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Global impacts of energy demand on the freshwater resources of nations

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The growing geographic disconnect between consumption of goods, the extraction and processing of resources, and the environmental impacts associated with production activities makes it crucial to factor global trade into sustainability assessments. Using an empirically validated environmentally extended global trade model, we examine the relationship between two key resources underpinning economies and human well-being—energy and freshwater. A comparison of three energy sectors (petroleum, gas, and electricity) reveals that freshwater consumption associated with gas and electricity production is largely confined within the territorial boundaries where demand originates. This finding contrasts with petroleum, which exhibits a varying ratio of territorial to international freshwater consumption, depending on the origin of demand. For example, although the United States and China have similar demand associated with the petroleum sector, international freshwater consumption is three times higher for the former than the latter. Based on mapping patterns of freshwater consumption associated with energy sectors at subnational scales, our analysis also reveals concordance between pressure on freshwater resources associated with energy production and freshwater scarcity in a number of river basins globally. These energy-driven pressures on freshwater resources in areas distant from the origin of energy demand complicate the design of policy to ensure security of fresh water and energy supply. Although much of the debate around energy is focused on greenhouse gas emissions, our findings highlight the need to consider the full range of consequences of energy production when designing policy.

energy | freshwater | nexus | MRIO | sustainability

Meeting society's demand for fresh water and energy has been identified as a major challenge for society over the coming decades (1, 2). Most of the estimated 35 million km^3 of fresh water that exists globally is inaccessible (3). Recent estimates put renewable freshwater resources in the region of between 40,000 and 66,000 $km^3 \cdot y^{-1}$ (4, 5), of which ∼10% is appropriated for human use (6–8). Although this global total might be considered to fall within the "safe operating space" of humanity (9), it hides substantial mismatches between availability and demand in different regions (7, 8, 10) and associated pressures on renewable freshwater resources (1, 11). Given that freshwater is central to maintain ecosystem function (12) and biodiversity (13), pressures on freshwater resources can result in the loss of ecosystem services (14–16) and associated benefits to society, ultimately impacting human wellbeing both directly and indirectly (17–19).

Fresh water is used by the energy sector along the complete supply chain from extraction and conversion of raw material through to generation of power (2, 20), such that limits on access to fresh water through physical scarcity or regulatory control can have significant implications for security of energy supply (21). At the same time, energy is needed for extraction, treatment, and distribution of fresh water (2) to meet societal demand. This interdependence of fresh water and energy (2, 22–25) means that limits on one will impact the other, potentially causing significant economic, environmental, and social costs (23). Despite growing recognition of the importance of this water–energy nexus (26), policy objectives relating to fresh water and energy are often poorly integrated and concerned primarily with exploitation of fresh water and/or implications of climate change on freshwater resources required for energy production (27, 28). Indeed, alignment of climate and energy policy has led to the adoption of energy strategies that have the potential to negatively affect freshwater resources (25, 27).

A key difference between energy and fresh water is the relative ease with which the former can be transformed and transported between areas of production and demand (28). The resulting geographic disconnect between sources of inputs associated with energy production and final energy demand poses a significant challenge for resource management at the water–energy nexus. Countries can implement policies that improve energy and freshwater resource management within their own territories (23), with most developed countries exhibiting rapid reform of both sectors in recent years (26). However, movement of energy resources around the world, coupled with increasing trade in

Significance

Understanding the role of international trade in driving pressures on freshwater resources is key to meeting challenges at the water–energy nexus. A coupled trade and hydrological model is used to examine pressures on freshwater resources associated with energy production across the global economy. While the electric and gas sectors induce freshwater consumption predominantly within countries where demand originates (91% and 81%, respectively), the petroleum sector exhibits a high international footprint (56%). Critical geographic areas and economic sectors are identified, providing focus for resource-management actions to ensure energy and freshwater security. Our analysis demonstrates the importance of broadening the discourse on energy policy to address issues including freshwater scarcity, the role of international trade, and wider environmental and societal considerations.

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"virtual water" (29), adds complexity to the identification of policy and management options to ensure security of supply of both resources along global supply chains.

There is an increasing understanding that international trade in natural resources, driven by rising national wealth and the opening up of commodity markets since the 1980s, has led to a disconnect between final consumption of goods and production activities such as the extraction and processing of resources and associated environmental impacts (30). The implications of this disconnect have been explored predominantly for greenhouse gas emissions (31–34), but also for freshwater use (29, 35), land use change (36, 37), material use (30), and biodiversity (38). Consistent across these studies is a bias in environmental transfers in favor of net-importing developed nations at the expense of resource-exporting less developed nations. For example, emissions saved by industrialized countries bound by emissions reduction targets under the Kyoto Protocol were offset through emissions associated with the import of goods from countries without such emissions targets (34). There is considerable evidence to show that such carbon leakage can jeopardize climate targets (39) and that carbon-importing countries gain more socioeconomic benefits from international trade than carbon-exporting countries (40).

Such studies make a compelling case to incorporate the transfer of resources through international trade within national policies and sustainability assessments, so that the implications of consumption of goods for environment and society can be fully considered (30, 37). In the case of renewable freshwater resources, where impacts will be congruent with areas of resource extraction or production of goods, understanding and locating the geographic disconnect between use of fresh water and drivers of demand (29, 35, 41, 42) is key for assessing sustainability. In the present study, we investigate differences between energy sectors in the magnitude and geographical distribution of consumption of renewable freshwater resources, explore the geographical relationship between energy-induced freshwater consumption and the demand that drives it, and consider the implications in the context of freshwater scarcity. We use an empirically validated, environmentally extended multiregional input–output (EE-MRIO) approach that is spatially resolved at subnational scales. A spatially resolved, comprehensive analysis is vital, because energy-driven demand can be an important contributor to pressures on freshwater resources in localized regions (21, 43). Our analyses focus on freshwater consumption as this factor represents loss of the resource to the immediate environment (8) and so an opportunity cost in terms of ecosystem benefits (44). We do not consider freshwater withdrawal, which refers to fresh water removed from a source and used for human activity before being returned to the environment (8). Our analyses isolate freshwater consumption embodied in the three main energy sectors (gas, electric, and petroleum) globally, taking into account all processes along the supply chain from material extraction, transformation to energy carriers, and distribution to final consumers. Although a number of studies have examined the water–energy nexus at regional and national scales using EE-MRIO techniques (24, 45), ours is, to our knowledge, the first to attempt such an analysis at a global scale.

