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Human Impact on Freshwater Ecosystem Services: A Global Perspective

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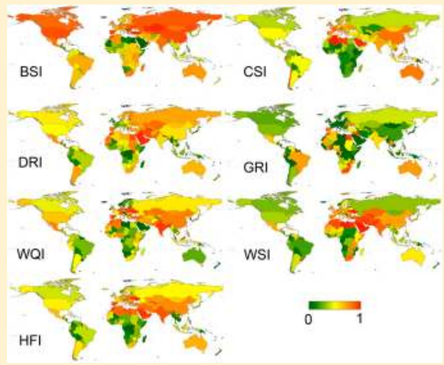
S Supporting Information

ABSTRACT: Human environmental change influences freshwaters as well as the regulating, provisioning, and cultural services that ecosystems provide worldwide. Here, we assess the global human impact on the potential value of six freshwater ecosystem services (ES) and estimate the proportion of each used globally (the mean value across all countries is in parentheses): biodiversity (0.37), disturbance regulation (0.24), commodities (0.39), greenhouse gases (0.09), water availability (0.10), and water quality (0.33). We also created a composite index of the impact. Using different valuation schemes, we found that humans have used potential global freshwater ES scaled by a relative value of roughly 4–20%, with a median of 16%. All countries use a considerable amount of the potential ES value, invalidating the idea that wealthier countries have less impact on their ES once they have developed. The data suggest that humans have diminished the potential ES provided by freshwaters across the globe and that factors associated with high population growth rates are related to the overall degradation.



■ INTRODUCTION

Anthropogenic impacts on freshwaters are global and include flow alteration, pollution, species extinctions,[1] species invasions, thermal alterations, global climate change, and increases in ultraviolet radiation. Given that humans use a substantial portion of the supply of freshwater globally,[2] require supplies of freshwater for survival, and are altering water security across the planet,[3] a global perspective on impact is warranted. One way to characterize the global impacts on freshwaters now and in the future is to place them into the context of the ecosystem services (ES, the benefits humans obtain from ecosystems) that freshwaters provide to humanity. Such analyses can pinpoint diverse effects and complex interactions among the drivers influencing the potential availability of freshwater as well as the supply rates of ES worldwide.[4]

The relationships among the drivers of changes in ES are generally complex, and managers must often weigh the importance of one ES at the expense of another.[5−7] Eutrophication exemplifies the contrasting anthropogenic impacts on ES. Nutrient addition can stimulate primary producers and can increase fish production, but it can decrease diversity and damage water quality with taste, odor, and toxicity problems associated with cyanobacterial blooms.[8] Consequently, managers could be forced to decide how the ES of fish production are weighted against water quality. Once such a framework is in place; multiobjective management approaches can optimize benefits and minimize harm.[9]

Factors (drivers) influencing ES have been identified for many spatial and temporal scales (e.g., Limburg et al.[10]). The incorporation of ES into a broader context in which their relative rankings are included as well as how the components of the ES are related to each other is just beginning to be explored (e.g., Naidoo et al.[11] and Nelson et al.[6]). The preservation and maintenance of water quality and quantity requires cross-disciplinary cooperation,[12] and an understanding of ES along with how human activities influence their availability might guide such cooperation.[13] As a next step, ES[14,15] can be used to rank management options in cases such as restoration,[16] water quality,[13] and eutrophication control.[8]

We assessed the global human impact on potential freshwater ES. The general approach was based on finding the proportion of each category of potential ES that is currently used. First, we constructed a series of indices that gauge human impacts on continental waters as categorized by ES. Next, a composite index was created by summing those proportions after they were each weighted by the ratio of the value of the category to the total potential value of ES across categories (Figure 1). Human use was assessed within categories of ES by creating a biodiversity stress index (BSI), freshwater commodities stress index (CSI), disturbance regulation index (DRI), greenhouse gas release index (GRI), water quality stress index (WQI), and water availability stress index (WSI). These categories were chosen on the basis of the features of each ES for which we could find data that indicated their degree of use. Our categories map to the Millennium Ecosystem Assessment[15] categories of provisioning (CSI, WQI, and WSI), regulating (BSI (biodiversity as a form of disease regulation), DRI, and

