesticide, and organic loads dominating pollution sources. For the remaining themes, stressors act more independently, reflecting distinctions between *HWS* and *BD* perspectives. Stressors associated with impoundments and flow depletion are the clearest sources of *BD Threat* by directly and strongly degrading habitat, while negligibly affecting *HWS*. 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 have enhanced *HWS* for millennia. To capture this effect, we derived an *Investment Benefits Factor*, depicting supply stabilisation, improved water services, and access to waterways, then used it to calculate an *Adjusted HWS Threat*. Comparison of *Incident* and *Adjusted HWS Threats* reveals that technological investments produce globally-significant, positive impacts on human water security and substantially reconfigure exposure to threat (**Table 1, Figure 4**). Developed regions displaying high *Incident Threat* (*e.g.,* United States, Europe) show much lower *Adjusted Threat* indices, gaining benefit from massive investments in water infrastructure, the total value of which is in the trillions of USD[2,3,30]. Investments by high income countries benefit 850M people, lowering their exposure to high *Incident Threat* by 95%, with corresponding values for upper middle income countries of 140M and 23%. Minimal investment in developing countries means vulnerabilities remains high, with 3.4Bn poor people 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 fragmentary global data[2,6,12] (**Figure 4**). Most of Africa, large areas in central Asia and countries including China, India, Peru, or Bolivia struggle with basic water services like clean drinking water and sanitation[31], and emerge here as regions of greatest *Adjusted HWS Threat*. Lack of water infrastructure yields direct economic impacts. Drought and famine-prone Ethiopia, for example, has 100 times less reservoir storage per capita than North America[2] and its climate and hydrologic variability takes a 38% toll on GDP[32]. The number of people under chronically high water scarcity, many of whom are poor, is 1.7Bn or more globally[2,3,15], with 1.0Bn of these living in areas with high *Adjusted HWS Threat* (>0.75).

Contrasts between *Incident* and *Adjusted HWS Threat* are striking when considered relative to national wealth. *Incident HWS Threat* is a rising but saturating function of per capita GDP, while *Adjusted HWS Threat* declines sharply in affluent countries in response to technological investments **(Figure 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, which can be regulated at the source[33]. The global investment strategy for *HWS* shows a distinctly different pattern. Rich countries tolerate relatively high levels of ambient stressors, then reduce negative impacts by treating symptoms instead of underlying causes of *Incident Threat*.

The Biodiversity Dilemma

We were unable to compute a global estimate of adjusted *BD Threat* due to the paucity of relevant data but also the reality that much less comprehensive investment has been directed to *BD* conservation than to *HWS*[34,35]. Limited global investment in environmental protection and rehabilitation means that stresses on *BD* for many locations are beyond control. In addition, the substantial reductions in *Incident HWS Threat* through point-of-service strategies emphasising water supply stabilisation and delivery incorporate some of the very factors that negatively impact *BD* 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 *BD Threat* despite concerted, high-level efforts aimed at achieving the contrary[35,37].

While we have not established causal links, our results establish a precursor to future studies that could link the role of stressors to biodiversity loss more directly. In addition, the worldwide pattern of river threats documented here offers the most comprehensive explanation to date 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].

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 *HWS* will continue to separate rich from poor. We are already off-pace for meeting the *Millennium Development Goals* for basic water services[31], a testament to the lack of political willpower since a century of engineering know-how is available and returns on investment in facilities are high[2]. For OECD and BRIC countries alone, \$800Bn *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 *BD*. International goals for its protection lag well behind expectation and global investments are poorly enumerated but likely to be orders of magnitude lower than those for *HWS*[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 *HWS-BD* 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[cf. 16]. While our intent is not to develop formal priorities to mitigate risk, we present a final analysis that is instructive in considering options. Comparing *Adjusted HWS* to *Incident BD Threats* highlights regions where either *HWS* or *BD*, or their conjunction, predominate (**Figure 5**). Such patterns are important to identify, since the main stressors determining *HWS* and *BD Threat* are sometimes distinct, thus requiring different and often conflicting management solutions (**Figure 3**).

In remote areas with low indices of both *HWS* and *BD 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. While there may be easy consensus on controlling factors that lead to both *HWS* and *BD Threat* (*e.g.,* pollution), the decision to construct large-scale dams is a prime example of how development pressure is often at odds with *BD* conservation and thus more contentious[11,48]. In populated regions of the developed world, existing *HWS* infrastructure will require re-engineering to protect *BD* while retaining human water services. Across the developing world, establishing *HWS* for the first time while preserving *BD* constitutes a dual challenge, best met through integrated water resource management[2] that expressly balances needs of humans and nature. While 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 achieve economic targets while simultaneously conveying adaptive environmental flows for biodiversity[49]. Protecting watersheds reduces costs for drinking water treatment, while 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 hard-path water development has produced elsewhere[11].

