Assessment of human–natural system characteristics influencing global freshwater supply vulnerability

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Abstract

Global freshwater vulnerability is a product of environmental and human dimensions, however, it is rarely assessed as such. Our approach identifies freshwater vulnerability using four broad categories: endowment, demand, infrastructure, and institutions, to capture impacts on natural and managed water systems within the coupled human–hydrologic environment. These categories are represented by 19 different endogenous and exogenous characteristics affecting water supply vulnerability. By evaluating 119 lower per capita income countries (<$10 725), we find that every nation experiences some form of vulnerability. Institutional vulnerability is experienced most commonly, occurring in 44 nations, and 23 countries suffer deficiencies in all four categories. Of these highly vulnerable countries, Jordan is the most vulnerable, reporting the greatest number of characteristics (5 of 19) at critical vulnerability levels, with Yemen and Djibouti nearly as vulnerable. Surprising similarities in vulnerability were also found among geographically disparate nations such as Vietnam, Sri Lanka, and Guatemala. Determining shared patterns of freshwater vulnerability provides insights into why water supply vulnerabilities are manifested in human–water systems at the national scale.

1. Introduction

Impending regional water crises represent a new set of challenges for the world (Jury and Vaux 2007). Over the past 50 years, the global population has doubled while the total volume of water withdrawn for human use has nearly tripled—from roughly 1400 km³ yr⁻¹ in 1950–4000 km³ yr⁻¹ in 2010 (Clarke and King 2004, FAO 2013). The worldwide distribution of water resources is naturally unequal, and as more water has been allocated for human use, deficient management of coupled human–hydrologic systems has created regional water scarcity threats (Oki and Kanace 2006). Over-exploitation of freshwater resources has not only increased concerns of availability in these areas, but has destroyed ecosystems and threatens the future of many others (Gleick 2003). Many symptoms of water crises are identifiable, with causes covering a wide array of institutional, political, socio-economic, and biophysical factors (Srinivasan et al 2012).

2. Water stress indices

Various indices and indicators have been developed to improve understanding of water scarcity and identify which locations are most at risk (Rijsberman 2006, Brown and Matlock 2011, Plummer et al 2012, Sullivan 2013). Water stress has been quantified by estimating the water endowment and comparing available resources to a fixed minimum water requirement (Falkenmark et al 1989, Gleick 1996, Postel et al 1996, Ohlsson 2000). These indices are simple and valuable, but fail to account for variability in demand and water management practices (Rijsberman 2006). ‘Critical ratio’ indices have considered demands relative to available water across a wide range of spatial scales...
(Shiklomanov 1991, Arnell 1999, Vörösmarty et al 2000, Alcamo et al 2003, 2007, Oki et al 2003, Smakhtin et al 2004, McDonald et al 2011), as a function of system inflows and outflows (Allan 1998, Jenerette and Larsen 2006, Hoekstra and Chapagain 2007, Islam et al 2007, Qadir et al 2007), and in terms of physical versus economic water scarcity (Seckler et al 1998). However, a full suite of demand, endowment, infrastructure, and institutional characteristics have not been considered despite the fact that water supply vulnerability is as often a product of natural availability as it is of management decisions (Jenerette and Alstad 2010, Srinivasan et al 2012). Results from indices that avoid incorporating harder-to-quantify, water-specific infrastructure and institutional characteristics provide little clarity for water managers and policy-makers who try to use those indices to identify and overcome water supply vulnerability. While a limited number of frameworks and indices that account for both social and biophysical factors exist, they are often more theoretical than practical, not providing an explicit assessment of vulnerability (Biswas 2004, Medema et al 2008, Ostrom 2009), use metrics that are not directly tied to water resources or management, or use arbitrary weights to aggregate index components into a single ‘score’ (Sullivan et al 2003) which obscures critical information provided by individual indicators (Garriga and Fougnet 2010).

3. Methodology

We present a set of characteristics to identify broadly those human management and natural system qualities that contribute to freshwater supply vulnerability without simplifying or reducing system complexity by consolidating individual metric values. Using this approach, we also identify freshwater vulnerability characteristics that are similar across regions.