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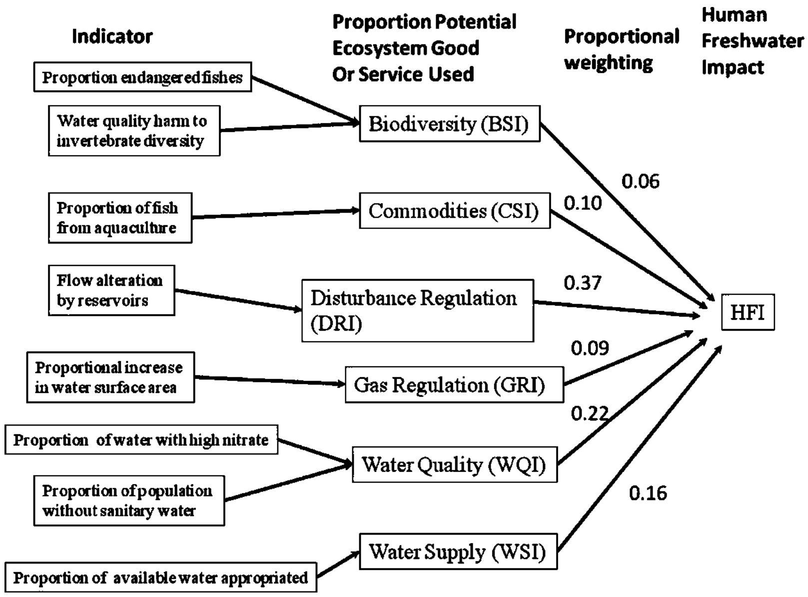

Figure 1. Conceptual diagram of the calculation of the proportion of ecosystem services used and how they are weighted to calculate overall impact. The values for proportional weighting are based on the median values from the literature and are reported in Table 1. See the text for the discussion on the specifics of how each box was calculated.

Table 1. Relative Importance for Each Category of Ecosystem Services As Reported from Six Sources That Had Values Per Unit Area for Freshwaters (Rivers, Lakes, and Wetlands)[a]

	data source								
ecosystem goods or services	1	2	3	4	5	6	mean value	median value	scaled median values
disturbance regulation (DRI)	0.50	0.42	0.55	0.14	0.17	0.16	0.32	0.29	0.37
water quality (WQI)		0.04	0.28	0.43	0.12	0.18	0.21	0.18	0.22
water supply (WSI)	0.42	0.48	0.05	0.10	0.13	0.12	0.22	0.13	0.16
commodities (CSI)	0.03	0.01	0.11	0.13	0.09	0.07	0.07	0.08	0.10
gas release (GRI)	0.01	0.02	0.00	0.13	0.21	0.20	0.09	0.07	0.09
biodiversity (BSI)	0.03	0.03	0.01	0.06	0.30	0.28	0.12	0.05	0.06

[a]Median values (scaled to 1) were used to calculate the proportional contribution of each category to the total values of freshwater ecosystem services for the overall human freshwater impact. The data were obtained for multiple systems, including (1) Global wetlands,[14] (2) Brazilian wetlands,[37] (3) U.S. wetlands,[16] (4) Sanyang wetlands,[38] (5) Australian reservoirs and dams,[35] and (6) Australian rivers.[35]

GRI,) and supporting (BSI), but they do not overlap with the cultural category. We then explored how different drivers (e.g., population and gross domestic product) influence the degree of impact on each categorical index of ES as well as the composite index. We took advantage of the idea that ES have been assigned values and that each ES has a maximum potential value (i.e., there are limits on the rate that ES are provided globally). However, our analyses were not sensitive to the actual values assigned but rather to the relative proportion of the value assigned to each category. Thus, we were able to use the relative rankings of ES on the basis of published values to scale the indices relative to each other and create an overall index of global human freshwater impact (HFI).

■ MATERIALS AND METHODS

Global Freshwater Ecosystem Services. We started with a set of categories of ES with global data available in which prior valuation frameworks had been assessed.[14,15] We did not include cultural values in our impact assessment because of difficulty with global accounting for these values. We constructed indices of anthropogenic stress on each of these categories of freshwater ES using global data sets (more on this later and in the Supporting Information). The variables were calculated at the finest possible grain size, but the final values were calculated per country because that is the unit under which most global data were available.