The need to mobilise financial resources to support integrated approaches remains urgent, lest further deterioration of freshwaters 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. Tradeoffs and difficult choices involving competing stakeholders are already the order of the day[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 world 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 under **Supplementary Methods**. Briefly, impacts of individual drivers originated from the spatial distribution of loadings onto 30' (latitude x longitude) cells covering the actively discharging portion of global landmass bearing local runoff or major river corridor flow (46,517 grid 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 standardised 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 (*HWS*) and biodiversity (*BD*) 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 *HWS*. By applying this *Investment Benefits Factor* to the *Incident HWS Threat* index and then re-ranking the global results, we produced the map of *Adjusted HWS Threat*. There was insufficient information to map corresponding adjustment of *Incident BD Threat*.

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Author Contributions

All authors contributed to project conceptualisation during workshops led by CV. CV designed the global analysis, and PM, AP, PG, and MG designed and implemented the analytical approach with essential input from SB, DD, CS, PD, and CR. AP, PG, and SG developed the database and mapping tools. Several authors led a separate component of data set development and all provided quality assurance. CV, PM, and MG wrote the manuscript with input from all authors.

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Table 1. **Reconfiguration of global exposure to *Incident HWS Threat* before and after beneficial water infrastructure and service investments.** Percentages were determined by summing populations within national-scale designations of income that were exposed initially to high levels of *Incident HWS Threat* and then to residual *Adjusted HWS Threat*, after benefits were tabulated and results re-ranked globally. Differences between the two percentages indicate a major global-scale realignment of relative risk, and reflects the reality that human water security is most assured for wealthy nations and least so for the world's poor. Spatial patterns are given in **Figure 4** over discharging landmass.

Income Level[1]	**GDP (PPP)**[2] (10^3 USD per capita)	**Global Population by Income Level** (Percent)	**Fraction of Population within Each Income Level HWS Threat >0.75**	
			Incident HWS Threat (Percent)	**Adjusted HWS Threat** (Percent)
Low	< 1	7	43	96
Lower Middle	1 -5	61	85	88
Upper Middle	5 - 10	14	79	61
High	> 10	18	90	5

[1]Approximated from World Bank categories[50].

[2] Classifications are for 2008[50].

Figure 1. Global geography of *Incident Threat* to human water security (HWS) and biodiversity (BD). The maps demonstrate pandemic impacts on both *HWS* and *BD* and are highly coherent, though not identical (*BD Threat* = 0.964 *HWS Threat* + 0.018; $r = 0.97$, $p<0.001$). Statistical independence of input drivers (stressors) was also confirmed (mean $|r| = 0.34$; $n = 253$ comparisons). Regional maps exemplify main classes of *HWS Threat* (see **Main Text**). Spatial patterns proved robust in sensitivity tests using a variety of analytical methods (**Supplementary Methods**, **Discussion**). *Threat* indices are relative and normalised over discharging land.