Vulnerability here follows the commonly used theoretical definition: ‘Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stressor.’ (Turner et al 2003). The time scale of vulnerability is annual to inter-annual. Temporally, it lies in between matters related to reliability, which can reflect daily, seasonal, or annual supply disruptions, and sustainability, which considers uninterrupted resource provision over decades and centuries.

Freshwater supply vulnerability represents a set of human and natural attributes that can be fixed physical features, such as those dictated by geology and hydrology, or relatively transient anthropogenic factors in the form of institutions and government policies. We focus on four major categories of vulnerability characteristics: demand, endowment, infrastructure, and institutions (figure 1) based on the explicit set of causal factors recently identified as driving water scarcity in couple human–water systems (Srinivasan et al 2012). In our analysis, demand characteristics, including those related to urban (e.g., domestic/industrial), agricultural, and ecological/environmental water needs, address demand requirements that have the potential to dramatically alter where and how water is allocated (e.g., water required for urban populations or protection of endangered species). Endowment characteristics are associated with the volume of water available (quantity), the degree of water pollution (quality), and the temporal variability in human–water systems. Infrastructure characteristics capture the impact of centralized and decentralized projects for collecting and distributing both groundwater and surface water supplies. Institutional characteristics are the least common in water vulnerability analyses. To address this gap, we examine the relative functionality of existing governance frameworks and their capacity to manage water. Specifically, we identify where governance mechanisms, such as regulations designed to deal with water quantity and quality problems, have been implemented and how effective those mechanisms are likely to be given the level of governmental stability and transparency. We also consider mechanisms for reallocating water among users and across regions through virtual water trade. Water embedded in the goods exported and imported between countries can account for substantial volumes of water and lead to vulnerability via a systematic overexploitation of the exporting nation and a precarious dependence on the importing nation.

The datasets chosen to reflect system characteristics in this analysis only represent a subset of all the possible information that could be used to assess freshwater supply vulnerability. However, as we are using information from currently existing datasets, the characteristics used in this analysis (and outlined in table S-1) provide a reasonable representation of the systems of interest, even if they may capture only a portion of the many and varied human and natural attributes that could be used to represent each of the characteristics we identify as important. Given the use of publicly available datasets, there is unavoidable overlap between information contained in some of the metrics. For example, the metric for national population density and the metric reflecting the fraction of those residing in urban centers may have similar implications for water supply vulnerability, but not necessarily (e.g., if there is a significant peri-urban population). However, our aim is to present results that are transparent with the metrics for each of the characteristics shown separately even though the information is complementary in some cases. Since we use publicly available data for our analysis, we were careful to use only datasets from well-recognized organizations, and selected only those data that represent a breadth of information within each major category and that contained clear and well-documented
information outlining the methods and other meta-data associated with each dataset. We analyzed the freshwater supply vulnerability at the national level for 119 countries and territories in the world using characteristic data described in figure 2. While biophysical data are often available at a sub-national scale, a national analysis was implemented here because nearly half of the world’s countries manage water at the national level (United Nations 2012) and therefore much of the infrastructure and institutional data concerning water resources are also compiled at this scale. We identify a subset of nations based on data availability, and we exclude those countries categorized by the World Bank as having a ‘high’ (>$10,725) per capita GDP income as vulnerability can often be reduced by economic investment in a solution (e.g., desalination, importing water from distant locations). Of the 258 countries and territories included in the various datasets used to populate the vulnerability characteristic values, 155 countries had two or fewer missing values. Of these 155 countries, 35 were eliminated for supporting a ‘high income’ (>$10,725) in 2005 according to the World Bank. One country, Libya, fell below this GDP threshold, but was also eliminated based on their extensive economic investment in the Great Man-Made River project. The remaining 119 countries create the sub-sample of nations that were used to generate the global water vulnerability assessments detailed in this study. Of these 119 countries, 83 had data available for all of the characteristics, whereas 36 had one or two missing characteristic values of the 19 characteristics we considered. In those cases, the missing values were ignored and set to 0. Values for each characteristic were obtained from publicly accessible global databases for which recent data (2000–2010) were available (figure 2). Of the 19 total characteristics, 15 are endogenous, ones controlled by, or derived from, features or policies existing within a given national boundary. The other four characteristics are exogenous having the potential to make a nation’s freshwater supplies more vulnerable because they are controlled either wholly or partially by neighboring countries or other forces beyond the jurisdiction of a given country. Considering water supply and its vulnerability, exogenous characteristics are those representing influxes of freshwater or water of poor quality from beyond a country’s borders. Influxes of water may be physical or virtual. The difference between endogenous and exogenous characteristics can easily be seen in riverine systems. Being able to control the quantity and quality of water in a river is important to a nation’s well-being. However, there are some countries (e.g., Vietnam, Jordan) that rely on water generated in headwaters originating in other countries. For these countries, the quantity and quality of water crossing their border from another country represent exogenous characteristics, where any modifications to the flow (freshwater dependency), or the quality of the water (pollution dependency) by an