We estimated the BSI by dividing the number of freshwater threatened fish species (IUCN red list) by the total freshwater fish species richness[17] for each country. We also estimated the proportional reduction in aquatic invertebrate diversity using previously published empirical relationships between the percentage reduction in invertebrate species richness and the total water nitrogen concentration.[18−20] Each of these two aspects of diversity was weighted equally in our analyses, although we acknowledge the portion of the index regarding fish is likely a more robust measure of impact given the greater availability of data, and we treat the components separately in some statistical analyses.

We estimated CSI using the relationship between the wild fisheries capture production and freshwater aquaculture production because an indication of the overexploitation of fishery stocks occurs when capture production is replaced by aquaculture production.[21]

We estimated DRI, streamflow regulation in particular, using previously published estimates of the relative residence time of water in large reservoirs, as determined by hydrologic modeling.[22] Residence time is an indirect estimate that assumes countries that have highly modified their hydrology by impounding large portions of their runoff have also altered the natural capacity for disturbance regulation. An increase in impoundments also increases the surface area of water, leading to increases in greenhouse gas production. We estimated GRI by accounting for the relative increase in the surface area of freshwater attributable to reservoirs.[23]

We calculated WQI using the amount of surface water exceeding 10 mg L^{-1} nitrate−N[23] and the relative population density of people without access to sewage-treatment facilities (World Health Organization) to indicate the relative potential for contamination by human diseases. Nitrate contamination and a lack of access to clean water were weighted equally. Finally, we measured WSI by accounting for the proportion of available water used by humans in each country according to the CIA World Factbook.

We calculated the final values for the indices on a per-country basis because much of the data were only available at this resolution. All indices were scaled from 0 to 1 for mapping but not for statistical analyses. For mapping, each index was weighted on the basis of neighboring countries when mapping countries for which data were not available (Supporting Information). We used only countries for which all data were available for statistical analyses.

Human Freshwater Impact and Drivers. The HFI for each country was estimated by weighting each of the categorical indices by their proportional contribution to the literature-derived ES values. The overall proportion of the contribution of each ES, as calculated across all studies, was scaled to 1 because the sum of the medians of the proportions came out to be slightly less than 1. These values as well as the amount of the value was lost because of impact within each category were used to calculate impact per country:

$$\mathrm{HFI} = \sum_{i=1}^{j} P_{i,\text{total value}} P_{i,\max} I_i \quad (1)$$

With j categories of each impact index (I; i.e., BSI, CSI, DRI, GRI, WQI, and WSI), then the overall weighted index of human freshwater impact (HFI) is the sum of the products of the proportion of total value of ES made up by index I ($P_{i,\text{total value}}$), the maximum proportion of index I that is influenced by human impact ($P_{i,\max}$), and the value of each index I. $P_{i,\text{total value}}$ was computed from the literature, and the individual indices (I) were rescaled proportionally to the part of total potential value lost with the maximum effect for an individual index ($P_{i,\max}$). Although for some indices, the total potential value lost was 1 (i.e., some countries use all of the available water supply), for others it is not (i.e., diversity does not go to 0 with most forms of pollution, just to a much lower level). For more detailed information on how this proportion was set, see the Supporting Information. For mapping, HFI was also scaled from 0 to 1 for each country by dividing each estimate by the greatest value among all countries, $\mathrm{HFI}_{\max}$. The values of HFI for countries that had missing data were interpolated for mapping (but not for statistical analyses) by weighting each neighboring country's index value on the basis of the proportion of the total border shared (Supporting Information).

Given the divergence in the relative contributions among the published literature values, we calculated a scaled median across all of the studies and conducted a sensitivity analysis of the HFI to the variances across the studies to account for the fact that different studies reported different total values for ES and apportioned them differently among the categories. We assessed the accuracy of this value in two ways to explore the biases related to country size and the amount of water in each country. First, we weighted the contribution of each country's HFI by the surface area of the country relative to that of the sum area of all countries. Second, we weighted the countries by the surface area of water in each country relative to the sum of the total global water surface area and by the water availability in each country relative to the sum of total water available across all countries.