In the first stage of the analysis, a MRIO table derived from the Global Trade Analysis Project (GTAP; ref. 46) (*SI Appendix*, section 1) that quantifies economic transactions between 57 sectors across 129 countries/regions, is linked to data from the hydrological model WaterGAP that provides freshwater consumption data associated with agricultural, energy, domestic, and industrial activity (47–49) (*SI Appendix*, section 2). The environmental extension to the MRIO that this link provides allows us to reattribute direct sectorial freshwater consumption after the trade transactions to the final consumer of a finished commodity, a process known as footprinting (*SI Appendix*, section 3). The approach to this country/region-scale analysis is comparable to other studies that have examined international trade as a driver of pressures on freshwater resources (29) but which have not specifically addressed issues around the water–energy nexus. The second stage of analysis refines country/region values for freshwater consumption calculated in the EE-MRIO to sub-country/region scales (0.5- × 0.5-degree grid cell resolution) to describe spatial heterogeneity in freshwater consumption (35) (*SI Appendix*, section 4). This is a vital step, because locality is critical to determining the implications of freshwater consumption given the uneven distribution of renewable freshwater resources (7, 42). Based on this 0.5 × 0.5 degree grid cell resolution data, patterns of freshwater consumption associated with energy demand are considered within the context of available renewable freshwater resources in the world's river basins (4) to identify areas of critical importance for security of fresh water and energy supply (*SI Appendix*, section 6).

Results

Overview of Freshwater Consumption. Before presenting the results of the EE-MRIO analysis and considering freshwater consumption induced by the global energy sector from a consumption-based perspective, we provide a brief overview of the underpinning data to place our analysis within the wider context of freshwater consumption associated with human activity. Data from the WaterGAP model indicate that the crop sector dominates freshwater consumption, accounting for 91.85% (1,237 $km^3 \cdot y^{-1}$) of the 1,314 $km^3 \cdot y^{-1}$ of global annual freshwater consumption. This figure corresponds to findings in previous studies (35) that have emphasized agricultural production as the principal driver of pressures on freshwater resources globally. Industrial and domestic demand accounts for 5.88% (77 $km^3 \cdot y^{-1}$) of the remaining freshwater consumption, again corresponding to findings stated in ref. 35.

Of this industrial and domestic freshwater consumption, 23.78% (or 1.40% of global total freshwater consumption) is directly associated with the energy sectors considered in this analysis. Although this figure is comparatively small, the importance of considering freshwater consumption associated with energy sectors arises for two reasons. Firstly, freshwater consumption associated with energy extraction and refining may be highly locally concentrated and so contribute to social, environmental, and economic problems in specific regions (21)—a question we examine through our spatially explicit impact analysis. Secondly, our assessment employs EE-MRIO analysis to calculate the sum of embodied freshwater within all of the products required to meet final demand in isolated energy sectors. Thus, we identify not only freshwater consumption associated with specific energy sectors (e.g., oil extraction, oil refining, etc.), but also freshwater consumption associated with inputs required by these sectors (e.g., steel production for infrastructure and crops for biofuel) that could contribute to pressures on freshwater resources through higher intensities or in different geographic areas than the directly energy-related activities.

Country/Region Energy-Driven Freshwater Consumption Footprints. Our analysis finds that when measuring total freshwater consumption along global supply chains, the electricity sector consumes 6.48 km^3 of freshwater per year, with the petroleum sector consuming 1.60 $km^3 \cdot y^{-1}$ and the gas sector 0.30 $km^3 \cdot y^{-1}$. For each of the 129 countries/regions within the EE-MRIO, total freshwater consumption is disaggregated to describe the amount that occurs within the country/region where demand originates (i.e., territorial consumption) and the amount that is sourced internationally along energy supply chains (Fig. 1). The proportion of internationally sourced freshwater consumption is highest for activity induced by the petroleum sector (Fig. 1*A*), at 56% of total consumption for this sector. For the electricity (Fig. 1*B*) and gas (Fig. 1*C*) sectors, respectively, 9% and 19% of total sector-induced freshwater consumption is sourced internationally. For the

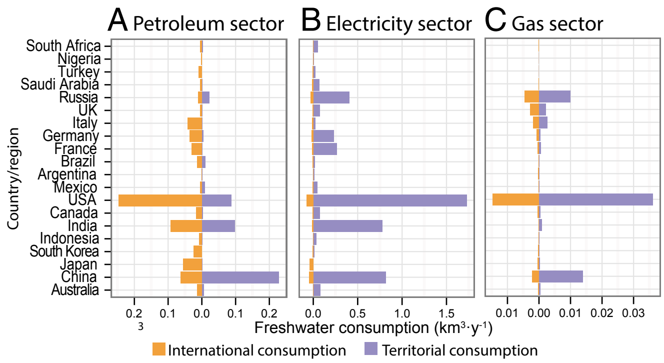

Fig. 1. Territorial and international freshwater consumption associated with petroleum (*A*), electricity (*B*), and gas sectors (*C*) for major economies [the G20, BRICS (Brazil, Russia, India, China, and South Africa), and MINTs (Mexico, Indonesia, Nigeria, and Turkey)]. An expanded version showing all countries/regions can be found in *SI Appendix*, Fig. S1.

petroleum sector as a whole, the largest consumers of fresh water are the United States (0.34 $km^3{\cdot}y^{-1}$), China (0.29 $km^3{\cdot}y^{-1}$), and India (0.19 $km^3{\cdot}y^{-1}$). Together, these three countries account for 50% of total freshwater consumption within this sector. These countries exhibit markedly different patterns of territorial and international consumption (Fig. 1). For the United States, 73% of total freshwater consumption associated with the petroleum sector occurs internationally; this finding contrasts with China, where 22% occurs internationally, and India, where there is an almost even division (52% territorial and 48% international).

Given that the United States and China have comparable total freshwater consumption associated with their energy sectors (Fig. 1), we focus on the geographic and sectorial patterns of freshwater consumption of these two in further detail, while noting that the technique can be extended to all countries/regions (*SI Appendix*, Fig. S1). Countries and sectors have been aggregated for illustration purposes (Fig. 2), with the underlying analysis based on 129 countries/regions and 57 sectors (*SI Appendix*, section 3). Consistent with the patterns shown in Fig. 1, freshwater consumption by the petroleum sector in the United States is geographically diverse (Fig. 2*A*), occurring in northern America (27%), western Asia (29%), southern Asia (13%), eastern Asia (7%), and northern Africa (6%). This diversity contrasts with the Chinese petroleum sector (Fig. 2*B*), where 78% of freshwater consumption occurs within China, with the remainder occurring mainly in other Asian countries/regions (13%) and in eastern Africa (4%). The majority of freshwater consumption associated with the electricity (Fig. 2 *C* and *D*) and gas (Fig. 2 *E* and *F*) sectors for the United States and China is located within the territory where demand originates.

