The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies

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[1] Freshwater scarcity has been cited as the major crisis of the 21st century, but it is surprisingly hard to describe the nature of the global water crisis. We conducted a meta-analysis of 22 coupled human–water system case studies, using qualitative comparison analysis (QCA) to identify water resource system outcomes and the factors that drive them. The cases exhibited different outcomes for human wellbeing that could be grouped into a six "syndromes": groundwater depletion, ecological destruction, drought-driven conflicts, unmet subsistence needs, resource capture by elite, and water reallocation to nature. For syndromes that were not successful adaptations, three characteristics gave cause for concern: (1) unsustainability—a decline in the water stock or ecosystem function that could result in a long-term steep decline in future human wellbeing; (2) vulnerability—high variability in water resource availability combined with inadequate coping capacity, leading to temporary drops in human wellbeing; (3) chronic scarcity—persistent inadequate access and hence low conditions of human wellbeing. All syndromes could be explained by a limited set of causal factors that fell into four categories: demand changes, supply changes, governance systems, and infrastructure/technology. By considering basins as members of syndrome classes and tracing common causal pathways of water crises, water resource analysts and planners might develop improved water policies aimed at reducing vulnerability, inequity, and unsustainability of freshwater systems.

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1. Introduction

[2] Freshwater "scarcity" [*Jury and Vaux*, 2005] and security [*Vörösmarty et al.*, 2010] have been identified as major global environmental problems of the 21st century. Although global population is expected to increase to about 9 billion by 2050 [*Gleick and Palaniappan*, 2010], the planet's endowment of accessible renewable freshwater has been and will remain more or less constant [*Postel et al.*, 1996]. Although some additional freshwater could be appropriated for human uses by capturing flood waters and increasing storage capacity, humans already appropriate over 50% of all available renewable freshwater, raising legitimate concerns that water shortages may limit agricultural and industrial production and human wellbeing in the future.

[3] In the past decade, there has been increasing evidence of the interconnected nature of the global system [*Alcamo et al.*, 2008] through the hydro-climatic system and "virtual water" transfers among regions. But despite the recognition of the existence of a global hydro-commons [*Hoekstra and Chapagain*, 2008; *Hoekstra and Mekonnen*, 2012], most water is abstracted, managed, and used at the regional to local scale (state, city, micro-watershed, basin). Depending on the local socioeconomic, political, and hydrologic circumstances, the common global drivers of change, such as climate change, population growth, and globalization, have diverse regional impacts.

[4] Much recent research [*Vörösmarty et al.*, 2000, 2010; *Alcamo et al.*, 2008] has been devoted to illustrating the location and nature of these impacts at a global scale. These studies consistently predict that some regions of the world will face water crises: India, northern China, north and sub-Saharan Africa, the Middle East, and parts of Eastern Europe. But these "top-down" predictions of water crises pose several problems. To derive water stress indicators, they often rely on state variables—climate, precipitation, runoff, population density, aquifer characteristics, land use, and biodiversity—in effect, suggesting that water crises are driven by geospatial factors and therefore are not controllable by human action. They do not offer a roadmap to finding tangible, implementable policy solutions at the local to regional scale. To address this deficiency, we present a "bottom-up" approach to understanding the nature and causes of water crises by synthesizing findings from recent

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interdisciplinary case study research on water supply. An emerging body of empirical scholarship concerned with the coupled interactions between human and natural water resources in different regions of the world [*Booker et al.*, 2005; *Cai et al.*, 2003; *Wester et al.*, 2005; *Harou and Lund*, 2008; *Jowett*, 1986; *Ringler et al.*, 2004; *Rosegrant et al.*, 2000] chronicle the social–ecological cross-linkages of water systems. The works of these scholars demonstrate that human management of water resources reflects cultural values, historical context, and political realities. In addition, human behavior is molded and constrained by the limits of the natural environment [*Molle*, 2007; *Walker*, 2005]. Furthermore, although supply is generated by natural processes, humans increasingly do not rely entirely on nature for water; human consumption, and by extension, water left in natural ecosystems, is shaped by engineered or managed water systems, or through the virtual water trade.