We chose drivers that we thought could have global impacts on ES and that data were available on a global scale. Drivers of ES that were investigated included population growth rate, economic activity, intensity of agricultural land use modification, intensity of agricultural production, and population density. (For the data sources, see the Supporting Information.)

Statistical Analyses. All statistics were done in Statistica ver. 9.0 (Statsoft, Tulsa, OK) on data from 114 countries for which all indices and all drivers could be assigned values. The 114 countries likely represent global conditions because they account for about 95% of the world population. Gross domestic product per km^2 varied by almost four orders of magnitude across these 114 countries, and the proportion of cropland and population density varied 138- and 437-fold, respectively. For statistical analyses, the proportional values were arcsin transformed for normality only when they were not normal, and other variables (gross domestic product per km^2, gross domestic product per capita, and population density per km^2) were log transformed when necessary. Economic and population growth rates did not require transformation because their distributions did not deviate from normal ($p > 0.05$, Kolmogorov−Smirnov). The relationships among the transformed indices and the potential drivers were examined by Pearson correlation to investigate the relationships among the indices, to control for mulit-colinearity among the drivers, and to find relationships of the drivers with the indices. The gross domestic product in each country was closely related to the values of agricultural production, energy use, and the number of reservoirs, so only gross domestic product per km^2 was used in the regression analyses.

Regression analysis of the relationship between the component indices and the HFI was used to understand which indices most strongly influenced the variation in HFI. Multiple forward stepwise linear regressions were used to assess more complex interactions among the drivers and the indices. The results were compared to model selections with Mallows CP (an information criteria index that can account for problems associated with adding additional drivers that increase statistical significance but offer little increased predictive ability), but they varied little from the straightforward regression results.

Environmental impact can follow an environmental Kuznets curve,[24] which leads to an expectation of an inverted U-shaped relationship of pollution as per-capita GDP rises.[25] We used a regression to fit all of our indices except for WQI against per-capita GDP (because per-capita GDP was used to calculate WQI) with a second-order polynomial. An inverted curve was indicated if the first-order term was positive, the second-order term was negative, and both terms were significant.