Utilization of goods or services along the supply chain of energy provision is reflected in the breakdown of freshwater consumption by sector of activity. For both the United States and China, the EE-MRIO demonstrates that the majority of freshwater consumed to produce petroleum (Fig. 2 *A* and *B*) is by the crop sector (76% and 44%, respectively), the electric sector (12% and 10%, respectively), the oil sector—relating to extraction of raw materials (2% and 16%, respectively), direct use in the petroleum sector itself (2% and 8%, respectively), and, to a lesser extent, sectors relating to industry (e.g., metal and machinery production) and services (e.g., insurance, banking, and other support services). A similar pattern is found for the gas sector (Fig. 2 *E* and *F*), with crops (71% and 37%, respectively, for the United States and China) dominating. In contrast, the majority of freshwater consumption by the electricity sector (Fig. 2 *C* and *D*) is associated with the sector itself (91% and 64%, respectively, for the United States and China), followed by crops (8% and 19%, respectively).

To illustrate the mechanism that drives the dominance of freshwater consumption associated with crops within energy sectors (Fig. 2), the EE-MRIO was used to describe how an increase in one unit (i.e., US$1) of output of the US petroleum sector induces production activities and corresponding freshwater consumption to support them (*SI Appendix*, section 3.2). For an increase in US$1 of output from the US petroleum sector, US$2.52 of economic activity is induced upstream in the global economy. This increase is associated with an additional 2,500 $m^3{\cdot}y^{-1}$ of freshwater consumption. In economic terms, of the US$2.52 of induced activity, 31% is in the oil sector (extraction of materials), 45% in the petroleum sector itself (refining, distribution etc.), and 1% in crop production. Expressed in terms of freshwater consumption ($m^3{\cdot}y^{-1}$), the 1% of additional economic activity in the crop sector accounts for 76% of the additional fresh

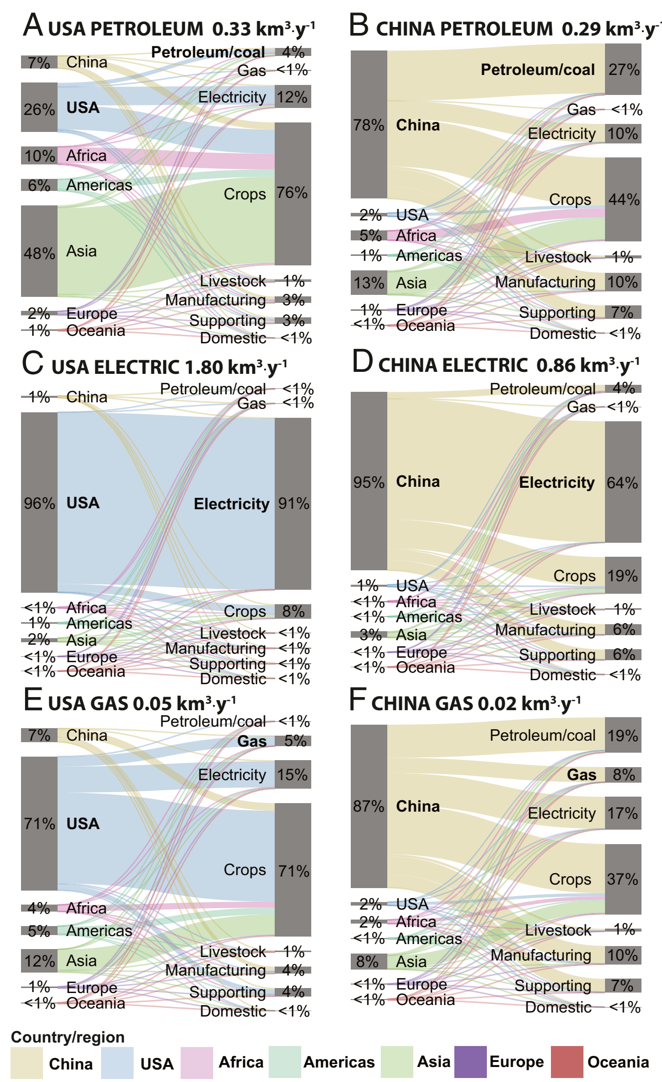

Fig. 2. Freshwater consumption by country/region and sector across three energy sectors. Sankey diagrams capture the relationship between the regional and sectorial consumption of freshwater driven by demand for petroleum products (*A* and *B*), for electricity (*C* and *D*), and for gas (*E* and *F*) in the United States (*A*, *C*, and *E*) and China (*B*, *D*, and *F*). Gray bars indicate percentage of total freshwater consumption by geographic region and sector. Colored lines describe the relationship between the region where demand originates and the sector within the region where freshwater consumption is occurring. See *SI Appendix*, Table S2 for details of country/region and *SI Appendix*, Table S1 for sector aggregation.

water consumed. This finding contrasts with induced activity in the oil and petroleum sectors, which drive only 4% of additional freshwater consumption, but accounts for three quarters of additional economic activity.