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**Figure 1.** Characteristics of freshwater vulnerability. Four major characteristic categories (demand, endowment, infrastructure and institutions) are identified. Characteristics can be endogenous or exogenous. We evaluate 19 characteristic values (displayed radially) to determine a region’s vulnerability. Greater vulnerability pushes a characteristic value towards the circle’s outer boundary, whereas a value with low vulnerability falls near the center.
upstream neighbor has the potential to greatly increase the receiving country’s water supply vulnerability.

In some cases, a particular characteristic can be either exogenous or endogenous. For example, the water used to produce food in a nation is assessed here as a function of both endogenous and exogenous characteristics. Endogenous characteristics represent a nation’s ability and desire to produce food calories both physically (e.g., climate, availability of water, land, labor, etc) and institutionally (e.g., crop subsidies, independent food security as a policy priority, access to markets, etc). Meanwhile, imported food calories are subject to the exogenous characteristics—those representing forces on and limitations of exporting countries such as trade embargos or crop failures due to drought and pests. A high metric value for this

| Characteristics Categories | Characteristic Type | Stress Source | Characteristic Descriptions |
|----------------------------|--------------------|--------------|-----------------------------|
| DEMAND                     | Urban              | Endogenous   | Urban Population (% of total) |
|                            |                    | Endogenous   | Population Density by country (per/km²) |
|                            | Agricultural       | Exogenous    | Food Calories Imported / capita (% of required) |
|                            |                    | Endogenous   | Food Calories Exported / capita (% of required) |
|                            | Ecological         | Endogenous   | Water for Ecosystem Maintenance- mean annual discharge required (% of total discharge) |
|                            |                    | Endogenous   | Number of Endangered Species |
| ENDOowment                 | Quantity           | Exogenous    | Freshwater Dependency- renewable water originating outside the country (% of total) |
|                            |                    | Endogenous   | Renewable Freshwater resources (m³/person/y) |
|                            | Quality            | Endogenous   | Access to Improved Sanitation (% of population) |
|                            |                    | Endogenous   | Access to Improved Sources of water supply (% of population) |
|                            |                    | Exogenous    | Pollution Dependency- severity of water pollution from inflows originating in other countries (scale of 1-5) |
|                            | Variability        | Endogenous   | Rainfall Variability- coefficient of variation for national precipitation |
| INFRAstructure             | Centralized        | Endogenous   | Surface Water Dependency - mean annual consumption/(reservoir +desalination capacity) |
|                            | Decentralized      | Endogenous   | Groundwater Dependency- degree of pumping (as % of recharge) |
| INSTITUTION                | Extraction         | Endogenous   | Regulation of Water Quantity- degree of implementation (scale 1-5) |
|                            | Pollution          | Endogenous   | Monitoring of Water Quality- degree of implementation (scale 1-5) |
|                            | Political State    | Endogenous   | Governmental Corruption- perceived degree of corruption (scale: 1-100) |
|                            | Reallocation       | Exogenous    | Virtual Water Imported (% of total renewable water resources) |
|                            |                    | Endogenous   | Virtual Water Exported (% of total renewable water resources) |

Figure 2. Description of 19 vulnerability characteristics used in national water vulnerability analyses.
exogenous characteristic means that a country’s water supply may be vulnerable because of an over dependence on imported calories. Due to decisions made by exporting nations, a country’s reallocation of water to promote greater food production can increase vulnerability of freshwater supply for other human needs. Jordan is a good example of this strong dependence on imported calories and their internal policy that favors water security over sovereign food security.