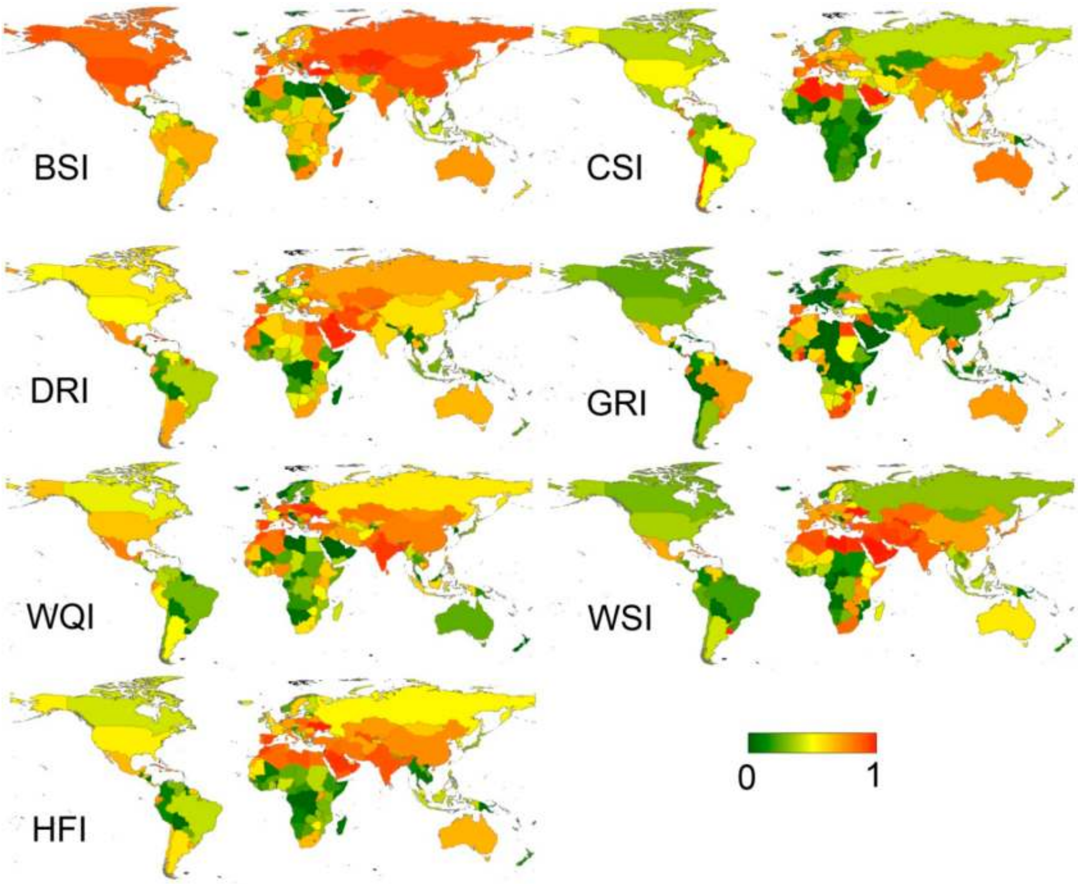

Figure 2. Distribution of stresses on the relative values of freshwater ecosystems globally. Each index is scaled to 1. BSI = biodiversity stress index, CSI = commodities stress index, DRI = disturbance regulation index, GRI = greenhouse gas release index, WQI = water quality stress index, WSI = water availability stress index, and HFI = the overall index of global human freshwater impact. HFI was created by determining the proportion of the value compromised in each index and summing within each country after scaling by the proportion of the total value made up by each individual ecosystem service category.

RESULTS

Human Freshwater Impact. The global plots indicated heterogeneity within and among the individual indices (Figure 2). The biodiversity and commodity impacts were greater overall followed by disturbance regulation and water quality (Figure 3A). Water stress (WSI) exhibited the greatest range because some countries use all of their water and others use almost none. Water quality also varied widely because some countries have highly contaminated water and others are fairly clean. Disturbance regulation and greenhouse gas release were difficult to set upper limits on with respect to the value compromised, so they were arbitrarily (conservatively) scaled such that 0.5 was the maximum value (Supporting Information).

Correlation (Table 2) as well as visual inspection of the global plots (Figure 2) indicated that patterns of human freshwater impact across the globe varied depending upon the index of ES being considered. Positive significant correlations among the indices indicated broadly consistent anthropogenic effects in spite of the varied strength and significance of the correlations.

The summed impact of these disturbances (i.e., the HFI) varied on average between 4 and 20%, depending on the weighting method, and they indicated that on average humans have used 16% of the global value of freshwater ES (Figure 3B). Sensitivity analysis indicated that methods that gave relatively high weighting to WSI (i.e., method 4) and BSI (i.e., methods 5 and 6) led to greater estimates of the overall impact. Finally, sensitivity analyses to determine the influence of land mass and water availability revealed that the overall global median HFI was 15 (weighted by land area), 11 (weighted by water surface area), and 16% (weighted by water availability), suggesting little influence of the weighting method on the final calculated value of the overall impact to freshwaters as indicated by HFI. The stepwise regression of HFI calculated by the median ES value against its component indices indicated that the proportion of the variance explained was WQI (0.62), CSI (0.23), WSI (0.12), BSI (0.03), GRI (<0.001), and DRI (<0.001). Indices with a constant impact on the HFI across countries are accounted for in the intercept term of the stepwise regression for the overall HFI and component indices. The weighting of these indices suggests that humans have some impacts that are pervasive and either have substantial international variance (e.g., WQI) or are relatively invariant globally yet can have a large impact on the total value (e.g., DRI, Figure 3).

Drivers of Human Freshwater Impact. Some drivers of the indices had opposite effects. For example, WQI and WSI both tended to have the opposite sign of correlation with drivers compared with BSI and CSI. Similarly, the gross domestic product per km^2 was positively correlated with the BSI and CSI but negatively with WQI.