Subcountry/Region Energy-Driven Freshwater Consumption Footprints for United States and China. Using the approach of ref. 35, the global distribution of freshwater consumption associated with the individual energy sectors in the United States and China was mapped to 0.5- × 0.5-degree grid cells (Fig. 3; *SI Appendix*, Figs. S3 and S4). Data at the country/region scale were disaggregated based on intensity of freshwater consumption and location of economic activity within each 0.5- × 0.5-degree grid cell, corresponding to the economic sectors within the EE-MRIO (*SI Appendix*, section 4) to reveal spatial heterogeneity within countries/regions. Using the petroleum sector as an exemplar (Fig. 3) reveals a statistically strong correlation between geographic patterns of freshwater consumption for the United States (Fig. 3*A*) and China (Fig. 3*B*) ($r = 0.98$, F = 2776.78, df = 110, $P < 0.001$). This correlative relationship is likely driven by areas of common global resource extraction, manufacturing, and agricultural production across Asia, North Africa, Europe, and the Americas. However, there exist significant differences (*SI Appendix*, Table S6) between the United States (Fig. 3*A*) and China (Fig. 3*B*) in patterns of freshwater

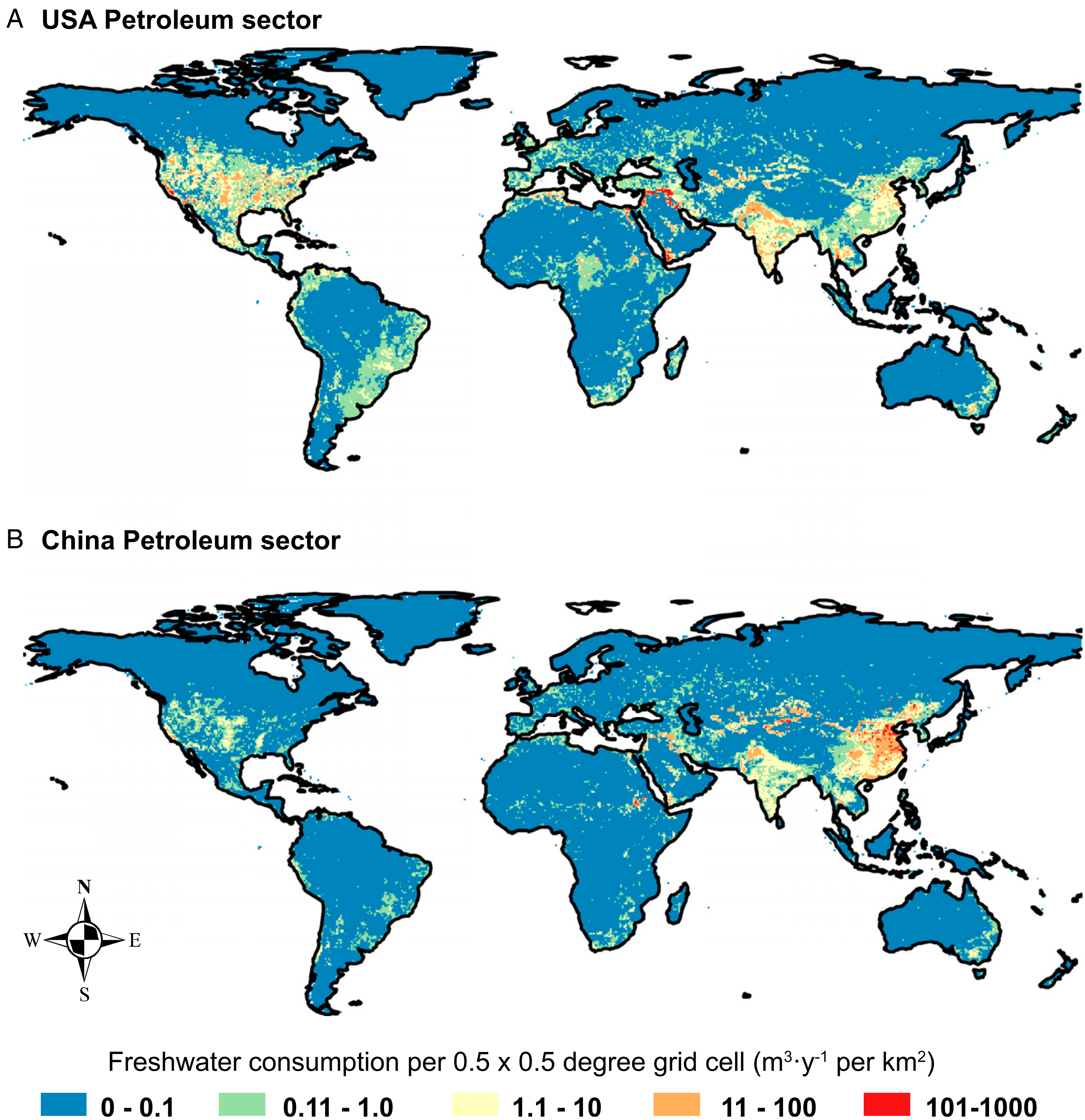

Fig. 3. Spatial pattern of global freshwater consumption driven by freshwater demand from the petroleum sector in the United States (*A*) and China (*B*). Numbers represent total freshwater consumption within each 0.5- × 0.5-degree grid cell standardized per unit area ($m^3 \cdot y^{-1}$ per km^2).

consumption in absolute terms driven by the higher international demand on freshwater resources associated with the US petroleum sector, as demonstrated at the country/region level (Figs. 1 and 2).

Implications of Freshwater Consumption. The implications of freshwater demand induced by energy sectors are dependent on the geographic overlap between location of activities required to meet demand (Fig. 3) and available freshwater resources (4). However, analyses of such relationships are complicated by the lack of a single universally accepted indicator with which to examine availability of freshwater resources (18) and the fact that impacts can arise through two mechanisms—first- and second-order water scarcity (50).

First-order scarcity represents a physical shortage of freshwater. Here we use two common metrics of first-order scarcity: (*i*) freshwater availability per person and (*ii*) the ratio of freshwater withdrawals to availability (18). We examine geographic concordance between these indices and aggregated freshwater consumption for the three energy sectors (petroleum, electric, and gas) for the United States and China. Bivariate mapping (*Materials and Methods* and *SI Appendix*, section 6) identifies common areas of spatial overlap between high freshwater consumption induced by the energy sector and river basins that can be considered to experience high first-order water scarcity based on thresholds proposed in the literature (18) (*SI Appendix*, Figs. S5–S8). An ensemble measure identifies major river basins in India, Pakistan, China, and the United States (Fig. 4) as being areas where energy-induced freshwater consumption is occurring within a context of high first-order water scarcity, irrespective of the metric used.