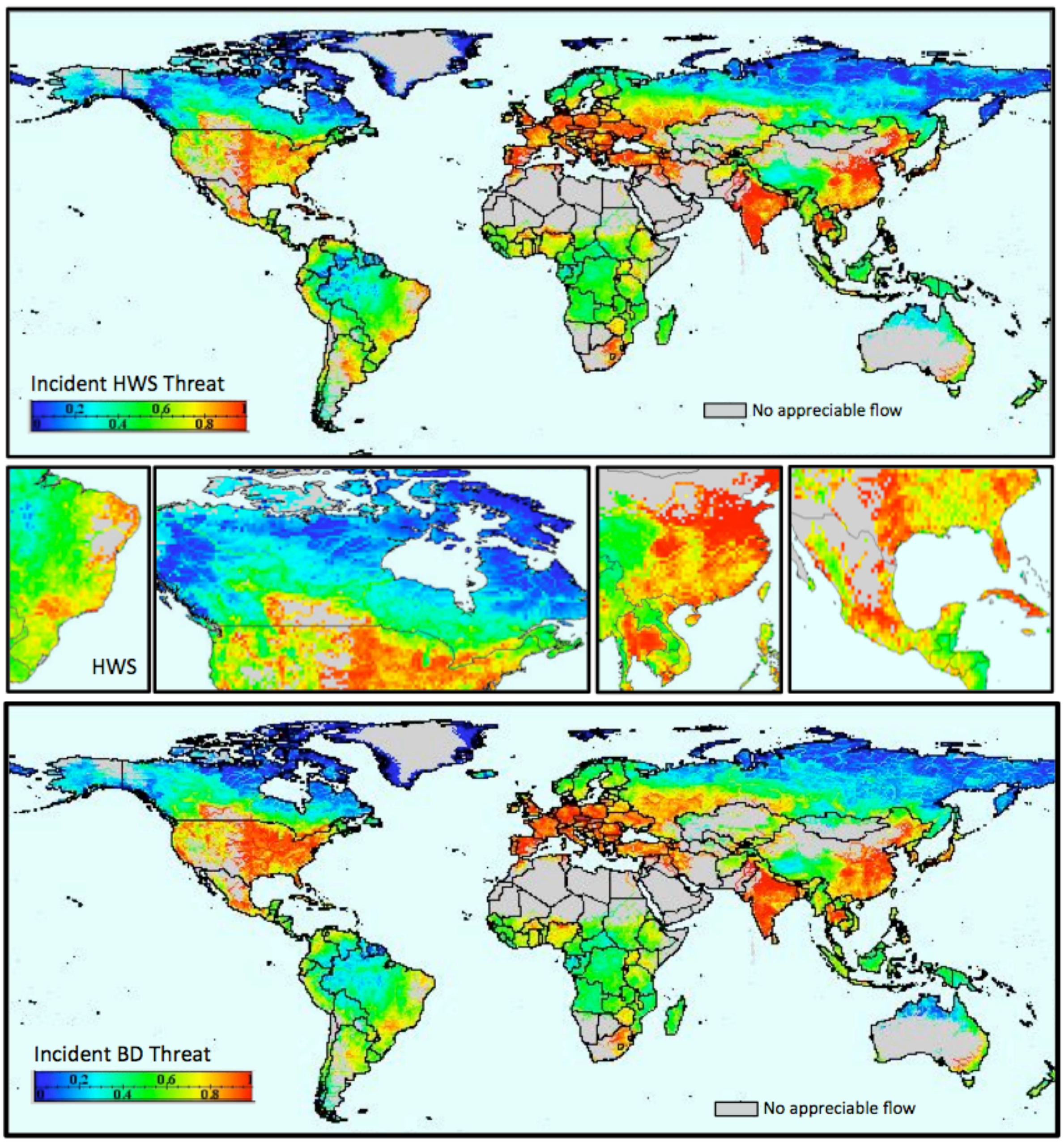

Figure 2. ***Incident Biodiversity Threat* transects from headwater to ocean.** Distinctive patterns characterise each river system resulting from complex spatial patterns of stressor loadings across the watershed plus mixing of higher and lower concentration tributary waters through river networks. 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 identify critical areas at risk, as shown for the Nile. 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.