The four categories of characteristics were chosen to represent the breadth of factors affecting regional vulnerability and because they are transparent and quantifiable through readily available, existing public datasets. Some characteristics are continuous, quantitative variables (e.g., mean river discharge \((m^3/s)\)), food calories imported or exported (cal/yr), population density (people per/km\(^2\)). Others are qualitative (e.g., political transparency, development stage of water quality monitoring programs) and were assessed using scales found in surveys. When compiled for this study, all characteristic data were set to a common 0–1 scale so that each country produced a unique but comparable vulnerability ‘fingerprint’. Of the 19 characteristics used, 15 were normalized to provide a standardized value from 0 to 1. For all characteristics, 0 represents relatively low vulnerability, >0.6 demarks the threshold for which scores above are considered relatively vulnerable, and scores of 0.9–1 indicate critical vulnerability. In certain cases, data presented limitations to characteristic assessment, (e.g., the groundwater characteristic assumes no important environmental discharges, indicating that environmental discharge to groundwater-dependent ecosystems is ignored). For a full description of characteristics used, see supplementary information table S-1.

Based on evaluation of these 19 characteristics (figure 2), nations that are critically vulnerable were identified. Critical vulnerability was associated with any characteristic values that ranged from 0.9 to 1.0. Values describing severe vulnerability were those with from 0.8 to <0.9, and values from 0.6 to <0.8 represented moderate vulnerability. In contrast to other indices, a key attribute of this approach is that it assesses freshwater supply vulnerability by identifying similar patterns among individual characteristic values rather than through the consolidation of characteristics values into a single vulnerability ‘score’. Using this pattern-matching approach, we identified similar vulnerability fingerprints from the difference in the sum of squares across all characteristics collected for each country. For endogenous characteristics, countries were considered to have comparable system weaknesses when the difference in the sum of squares was calculated to be within the lowest 5.5% of the maximum difference possible across each set of comparisons. Using the same methodology, exogenous characteristics used a slightly more refined threshold (including only the lowest 2.5% of the maximum difference). These fingerprint analyses provide greater clarity through their ability to show the relative vulnerability of 19 different water-specific characteristics in a way that does not aggregate individual values. We use this flexibility to identify, highlight, and group countries based on those particular characteristics that render each group most vulnerable, rather than assessing vulnerability based on a sum score.

4. Results

4.1. Global distribution of vulnerable nations

Twenty-five nations of concern were identified as those having at least two characteristics with critical values or one critical and one severe characteristic value (figure 3). A number of these vulnerable countries share critical characteristic values in groundwater dependency (11), surface water dependency (14), or in freshwater transboundary issues (5). Five countries, Mauritania, Turkmenistan, Moldova, Egypt and Bangladesh, all mine groundwater and have one or more major rivers with headwaters located within a neighboring country, leaving them vulnerable both in terms of groundwater and surface water supplies. Of these 25 countries of greatest concern, most cluster around the lower to middle latitudes, ranging from humid countries (e.g., Solomon Islands, Belize, Republic of Congo) to arid ones (e.g., Egypt, Yemen, Algeria), showing that lack of precipitation does not necessarily dictate freshwater supply vulnerability.

Within this subset, Jordan is the country of greatest concern (figure 4A), with five characteristics displaying critical vulnerability values, followed by Djibouti and Yemen each with three critical and two severe characteristic values. These three countries struggle with multiple dimensions of vulnerability and reveal critical values in both endogenous and exogenous characteristics. Each faces water quantity issues, having relatively low renewable freshwater supplies, and problems of groundwater over-extraction and/or limited surface water storage. Compared to other countries in this study, these three import much of their food and manufactured goods, maintaining a strong dependence on the products of other nations. Although Yemen appears to lack the growing, localized pressure for water that large urban populations in Jordan and Djibouti face, it must contend with relatively poor water quality from upstream neighbors. Jordan is the only one of the three countries to avoid serious issues associated with governmental corruption and lack of transparency.