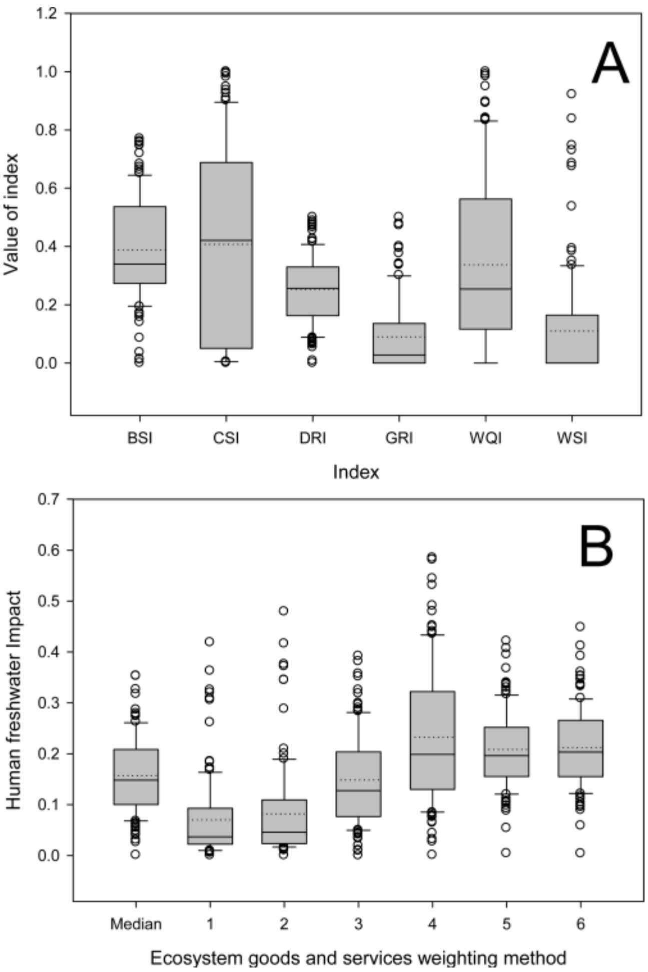

Figure 3. Box plots of the distribution of the individual indices for each country (for panel A, the abbreviations are in the Figure 2 legend) and the overall global human freshwater impact (HFI) calculated on the basis of scaled median and individual references (sensitivity analyses) by numbers listed in Table 1 (B). The bars are the 10th and 90th percentile, the boxes are the 25th and 75th percentile, the median is a solid line, and the mean is a dashed line.

The population growth rate was significantly correlated with the overall index (Table 3) in spite of the fact that several of the potential drivers had opposite relationships with individual HFI components. The best subsets regression (Mallow's CP) supported this trend, with the best model including the population growth rate with a positive coefficient and the second best model including the population growth rate and population density.

Our regression analyses to determine the environmental Kuznets curve with per capita GDP driving inverted U-shaped indices indicated significant ($p < 0.05$) positive first-order and negative second-order terms for only BSI and CSI. Increases in economic activity per person do not necessarily lead to an environmental Kuznets curve for most categories of ES.

DISCUSSION

Variance in the Driver Effects. Some indices respond oppositely to various drivers (e.g., BSI and CSI responded differently than WQI and WSI to individual drivers). Even composite portions of indices respond differently (e.g., the fish and invertebrate components of BSI). The opposite effects on the indices could be related to the fact that the actions to ensure supply and water quality (dams and centralized sewage outputs) may have simultaneous negative effects on fish and macroinvertebrate biodiversity and production.[26] In general, no correlation could be taken to suggest that individual drivers can explain more than one third of the variation within any individual index, with the possible exception of the per capita GDP and the population density, which were both fairly closely related to the commodities stress.

Kuznets Curves. Environmental impact can follow an environmental Kuznets curve,[24] which is represented as an inverted U-shaped relationship of the environmental impact as per-capita GDP rises,[25] representing the idea that environmental impact is an unavoidable symptom of development (e.g., Vörösmarty et al.[22]). Environmental Kuznets curves might be particularly expected with point sources of pollution.[25] Vörösmarty et al.[22] suggested an alternate model where more affluent countries tolerate higher levels of environmental

Table 2. Pearson Correlations among Transformed Indices and Potential Drivers[a]