Second-order water scarcity arises through a lack of social adaptive capacity and reflects the economic and social context in which pressures on freshwater resources are occurring (50–52). The socioeconomic context can be as important as physical

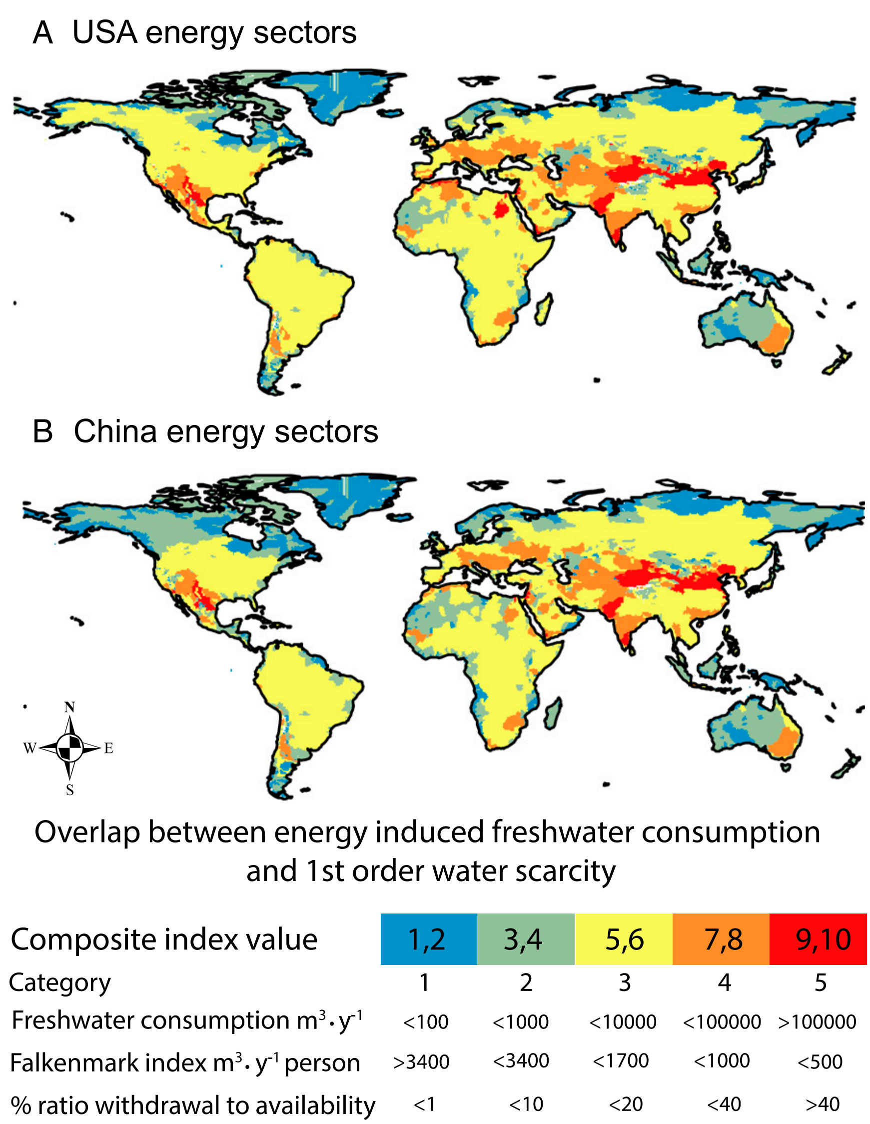

Fig. 4. Spatial relationship between freshwater consumption driven by demand for the US (*A*) and Chinese (*B*) energy sectors and pressures on freshwater resources. River basins were assigned to a category (1–5) based on freshwater consumption. This was combined independently with two measures of first-order scarcity assigned to categories (1–5) to produce two independent measures of overlap between energy-induced freshwater consumption and first-order scarcity. The mean of these independent measures represents a composite index value of coincident energy-induced freshwater consumption and first-order water scarcity (*Materials and Methods* and *SI Appendix*, section 6). High values (orange and red) indicate spatial overlap between river basins where high energy-induced freshwater consumption is occurring within a context of high first-order water scarcity.

scarcity in determining implications for society of pressures on freshwater resources (18, 52). Various approaches to calculate a "Water Poverty Index" reflecting second-order scarcity have been suggested (50, 51); however, varying availability of socio-economic data at subcountry/region scale limits their application in the current study.

We examine second-order water scarcity using two indices (*SI Appendix*, section 6) that provide socioeconomic indicators at differing spatial scales. The Human Development Index (HDI) is a multidimensional measure that captures a range of social and economic factors that could influence second-order water scarcity and has been used in previous studies that considered social adaptive capacity and freshwater resources (52, 53). Using this national scale measure, we find no correlation between HDI and freshwater consumption associated with the energy sector for the United States (rho = −0.01, df 119, $P > 0.05$) or China (rho = 0.03, df 119, $P > 0.05$) globally. However, spatial mapping suggests overlap between countries where high energy-induced freshwater consumption is occurring within the context of low and medium values for the HDI (*SI Appendix*, Figs. S10 and S11) in India, Pakistan, China, and parts of the Middle East.

Our second indicator provides data on the prevalence of child malnutrition at a 0.5- × 0.5-degree grid resolution and has been used in a previous study (54) as a measure of social adaptive capacity. Indicators of human health such as malnutrition have been used in a number of studies examining pressures on freshwater resources (53, 55) because, together with economic and social factors, they represent facets relevant to understanding social adaptive capacity (51, 52, 56) and therefore second-order scarcity. As with national scale analysis, the lack of correlation between energy-induced freshwater consumption and our indicator of social adaptive capacity (prevalence of child malnutrition) for both the United States ($r = 0.01$, F 0.01, df 43.70, $P > 0.05$) and China ($r = -0.01$, F 0.0045, df 40.47, $P > 0.05$) results from the complex spatial relationship between the two. This relationship is revealed by using bivariate mapping at subnational scales, where areas of high energy-induced freshwater consumption are demonstrated to be occurring within the context of low social adaptive capacity within India, Pakistan, Southeast Asia, Northeast Africa, and parts of the Middle East (*SI Appendix*, Figs. S12 and S13). The two independent metrics (i.e., HDI and prevalence of child malnutrition) are therefore consistent in identifying a number of geographic regions where energy-induced freshwater consumption is occurring within a context of low social adaptive capacity, potentially contributing to second-order water scarcity.

Considered in the context of first-order scarcity (Fig. 4; *SI Appendix*, section 6), there is spatial concordance between geographic areas experiencing high levels of first-order (physical-driven) (Fig. 4; *SI Appendix*, Figs. S5–S8) and second-order (socioeconomic-driven) (*SI Appendix*, Figs. S12 and S13) water scarcity and highest energy-induced freshwater consumption in a number of river basins, notably in India and Pakistan (*SI Appendix*, section 6).