4.2. Dominant characteristics of vulnerable nations

Figure 4B shows each nation’s total number of moderately, severely or critically vulnerable characteristics and the dominant cause of vulnerability by characteristic category. Three results are of interest. (1) Each of the 119 countries inspected had at least one
vulnerable characteristic value, and 41 countries had five or more vulnerable characteristics. (2) When assessed for their dominant causes of vulnerability, the plurality of countries (32%) were found to be vulnerable in at least two characteristic categories. (3) Institutional vulnerability was the most common single dominant characteristic category, occurring in 37% of all nations and most frequently in the form of governmental corruption. Countries that are typically more susceptible to institutional vulnerability appear to cluster in Africa.

Of the 119 nations, 23 were found to be at least moderately vulnerable in all four characteristic categories. Additionally, of all the countries analyzed, 21 were dominated by demand vulnerability, 15 by endowment vulnerability, and for 1 nation, Samoa, infrastructure was the dominant cause of vulnerability (figure 3(B)). Demand-based vulnerability represents a significant problem for Latin America and Southeast Asia. In contrast to other countries, the majority of these nations devote substantial portions of their renewable freshwater to ecosystem maintenance, and they have a large proportion of their population in urban areas. These attributes create water demand problems if cities do not have access to potable, large water bodies, sufficient backup reservoir storage, or ample groundwater. Those nations dominated by endowment vulnerability tend to be centered in northern Africa and south Asia and suffer three problems in common: poor access to sanitation which threatens local freshwater quality, low volumes of renewable freshwater, and high dependency on neighboring countries for freshwater.

Transboundary water conflicts are a common vulnerability concern, particularly in light of potential or actual upstream damming activities. Examples of this

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**Figure 3.** Countries with critical and severe vulnerabilities. These 25 countries have at least two characteristics with critical (CR) values or one critical and one severe (SV) characteristic. The total number of critical and severe characteristic values for each country is represented by the extruded height. The color represents whether these characteristics include endogenous only (yellow) or both exogenous and exogenous characteristics (red). Countries are numbered by the severity of their vulnerability (1 = most vulnerable).
type of threat include Syria’s damming headwater tributaries of the Yarmouk River before it flows into Jordan, Vietnam’s potential loss of food production and wealth generation pending Chinese dam development on the upper reaches of the Mekong River, and the precarious future of Botswana’s Okavango ecosystem and ecotourism industry, which relies on water generated from undammed rivers originating in the Angolan highlands. Although only Samoa is dominated exclusively by infrastructure vulnerability, this characteristic is a concern in many countries including the three most vulnerable nations, Jordan, Djibouti and Yemen.

4.3. Nations with similar endogenous vulnerability

Figure 5 is based on a pattern-matching approach described in section 3 and shows the endogenous vulnerability of four groups of nations with each group having similar patterns of characteristic values. The three countries in figure 5(A) (Iran, Egypt, and Algeria) have at least one characteristic with moderate endowment, infrastructure, and institutional vulnerability, with Iran and Algeria showing vulnerability in the demand category as well. These northern African and Middle Eastern countries have relatively large urban populations and limited volumes of renewable
freshwater. With limited supply options for meeting demands, these countries have focused on groundwater resources to compensate for low surface-water availability. Consequently, the large, sustained water withdrawals from slowly recharging or fossil aquifers have resulted in a trajectory of steady aquifer depletion. In addition, each country also exhibits a distinct lack of governmental transparency, both in terms of the perceived level of corruption measured in the public sector and in the case of Algeria, a lack of ability to regulate where and how water resources are used within their borders.