	BSI	CSI	DRI	GRI	WQI	WSI	HFI
Indices							
commodities stress (CSI)	0.36						
disturbance regulation (DRI)	0.24	NS					
gas regulation (GRI)	NS	NS	0.31				
water quality (WQI)	NS	NS	NS	NS			
water stress (WSI)	NS	NS	0.37	0.35	NS		
human freshwater impact (HFI)	0.28	0.38	0.23	NS	0.66	0.19	
Drivers							
economic growth rate	NS	NS	NS	NS	NS	NS	NS
population growth rate	−0.23	−0.25	NS	0.18	0.32	0.20	NS
GDP density	0.26	0.57	NS	NS	−0.31	−0.34	NS
proportion in cropland	0.28	NS	NS	NS	NS	NS	NS
population density	NS	0.40	NS	NS	NS	−0.29	NS

[a]Correlation values are shown where $p < 0.05$. NS = $p > 0.05$. BSI = biodiversity stress index.

Table 3. Significant Drivers from a Forward Stepwise Regressions on Environmental Indices across All Countries[a]

index	drivers	R^2
BSI (invertebrates)	econ growth rate (−)	0.13
BSI (fish)	population growth rate (−), cropland per km^2 (+)	0.26
BSI	econ growth rate (−), cropland per km^2 (+)	0.21
CSI	econ growth rate (−), population density (+)	0.40
DRI	none	
GRI	none	
WQI	population growth rate (+), GDP per km^2 (−), population density (+)	0.18
WSI	cropland per km^2 (+), population density (−)	0.19
HFI	population growth rate (+)	0.12

[a]Variables (drivers) are listed in order of their appearance in the model with the direction of the effect indicated (+ or −). See Table 2 for index abbreviations.

stressors and invest more in treating symptoms. Neither BSI nor CSI (the only two indices with significant U-shaped relationships) would be expected a priori to be more related to the point sources of pollution than any of the other indices. The water quality index (WQI) would be expected to be the most related to point source pollution, and it did not demonstrate an inverted U-shaped relationship with GDP (but it had a negative linear relationship). Our analyses cannot distinguish between the environmental Kuznets explanation and that of Vörösmarty et al.[22] because we did not assess the intermediate mechanisms driving the diversity and commodities stress. For example, with commodities stress, wealthier countries could simply buy fish from other countries rather than eat fish locally produced by aquaculture (i.e., a compensating effect of trade interfering with the calculation of the effect[27]). Thus, our data do not support the general application of environmental Kuznets curves to freshwater environmental impact categories when they are considered across the full range of ES.

Data Limitations. Our ability to compare impact across categories of ES depends upon the relative values assigned to each category of ES. Our individual estimates avoid the pitfalls of assigning economic value and allows us to assess impacts on potential values irrespective of their relationships to human economics. However our overall index uses relative ES valuation, and we acknowledge constraints with ES valuation.[28,29] Assigning costs to pollution on the basis of freshwater ES has advanced further in more developed countries with more data. For example, many but not all costs associated with nutrient pollution have been quantified for the United States.[8] Far fewer of these costs are known for developing countries; although clean water availability has received considerable attention, robust data sets of value remain sparse.[30] Furthermore, valuation of ES has potential problems such as poorly constrained estimates [28] and poorly defined goals of valuation[29] as well as in relating valuation to policy.[31] The general valuation of freshwater ES is a new field, and estimations may not be accurate.[32] The quality of the data is variable; most global data sets rely on self-reporting by countries and some could give incorrect numbers. For simplicity, we assumed equal values across countries, but the values may be skewed by data availability. Finally, the literature values assigned to freshwater ES that we could find most commonly considered wetlands, and it is unclear how proportional values transfer among freshwater types (e.g., rivers, groundwaters, lakes, wetlands, and different types of these habitats).

Perhaps most important, if all of our perceived value of freshwater is economic, then it leaves no room for cultural values or the intrinsic right of aquatic organisms to exist (e.g., Hein et al.[33]). We assigned no value to the cultural aspects of freshwater, although frameworks are being developed to do so.[34] Thus, by assuming that human activities on balance degrade cultural values, our summed values for HFI probably underestimate the true degree of the use of potential global freshwater ES values. Our estimates are also conservative because there are a number of impacts on potential value that we could not consider because of data limitations (e.g., metal, sediment, and pesticide pollution, the stimulation of harmful algal blooms from nutrient pollution, and the future extinction debt from overexploitation of water resources).