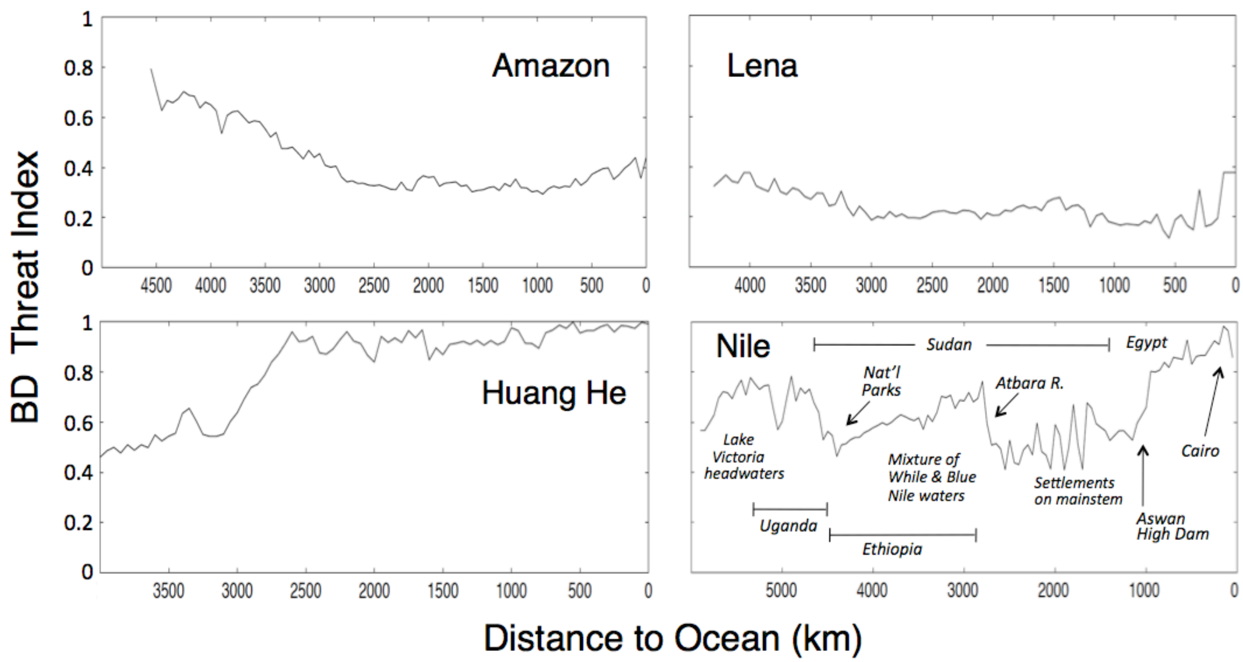

Figure 3. Theme and driver contributions in areas where *Incident Threat* exceeds the 75th percentile. High *Incident Threat* typically arises from the spatial coincidence of multiple themes and/or drivers of stress acting in concert. Aggregate influence of each of the four themes (**left**) is relative to their contribution to overall *Incident Threat*. For the individual drivers (**right**), scores are relative to other drivers in the same theme. Bar summarizes results over the entire globe.

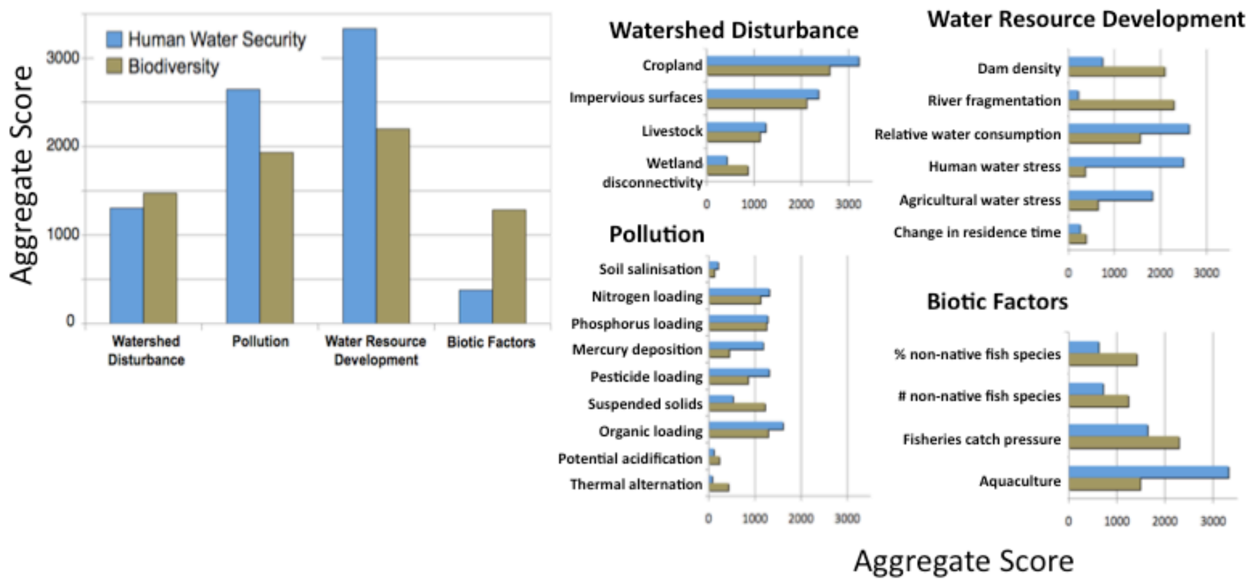

Figure 4. Shifts in spatial patterns of relative *HWS Threat* after accounting for water technology benefits. Inset maps illustrate the analytical approach and net impact of investments over a North-South transect (***top***). *Incident HWS Threat* is reduced to *Intermediate Threat* (**inset**), which is then globally re-ranked into *Adjusted HWS Threat*. The final map shows relative units: areas with substantial technology investments have effectively reduced 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; see **Supplementary Figure 3**).