Figures 5(B) and (C) show sets of countries that lack distinct geographical proximity, yet exhibit similar endogenous vulnerabilities. In the case of figure 5(B), Vietnam, Sri Lanka, and Guatemala show similar patterns of demand and institutional vulnerability. Relatively high population densities and high numbers of endangered species indicate that these countries are dealing with substantial water demands from both the environmental and the domestic sectors as re-allocation of existing water resources to accommodate these high-priority demands may reduce the volume of water available for other sectors. The flexibility of these nations to respond to these demands may be limited by their institutional capacity, which is also vulnerable. Vietnam and Sri Lanka have relatively low governmental transparency and trustworthiness. Based on the regulatory survey data used in this analysis, few mechanisms for controlling and enforcing water quantity regulations exist in any of the three. Additionally, Sri Lanka and Guatemala both export a relatively large percent of water through virtual water trade, thereby potentially exacerbating water supply problems. Figure 5(C) represents a different set of countries (Ukraine, Kazakhstan, and the Dominican Republic) that are also geographically separate but exhibit similar vulnerability, particularly in their demand and institutional characteristic categories. Like nations grouped in figure 5(B), these regions had vulnerable characteristic values for governmental corruption and transparency, and each has substantial virtual water exports. However, unlike the nations in figure 5(B), all have the majority of their populations living in urban areas, which introduces problems of large, localized demand. This may be particularly problematic when renewable freshwater supplies are limited, as they are in Ukraine and Dominican Republic.

Figure 5(D) shows a group of geographically-clustered vulnerable countries situated in Africa (Kenya, Uganda, Ethiopia, Tanzania, and Nigeria). This group shows similar characteristic value patterns across each of the four characteristic categories with a particular focus on endowment and institutional vulnerability.

Figure 5. Similarities in patterns of endogenously-derived water vulnerability. Systems can have similar weaknesses (vulnerable characteristics values, inner white area) and strengths (characteristic values, inner shaded area). Similar patterns can unfold between countries in local proximity to one another ((A) and (D)), or be geographically disparate ((B) and (C)). The type of vulnerability can extend from one (C) to all four categories (A) of characteristics.
because of the strong perceptions of governmental corruption, low availability of renewable freshwater and poor access to improved sanitation.

4.4. Nations with similar exogenous vulnerability
Countries also exhibit similar patterns of vulnerability in exogenous characteristics. Figure 6 shows examples of three different exogenous vulnerability pathways. Figure 6(A) represents a highly vulnerable cluster consisting of Jordan, Bosnia–Herzegovina, Estonia and Algeria. These four countries all experience similar vulnerability in institutional characteristic categories. All import the majority of their national supply of food and other goods containing embedded virtual water, leaving each susceptible to the policies and practices of the exporting countries upon which they rely. Figure 6(B) shows six countries with similar patterns of demand and institutional vulnerabilities, but display wide geographic diversity. Whether because they are small nations, arid countries, or are poorly equipped for self-supply, these geographically dispersed countries are similarly vulnerable. Finally, figure 6(C) shows that vulnerability need not arise only from covering a breadth of characteristics. The countries in this cluster are vulnerable because of their endowment characteristics, each experiencing substantial hydrologic dependency on adjacent countries for surface water supplies. Consequently, water availability for these downstream users is subject to the hydraulic developments of their upstream neighbors. Such transboundary dependency, in combination with the poor water quality of the rivers entering these regions, leaves them particularly susceptible to resource-related hydrologic shocks.

5. Discussion and conclusions
Our evaluation of freshwater supply vulnerability in human–hydrologic systems is based on a set of demand, endowment, infrastructure and institutional characteristics specifically related to water resources and water management. We examine how these characteristics can provide insight into the nature and source of water supply vulnerability for 119 low-income countries. Our analysis shows that every country was vulnerable in at least one characteristic category and that for the plurality of countries, the greatest vulnerability stems from more than one characteristic category. Of those countries with a single, dominant form of vulnerability, institutional problems are by far the most common, emphasizing the need for more comprehensive institutional assessments in water vulnerability analyses.