Some Benefits of and Applications of the Approach. The general approach used here could assess any environmental management action regardless of the spatial or temporal scale (e.g., Hein et al.[33]), and a comparison of ES values has been used to assess management options across broad spatial scales.[16] The advantage of our approach is to provide a common unit for comparison. The better the estimates of the values of ES, the more accurate the approach should be. Although the relative values of ES are generally derived according to region-specific socio-political processes, the approach of using relative ranked values from multiple regions provides a potential solution for determining global estimates of overall human impact. Given the global nature of economies and society, understanding these impacts on the largest scales is important for gauging how our species impacts global processes.

Our methodology provides one structured approach to complex environmental management problems that is potentially complementary to approaches that use the opinions of groups of experts. In the global work by Vörösmarty et al.,[22] a group of eight experts assigned weights to the relative threats to water security and biodiversity. Their approach led to a very complex matrix of weightings to threats and was useful because it permitted the careful parsing of disparate drivers influencing water security and biodiversity. Expert groups can serve as aids to management with limited information such as with Delphi panels[35] and Bayesian Belief Networks. Such approaches require a structural model to guide the expert group, and we provide one such model for the weighting of the drivers of environmental impact.

The valuation of ES has unique aspects relative to some other economic valuation categories. It is not possible to assign a full value to nonmarketed benefits (e.g., cultural values). Furthermore, ES might completely collapse if they are overexploited.[31] It is not known how marginal values of ES relate to the economic cost for most systems. Here, we do not establish the functional relationship between cost and ES or the point where the system collapses. An assumed linear relationship means that our estimates are intrinsically conservative; if the value of an ES falls to 0 abruptly, then our indices would underestimate how close we are to overappropriating any individual good or service. Furthermore, the ES are linked, so if one collapses (e.g., enough water is used that streams and rivers dry seasonally), then others might completely collapse as well (e.g., species will be lost when rivers and streams dry). The scheme here does not account for such linkages and is thus conservative.

It also is important that not all ES used will replenish if use is halted. Once a species is extinct, the value can never come back. In contrast, water that is contaminated with coliform can recover over time if the sources of pollution are controlled. Such considerations are important, and extending our approach to one that specifically accounts for sustainability would be one next step to take.

We document that humans are decreasing the provision of freshwater potential ES by about 16% overall. Regardless of the system of valuation used to weight the total global human impact on freshwaters, humanity has a global impact on the ability of freshwater to provide ES. If one accepts a linear relationship between the amount of ES and the values provided by freshwaters as well as the estimate of Costanza et al.[14] for global value of ES, then the 16% decrease represents a global loss of over $900 billion in 2013 dollars. An independent estimate by The Economics of Ecosystems and Biodiversity group[36] on the basis of the Millennium Ecosystem Assessment methodology[15] gives similar median values per hectare for freshwater habitats, providing independent confirmation of the global totals and the different accounting schemes

Humans are appropriating roughly half of all available water, or about $^1/_6$ of all freshwater,[12] and this is consistent with our observation that about $^1/_6$ of the potential freshwater value to humanity is used. Fortunately, many of the impacts accounted for here are reversible over reasonable amounts of time (with the exceptions being for all species extinctions, most species introductions, and cases of groundwater extraction). More detailed approaches, such as those outlined by Keeler et al.,[13] could further inform management approaches to solving these complex and intertwined problems.

Our documentation of the loss of value provides additional compelling evidence that may help society understand that freshwater is a limitedresource, that the values that freshwaters provide humanity have an upper limit, and that our water is subject to numerous threats. Humans have clearly compromised the ability of freshwater ecosystems to supply all of the ES that humanity requires to increase its standard of living and feed a growing population. Some of these ES can renew themselves (water supply), whereas others (e.g., biodiversity) will be lost forever. The overall index was most strongly influenced by the population growth rate, so lowering human population growth rates could potentially help minimize some of the damage we are doing to freshwaters.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Descriptions, methodology, and equations for each index; description and data sources for drivers; description and methodology for calculating the human freshwater impact (HFI); detailed mapping methodology; and additional refs. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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