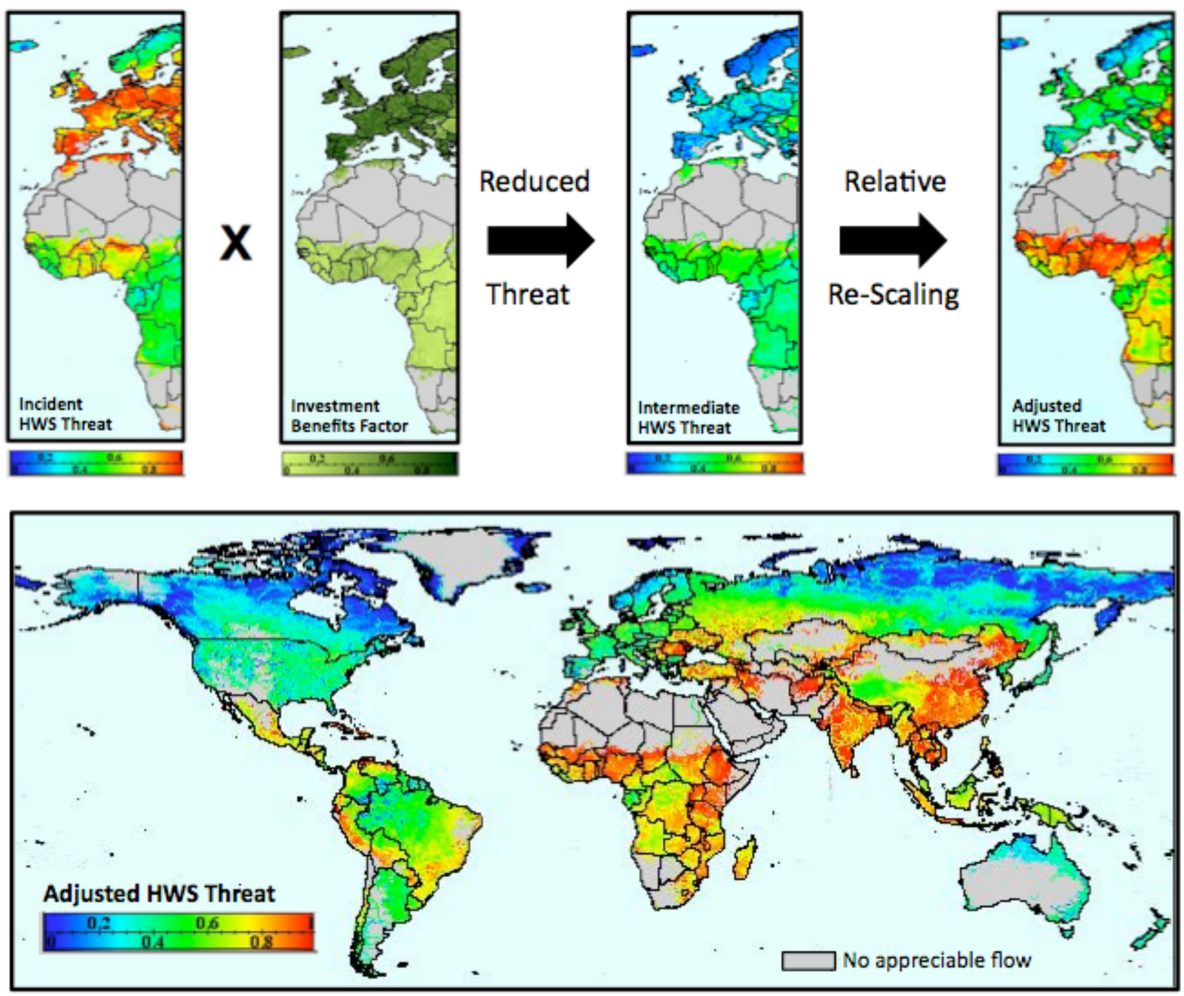

Figure 5. Globally aggregated *HWS Threat* indices linked to level of economic development. Investments in engineering infrastructure and services improve water security, with their value expressed here in reduced *Threat* units (*top*). GDP (PPP) refers to annual gross domestic product in 2008 at purchasing power parity exchange[50], with associated means of *Incident HWS Threat* (red) and *Adjusted HWS Threat* (yellow). Vertical lines represent ranges. Such investments greatly benefit wealthy nations, shifting them from most to least threatened status, with net benefits accruing to only a fraction of global population (*bottom*). Fraction of global population refers to the discharging landmass.