Twenty-five countries were identified as being of greatest concern for freshwater vulnerability. The most vulnerable are Jordan, Djibouti and Yemen, each showing critical vulnerability in all four characteristic categories. For these three nations, vulnerability arises from an overall lack of water resources coupled with multiple endogenously and exogenously-derived management issues. Groups of countries with similar vulnerability fingerprints were also identified, highlighting areas where comparable characteristic values indicate similar patterns in vulnerability. While some groups of similarly vulnerable countries were found to be in close geographic proximity to one another, other groups were geographically dispersed, suggesting that specific patterns of vulnerability are not solely a product of regional conditions.

Values for assessing the characteristics for human–hydrologic systems are based on best available data, yet there are some obvious caveats. In using pre-existing data, we are limited to information that may not always perfectly represent the system attributes we wish to assess (e.g., groundwater characteristic assumes no important environmental discharges). In addition, quantitative data on demand- and endowment-related characteristics tend to be more readily available both in terms of data volume and in spatial coverage than information describing institutional or infrastructural characteristics. This is partially because...
many institutional data are qualitative in nature and lack clear methods for consistently categorizing or standardizing information across systems. The institutional datasets selected for use in this study incorporate those data that have been standardized across nations, but represent only a portion of the broad range of governance mechanisms that exist. Although we acknowledge that the variety of institutional data currently standardized across nations is somewhat limited, we believe the datasets we have chosen to reflect the institutional characteristics of freshwater supply systems are satisfactory for this analysis. However, this relatively coarse assessment of institutional characteristics reflects in part the current dearth of information available at the global scale, making apparent the need for new high-quality institutional-related datasets. For instance, in this study, data were not available for all countries, nor across all characteristics. In particular, the institutional category contains the largest percentage of vulnerable nations, however this result is likely underestimated as data for 26 of the 119 countries included here were missing in the UN survey data used to assess regulatory and monitoring programs. In addition, the low percentage of countries dominated by vulnerable infrastructure-based characteristics may have been affected by only having two characteristics for infrastructure, versus five or six in the other three categories.

Considering that this analysis was done at the national scale, it provided valuable results and insights about the nature of vulnerability and similar patterns among different countries. Our approach extends knowledge of freshwater vulnerability by incorporating physical and socio-economic factors and including more thoroughly factors specifically related to institutions and infrastructure by which regions manage water. A pattern matching approach enabled us to identify countries with similar forms of vulnerability, providing a useful foundation for benchmarking types of water vulnerability issues in human–hydrologic systems. This study shows that a multitude of characteristics must be inspected that cover the many sources of water supply vulnerability of the human–hydrologic system. Currently, this information is only available at the national scale. We consider this a first step and future efforts are encouraged to consider these and other metrics at the basin and regional scales.