Discussion

Differences between countries in terms of the degree to which energy-induced freshwater consumption (Fig. 1) is derived from international sources have important implications for management of renewable freshwater resources. For countries such as China, where energy-induced freshwater consumption is largely sourced internally, there is a direct incentive to manage pressures on freshwater resources to ensure security of energy and freshwater supply. Pressures on freshwater resources, of which energy production represents one facet, are increasingly recognized by the Chinese government as a critical issue affecting human wellbeing, economic development, and national security within the country (57–59). Country-focused analysis using EE-MRIO techniques has demonstrated the physical and virtual transfer of freshwater resources between Chinese provinces to support economic activity (60, 61). In demonstrating that globally driven demand for freshwater resources, in this instance associated with energy sectors, contributes to pressures on freshwater resources within countries/regions far removed from where final demand lies our analysis compliments these findings (60, 61). Patterns of freshwater stress across China detailed by ref. 60 correspond to areas identified in our subnational scale analysis as being where demand induced by energy sectors is occurring within the context of high first-order scarcity (Fig. 4).

In contrast to China, for certain countries/regions and energy sectors (e.g., US petroleum sector), consumption of fresh water along complex international supply chains (35, 62, 63) complicates the development of policy responses and management options at the water–energy nexus. Territorial pressure on freshwater resources has been identified by the US government as a threat to energy security (64), a result supported by regional US analysis (25). However, our analyses demonstrate that the US petroleum sector is reliant on economic activity in countries/regions of the world that are exposed to significant pressures on renewable freshwater resources (e.g., India, Pakistan; Fig. 4) and where it may be difficult to implement the necessary market reforms (29) to safeguard freshwater resources. This finding is of particular relevance for activity in transboundary river basins such as the Indus, identified as an area of India and Pakistan associated with high energy-induced freshwater consumption occurring in the context of both first-order (Fig. 4) and second-order (*SI Appendix*, Figs. S12 and S13) water scarcity. Consideration of the water–energy nexus must be in terms of both the territorial and international demand for freshwater resources to enhance both our understanding of the security of energy supply, and broader issues of sustainability through the link between freshwater resources, human wellbeing, and economic development.

Findings in the present study can be placed within an emerging body of literature that suggests an imbalance in the use of natural resources (29, 30, 65–67) with exchanges between developed and less-developed countries having become increasingly ecologically unequal. The analysis of virtual freshwater transfers to affluent eastern provinces of China from other provinces in ref. 60 highlights that such an imbalance in resource use can also occur within countries. To address such transfers, ref. 60 suggests a number of policy mechanisms based on shared producer and consumer responsibility (68) that could be implemented and used to fund agricultural and industrial freshwater efficiency programs. In the context of findings in the present study, we would suggest that such mechanisms could also be used at the global level to ensure both the security of energy supply in areas where final demand lies and to address social, economic, and environmental issues where freshwater consumption to meet this demand originates. Ultimately, as argued by refs. 25 and 69, the analysis presented here provides information that can be used by policy makers to identify critical sectors and geographic regions at the water–energy nexus. When developing energy policy, decisions can then be made to invest in protecting these critical points to reduce social, environmental, and economic burdens. For example, in the 1970s, the government of Saudi Arabia identified threats to territorial freshwater resources as a major issue for the oil industry, such that the industry is now based almost entirely on the use of desalination technology and brackish water (70), a fact reflected in our analysis which finds comparatively low freshwater consumption in this region. Our analysis provides information that could enable transfer of resources between countries to enable similar sectorial changes to protect freshwater resources and ensure security of the energy supply.

Demand associated with each energy sector generates a long chain of interactions in its production processes because all of the resources—the material feedstock and energy inputs, the infrastructure requirements (factories, machinery, processing equipment, transportation, worker canteens etc.), the financial services used, and so on—need to be "produced" and in turn themselves require numerous inputs. The use of EE-MRIO therefore provides a different perspective on freshwater consumption that moves beyond considering a single aspect of energy production (e.g., petroleum refining or electric generation) to incorporate understanding of the inputs required to undertake such activity. Generation of each input consumes freshwater in the process, with the amount of consumption varying dependent on how freshwater-intensive the sector is, such that there can be large disparities between economic activity within a sector and the associated freshwater consumption. In breaking down energy sectors using EE-MRIO (Fig. 2), it is possible to identify in which inputs most freshwater consumption is embodied and thus consider strategies to reduce overall freshwater consumption by targeting specific sectors.

Across energy sectors, our analysis demonstrates that agricultural production represents a major contributor to total freshwater consumption (Fig. 2). The dominance of agriculture within our analysis (Fig. 2) is a reflection of high levels of freshwater consumption associated with crop production (35) that subsequently flows to energy sectors, as opposed to a high input of crop materials themselves. This finding was demonstrated in the analysis of the US petroleum sector in terms of both induced economic activity (US$) and freshwater consumption ($m^3 \cdot y^{-1}$). This result is also consistent with analysis that compares sectorial water footprint results across bottom-up (process based) and top-down (EE-MRIO) methods (71), finding substantial differences in water footprints in agricultural and industry sectors depending on the method used. These differences arise as EE-MRIO calculates the full supply chain water demands of final energy consumption, and hence it does not just sum the direct water consumption associated with only those supply chain components deemed important, as is the case in bottom-up approaches. As a result, ref. 71 demonstrates that, by using EE-MRIO, a higher proportion of a nations water footprint will be attributed to industry rather than crops and livestock, because a large proportion of agricultural water use is consumed by industrial sectors as production inputs (e.g., biofuel feedstock). *SI Appendix*, section 5 provides an overview of the different approaches to water footprinting.

Analysis based on MRIO therefore provides a complimentary perspective on freshwater consumption to bottom-up approaches that has a number of implications relevant for policy. Firstly, although transfer of technology and expertise between countries relating to the industrial side of energy production has a role to play in relieving pressures on renewable freshwater resources, particularly at point localities (e.g., industrial plants or power station), large gains could also be achieved in relation to agricultural production. Adoption of precision irrigation techniques and new crop varieties could represent a "soft path" to addressing pressures on renewable freshwater resources focused on improvements in efficiency (72) that would complement those already adopted on the industrial side of energy production. For example, ref. 73 demonstrates that reducing freshwater consumption of global crop production to a level that represents the top 25th percentile of current production values could deliver 39% freshwater savings compared with current levels of consumption. In the context of the present analysis, such savings would cascade through the global economy, reducing pressures on renewable freshwater resources associated with demand for crops driven by the energy sector (Fig. 2) and delivering benefits to the environment and society. It is not our purpose to propose the most effective form of governance, but, rather, to inform the debate encompassing those promoting market-based mechanisms and the monetary valuation of ecosystem services, to those advocating more collective and deliberative forms of local-level governance (74, 75).