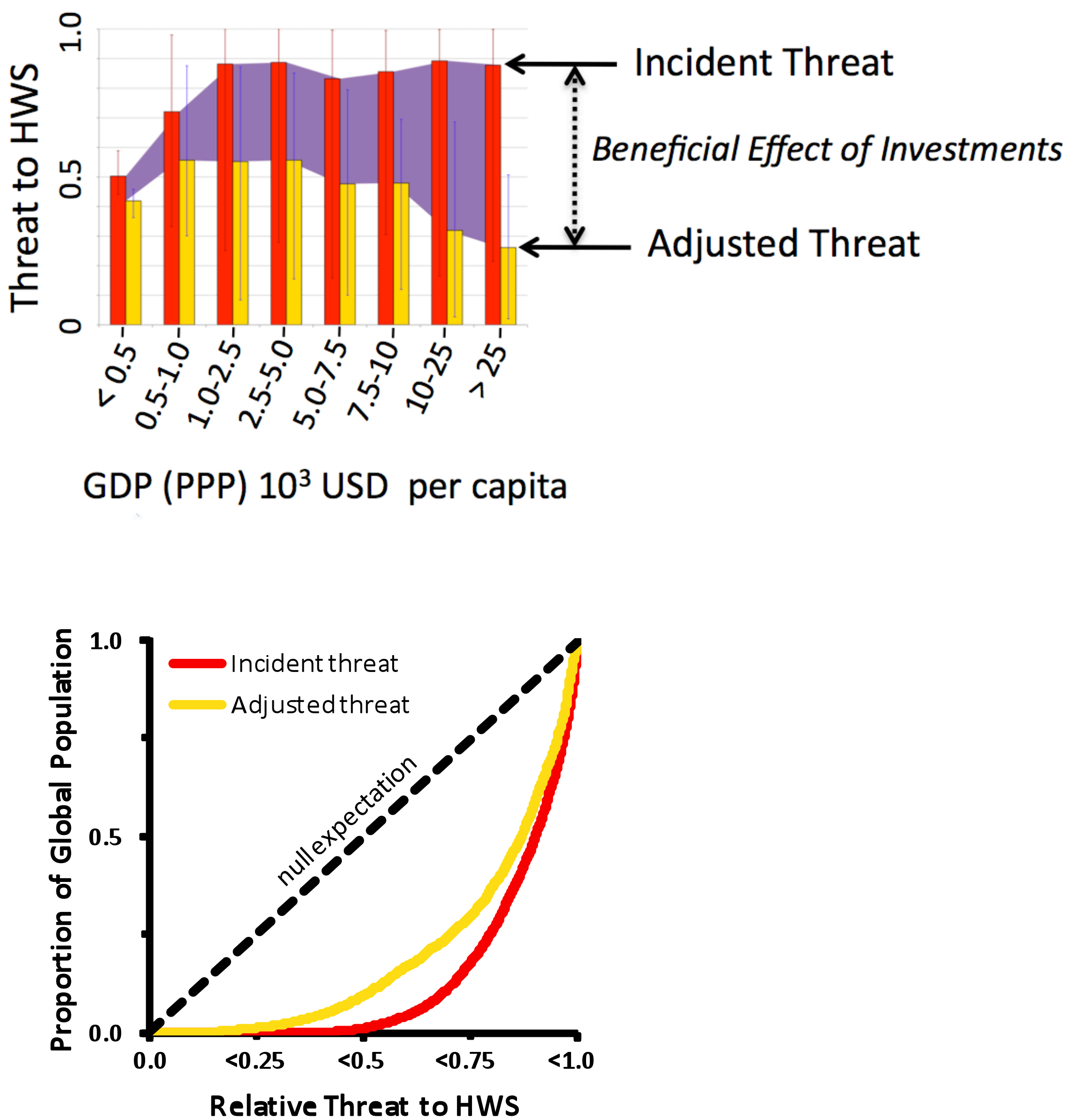

Figure 6. Prevailing patterns of *Threat* to human water security and biodiversity. *Adjusted HWS Threat* is contrasted against *Incident BD Threat*. The geographic pattern shows large, nearly contiguous blocks where *HWS Threat, BD Threat*, or both predominate. Much of the developed world faces the challenge of reducing *BD Threat* and protecting biodiversity, while maintaining established water services. The developing world often shows tandem *Threats* to *HWS* and *BD*, posing an arguably more significant challenge. These contrasts help to identify target regions and investment strategies in water stewardship and biodiversity protection[34,45]. A breakpoint of 0.5 delineates low from high *Threat.*