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References

Alcamo J, Doll P, Henrichs T, Kaspar F, Lehner B, Rösch T and Siebert S 2003 Global estimates of water withdrawals and availability under current and future ‘business-as-usual’ conditions Hydrol. Sci. J. 48 339–48
Alcamo J, Florke M and Märker M 2007 Future long-term changes in global water resources driven by socio-economic and climatic changes Hydrol. Sci. J. 52 247–73
Allan JA 1998 Virtual water: a strategic resource global solutions to regional deficits Ground Water 36 545–6
Arnell N W 1999 Climate change and global water resources Glob. Environ. Change 9 531–49
Biswas A K 2004 Integrated water resources management: a reassessment Water Int. 29 248–56
Brown A and Matlock M D 2011 A review of water scarcity indices and methodologies Unuv. Ark. Ark. USA Sustain. Consort. White Pap. 106 1–12
Clarke R T and King J 2004 The Water Atlas (New York: The New Press) pp 18–26
Falkenmark M, Lundyqvist J and Widstrand C 1989 Macro-scale water scarcity requires micro-scale approaches—aspects of vulnerability in semi-arid development Nat. Resour. Forum 13 528–67
FAO 2013 AQUASTAT Main Database Food and Agriculture Organization of the United Nations (www.fao.org/nr/aquastat/)
Garriga R and Foguet A 2010 Improved method to calculate a water poverty index at local scale J. Environ. Eng. 136 1287–98
Gleick P H 1996 Basic water requirements for human activities: meeting basic needs Water Int. 21 63–92
Gleick P H 2003 Water use Annu. Rev. Environ. Resour. 28 275–314
Hoekstra A Y and Chapagain A K 2007 Water footprints of nations: water use by people as a function of their consumption pattern Water Resour. Manage. 21 35–48
Islam M S, Oki T, Kanae S, Hanasaki N, Agata Y and Yoshimura K 2007 A grid-based assessment of global water scarcity including virtual water trading Water Resour. Manage. 21 19–33
Jenerette G D and Alstad K P 2010 Water use in urban ecosystems: complexity, costs, and services of urban ecohydrology Urban Ecosystems Ecology—Agronomy Monographs 55 (Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Society of America) pp 353–71
Jenerette G D and Larsen I 2006 A global perspective on changing sustainable urban water supplies Glob. Planet. Change 50 202–11
Jury W A and Vaux H J Jr 2007 The emerging global water crisis: managing scarcity and conflict between water users Advances in Agronomy vol 95 ed L. Sparks Donald (New York: Academic) pp 1–76 (http://sciencedirect.com/science/article/pii/S0066221307950014)
McDonald R I, Green P, Balk D, Fekete B M, Revenga C, Todd M and Montgomery M 2011 Urban growth, climate change, and freshwater availability Proc. Natl Acad. Sci. USA 108 6312
Medema W, McIntosh B S and Jeffrey P J 2008 From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector Ecol. Soc. 13 29 (www.ecologyandsociety.org/vol13/iss2/art29)
Ohlsson L 2000 Water conflicts and social resource scarcity Phys. Chem. Earth B: Hydrol. Oceans Atmos. 25 213–20
Oki T, Agata Y, Kanae S, Saruhashi T and Musiame K 2003 Global water resources assessment under climatic change in 2050 using TRIP Water Resources Systems—Water Availability and Global Change ed S Franks et al (Wallingford: IAHS) pp 124–33
Oki T and Kanae S 2006 Global hydrological cycles and world water resources Science 313 1068–72
Ostrom E 2009 A general framework for analyzing sustainability of social–ecological systems Science 325 419–22
Plummer R, Loë R and Armitage D 2012 A systematic review of water vulnerability assessment tools Water Resour. Manage. 26 4327–46
Postel S L, Daily G C and Ehrlich P R 1996 Human appropriation of renewable fresh water Science 271 785–8
Qadir M, Sharma B R, Bruggeman A, Choukr-Allah R and Karajeh F 2007 Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries Agric. Water Manage. 87 2–22
Rijsberman F R 2006 Water scarcity: fact or fiction? Agric. Water Manage. 80 5–22
Seckler D, Amarasinghe U, Molden D, de Silva R and Barker R 1998 World Water Demand and Supply 1990–2025: Scenarios and Issues (Colombo, Sri Lanka: International Water Management Institute)
Shiklomanov I A 1991 The World’s Water Resources (Paris, France: UNESCO/IHP)
Smakhtin V, Revenga C and Doll P 2004 A pilot global assessment of environmental water requirements and scarcity Water Int. 29 307–17
Srinivasan V, Lambin E F, Gorelick S M, Thompson B H and Rozelle S 2012 The nature and causes of the global water crisis: syndromes from a meta-analysis of coupled human–water studies Water Resour. Res. 48 W10516
Sullivan C 2013 Global water resources: where are the vulnerable? Glob. Stud. J. 34 1–10
Sullivan C A et al 2003 The water poverty index: development and application at the community scale Nat. Resour. Forum 27 149–99
Turner B L et al 2003 A framework for vulnerability analysis in sustainability science Proc. Natl Acad. Sci. USA 100 8074
United Nations 2012 Status Report on the Application of Integrated Approaches to Water Resources Management (Nairobi: United Nations Environment Programme) pp 1–119
Vörösmarty C J, Green P, Salisbury J and Lammers R B 2000 Global water resources: vulnerability from climate change and population growth Science 289 284–8