Secondly, the importance of agriculture as a driver of freshwater consumption has implications associated with production of energy from biofuel feedstocks, suggesting that even modest increases in biofuel production, driven by recent US and European mandates, could displace freshwater consumption associated with food production to that associated with the energy sector. This finding is consistent with scenarios produced by the International Energy Agency that project an 85% increase in freshwater consumption associated with energy between 2010 and 2035, driven primarily by expanding biofuel production (21), and results presented in ref. 25 that demonstrate the impact on freshwater resources of increased reliance on bioethanol in California as a result of changes in energy policy since 1990. Such findings emphasize the importance of the spatial aspect of EE-MRIO (29, 35) as such information will allow policy to target feedstock production toward countries/regions based on availability of renewable freshwater resources and local socioeconomic conditions (42), thus contributing to sustainable production.

Although our analysis advances our understanding of the relationship between energy production and freshwater resources, there are nonetheless a number of limitations and improvements that require future research. Many of these limitations are common to EE-MRIO analysis; Daniels et al. (42) provide a detailed discussion specific to freshwater resources. Of these limitations, aggregation error, which refers to a lack of product specificity within sectors and to the grouping of countries into regional blocks (29, 42), will most significantly affect our findings in relation to subcountry/region-scale mapping of industrial activity. Our estimates of freshwater consumption within a specific sector assume homogeneity in levels of freshwater use efficiency that may mask distinct differences in spatial patterns associated with different industrial processes. A second limitation of our analysis is that total freshwater consumption at the country/region level is assigned to individual 0.5- × 0.5-degree grid cells in proportion to the location of industry and intensity of freshwater consumption within the grid cell, without taking account of distinct subcountry/region patterns that may be associated with individual supply chains. For example, although freshwater consumption in the electricity sector is defined spatially based on the location and type of power stations (48), our analysis treats electricity as a pooled resource. In reality, within a specific country/region, colocation of electric production and industry may mean that a higher proportion of generated electricity is being used for industrial process in some areas, and a higher proportion for domestic use in others. A third limitation is that for any future analysis using our methodology, the expected rapid expansion of second-generation bioenergy feedstocks will need to be incorporated both with the MRIO table through disaggregation of agricultural sectors and within the crop models contained within WaterGAP.

In addition to the EE-MRIO–specific limitations discussed above, an additional limitation to our analysis relates to understanding the relationships between pressures placed on renewable freshwater resources and the implications such pressures have for individuals and communities. Difficulties in the construction of indicators that reflect pressures on renewable freshwater resources arise through the wide range of environmental, economic, and social factors that interact to contribute to freshwater scarcity (18, 51). Our analysis addresses this challenge by using a range of possible indicators relevant to both first- and second-order water scarcity (Fig. 4; *SI Appendix*, section 6 and Figs. S10–S13) to identify concordance between regions with high freshwater scarcity and consumption associated with energy sectors. However, the relative coarse scale of our analysis (0.5- × 0.5-degree grid; river basin; country/region) and difficulty in obtaining data of relevance for understanding second-order water scarcity limit our ability to understand this relationship. Nevertheless, we identify coincident locations of demand for freshwater resources associated with energy sectors and areas subjected to high first- and second-order scarcity, notably in India and Pakistan. In such areas, analysis indicates that demand induced by energy sectors is occurring within a context of both physical freshwater scarcity and low social adaptive capacity to address the challenges that freshwater scarcity poses for human wellbeing and economic development. This finding provides the information necessary to conduct targeted studies along critical supply chains and channel investment and expertise to address pressures at local scales.

Our analysis lies at the interface of global efforts to meet societal energy and freshwater needs while addressing climate change. By demonstrating the global connectedness of the energy system and demands on freshwater resources that can be far removed from where final energy demand resides, we provide decision-makers with a key piece of knowledge to address future energy security, while at the same time considering social, environmental, and economic consequences of decisions. Given rising populations and the critical interdependence of freshwater, food, and energy demand, our work examines an important threat for global freshwater resources that has not previously been considered in detail. The fossil-based sector represents a major contributor to increasing atmospheric CO_2 (76), and as such strategies to reduce greenhouse gas emissions form the dominant discourse within energy policy. We argue that energy policy should increasingly be designed to incorporate not only implications for greenhouse gas emissions, but also consideration of other consequences that will affect global ecosystems and the goods and services that flow from them to society. Failure to do so may mean that we address climate change at the expense of existing natural resources on which human wellbeing and economies depend.

Materials and Methods

Country/Region Freshwater Consumption Footprints. The freshwater resources embodied in a country's/region's consumption are calculated by using EE-MRIO analysis (*SI Appendix*, section 3.1). EE-MRIO analysis is well suited to calculating consumption-based environmental accounts at the national and supranational level (42, 63, 77) because it enables trade flows across the full supply-chain of product categories traded globally to be linked to non-economic measures such as freshwater consumption.

The MRIO is based on data from GTAP (78), which is constructed from 2007 global economic data and contains domestic and international monetary transactions among 57 industry sectors across 129 countries/regions (*SI Appendix*, section 1). Our analysis focuses on three of these sectors—electricity, gas, and petroleum—because these sectors represent major sources of energy for the global economy. These three represent the sectors in GTAP in which raw materials are transformed into energy carriers that then flow to end users. For example, the GTAP petroleum sector (as used in this analysis) receives inputs from the GTAP oil sector, with the latter relating to activity associated with extraction of raw materials (e.g., crude oil). Refined products from the petroleum sector are then sold to industry and final consumers (e.g., goods manufacturers, services, and households).

Sectorial freshwater consumption by country/region derived from the hydrological model WaterGAP (4, 47–49) (*SI Appendix*, section 2) provides an environmental extension to the MRIO model following the method given in ref. 79. Freshwater consumption data for 19 crop and 12 livestock sectors were derived from WaterGAP, with details of the development of the WaterGAP irrigation and livestock models and assumptions provided in refs. 49 and 80. These data were aggregated into the eight crop and two livestock sectors in the MRIO model for each country/region by allocating these to the corresponding sectors (*SI Appendix*, section 3). Freshwater consumption associated with electricity production in WaterGAP (48) was allocated to the corresponding country/region electricity sectors in the MRIO. WaterGAP allocates all other (i.e., excluding crops, livestock, electricity, and domestic) freshwater consumption into a single "industry" sector, which represents 4.18% of total freshwater consumption within the EE-MRIO (47, 48). To disaggregate this industry sector among sectors not yet assigned a freshwater consumption value, country/region totals for industry in the WaterGAP model are apportioned among the industry sectors in the MRIO based on their expenditure on the water sector. Here, the strength of the interaction with the GTAP water sector is taken as indicative of differences in freshwater consumption between the GTAP sectors (6). Water prices between countries are considered; however, the price of water within a country is assumed to be constant, because no within-country price data were available. Data validation for key industrial sectors was also performed against industry and modeling figures from the literature (*SI Appendix*, section 3.3).

Freshwater directly consumed by industry sectors is reallocated through supply chains to the finished products in which it becomes embodied using the standard input–output equation originating from Leontief (81) (*SI Appendix*, section 3.1) and used by many in footprint analysis (for example, see refs. 29, 30, 42, and 61). Total freshwater consumption for an individual country/region is the sum of embodied freshwater along these supply chains to meet absolute demand for finished products. Sectorial consumption is determined by the country/region's demand for a specific product, such as electricity or petroleum. The embodied freshwater can be traced back to the sector and country/region in which it was originally extracted from the environment to determine the location of appropriation for the consumption activity.

Subcountry/Region Energy-Driven Freshwater Consumption. Country/regional patterns of freshwater consumption were mapped to 0.5- × 0.5-degree grid cells by using the approach described in refs. 35 and 48. Country/region totals for freshwater consumption in each sector were derived from the EE-MRIO. Values for intensity of freshwater consumption associated with crops and livestock (49, 80), electricity (48), and dwellings (47) were derived from WaterGAP at the 0.5- × 0.5-degree grid cell resolution. Country/region totals from the EE-MRIO were then assigned to each 0.5- × 0.5-degree in proportion to the intensity of freshwater consumption for the corresponding sector within that 0.5- × 0.5-degree grid cell derived from WaterGAP. Because of aggregation of the industry sector within WaterGAP (48) outlined above, this approach was modified by initially using data from a range of sources (*SI Appendix*, section 4) to identify 0.5- × 0.5-degree grid cells in which activity associated with key industrial processes (e.g., mineral extraction and refining, oil extraction) was located. Freshwater consumption at the country/region level for the corresponding sector was assigned to each of this subset of 0.5- × 0.5-degree grid cells in proportion to intensity of freshwater consumption associated with industry derived from WaterGAP (47, 48). Finally, the remainder of freshwater consumption associated with industrial processes was assigned to each 0.5- × 0.5-degree grid cell based on aggregate industrial freshwater consumption derived from WaterGAP (47, 48), after accounting for that already assigned in the previous step. Correlations between patterns of freshwater consumption between the United States and China were assessed by using a modified *t* test to account for spatial autocorrelation (*SI Appendix*, section 4.1).

Implications of Freshwater Consumption. Freshwater consumption associated with the United States and China energy sectors mapped to a 0.5- × 0.5-degree grid resolution (Fig. 3; *SI Appendix*, Fig. S3) was aggregated to river basins as defined by the WaterGAP model. Patterns of first-order water scarcity within each river basin were assessed by using two common measures: (*i*) the Falkenmark water stress indicator (18), which measures freshwater availability per person (*SI Appendix*, Figs. S5 and S7); and (*ii*) the percentage ratio of total freshwater withdrawals to availability (18) (*SI Appendix*, Figs. S6 and S8). In both cases, freshwater availability was defined as the total renewable freshwater resources derived from the WaterGAP model (4). To create an ensemble measure based on these two indices, firstly total freshwater consumption associated with the US and China energy sectors was categorized from low (category 1) to high (category 5) by using a logarithmic scale (*SI Appendix*, Figs. S5–S8). Secondly, each basin was assigned to a first-order water scarcity category from low (category 1) to high (category 5) based on proposed thresholds for each of the indices (*SI Appendix*, section 5; ref. 18; *SI Appendix*, Figs. S5–S8). For the Falkenmark water stress indicator, thresholds for freshwater scarcity were taken from ref. 18 such that (*i*) river basins with <1,700 $m^3 \cdot y^{-1}$ per person are considered to experience water stress; (*ii*) river basins with <1,000 $m^3 \cdot y^{-1}$ per person are considered to experience water scarcity; and (*iii*) river basins with <500 $m^3 \cdot y^{-1}$ per person are considered to experience absolute scarcity. For the water resources vulnerability index using thresholds taken from ref. 4, a river basin can be considered as: (*i*) water scarce if the percentage ratio of withdrawals to availability is between 20% and 40%; and (*ii*) severely water scarce if the percentage ratio of withdrawals to availability is >40%. Thirdly, the score for total freshwater consumption associated with the energy sector (category 1–5; *SI Appendix*, Fig. S9) was combined with each of the first-order water scarcity indicators (category 1–5; *SI Appendix*, Fig. S9) independently to calculate an index of coincident energy-induced freshwater consumption and first-order water scarcity. A river basin with high energy-induced freshwater consumption (category 5) and high first-order scarcity (category 5) would score the maximum of 10 on this coincident index (*SI Appendix*, Figs. S5–S8). Finally, an ensemble measure was calculated by taking an average score of the index of coincident energy-induced freshwater consumption and first-order water scarcity calculated from the two indices (Fig. 4; *SI Appendix*, section 6).

Second order scarcity was examined using two proxy indices for social adaptive capacity, the HDI at country/region scale and prevalence of child malnutrition at 0.5 × 0.5 degree grid resolution (*SI Appendix*, section 6). Correlation between these two indices at country/region level ($r = -0.75$, df = 118, $P < 0.001$) suggests that data on the prevalence of child malnutrition, which capture within country/region heterogeneity, is indicative of patterns revealed by the HDI which represents a more complex view of social adaptive capacity based on social, economic and health factors. Bivariate mapping was used to identify areas of coincident low adaptive capacity and high energy induced freshwater consumption associated with the United States (*SI Appendix*, Figs. S10 and S12) and China (*SI Appendix*, Figs. S11 and S13), for both HDI and prevalence of child malnutrition. Spatial overlap between river basins identified in the context of high first and second order stress and high energy induced freshwater consumption were assessed visually due to difference in spatial scale of data (*SI Appendix*, section 6).

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