[5] In the past 6 years, there have been several attempts at generalizing and comparing findings across case studies [*Dinar et al.*, 2005; *Giordano and Villholth*, 2007; *Molle and Wester*, 2009; *Mukherji et al.*, 2009]. These have added to an improved understanding of the common processes contributing to overutilization of water resources. Similarly, within the water resources community, there has been significant interest in "hydrologic synthesis" [*Hubbard and Hornberger*, 2006], focusing on coupled processes and complex feedbacks in the face of global change. In the special issue on hydrologic synthesis published in *Water Resources Research*, *Blöschl* [2006] articulates that the challenge is in synthesizing the plethora of case studies around the world, lamenting that while these programs have provided valuable insights, generalizing the findings beyond the areas of interest has been difficult. No convergence towards common language, ideas, or metrics on freshwater resource sustainability has yet emerged from the synthesis of the case studies that could help prioritize research questions, collate findings, or standardize metrics. Without a common framework to organize relevant variables identified from theories and empirical research, the knowledge acquired by diverse studies from different countries using different disciplinary lenses is likely to be fragmented and unlikely to cumulate [*Ostrom*, 2009; *Glass*, 1976]. There is a need to synthesize this emerging literature in coupled human–water systems.

[6] The goal of this article is to synthesize existing research on water resources systems globally by addressing two basic questions: What types of water resource utilization patterns and problems are observed in different regions of the world? What factors cause them? To address these queries, we conducted a meta-analysis of 22 case studies in subnational regions or watersheds. This article is organized as follows. We briefly review comparative methods in section 2 and present in section 3 the qualitative comparison analysis (QCA) method used here. In section 4 we discuss how the meta-analysis was approached in terms of case study selection, variable coding, and so forth. We present our results in section 5 and discuss them in section 6. Finally, in section 7, we conclude by pointing out some implications for policy.

2. Brief Review of Comparative Methods

[7] Scientists have long acknowledged the problem of scale in studying both natural and human systems; that is, different insights are obtained by studying problems at different scales, and fresh insights can be obtained from investigating the same phenomenon across a region or a wide range of communities, beyond that which can be obtained from site-specific studies. Achieving this requires aggregating or comparing results from multiple site-specific studies [*Rudel*, 2008]. Previous attempts to understand water issues in different regions of the world have followed two distinct pathways operating at two different scales: large-N or variable-oriented, top-down studies and small-N or case-oriented, bottom-up research [*Ragin*, 1987]. Large-N or variable-oriented studies have focused on identifying statistically significant relationships among variables across a large population of cases [*Ragin*, 2000]. Variable-oriented approaches have typically involved quantifying the relationship between water use and variables such as renewable freshwater availability, population, and income, e.g., the Water Stress Index [*Falkenmark*, 1986]. Such variable-oriented approaches are popular because the data are relatively easy to find and are inherently comparable, making it possible to identify vulnerable regions. The problem is that variable-oriented studies tend to emphasize state variables (e.g., geology, rainfall, demography), overlooking human agency altogether [*Ragin*, 2000], in part because nuances of culture and institutions are difficult to codify, standardize, and aggregate into cross-national databases. This neglect of human decision-making and adaptive capacity implicitly suggests that water stress is predetermined and inevitable, and that humans can do little to avert crises. Such studies cannot point to implementable solutions at the regional and local scales.

[8] In contrast, small-N studies or single-case studies focus on identifying patterns of abstraction and their causes within a single region, usually one watershed or basin. These studies have a diversity of objectives and research questions. For instance, studies have examined the implications of various policies and management options such as conjunctive use of surface water and groundwater [*Harou and Lund*, 2008; *Schoups et al.*, 2006], water infrastructure planning [*Lund et al.*, 2009], decentralized water resources management [*Srinivasan et al.*, 2010], water institutions [*Ward and Pulido-Velázquez*, 2008; *Characklis et al.*, 2006], or ecosystem protection regulations [*McCarl et al.*, 1999]. Others have focused on the implementation of governance mechanisms such as Integrated Water Resources Management (IWRM) or decentralization of water resources management [*Dinar et al.*, 2005]. Case studies have the advantage of being rich in detail. Such studies often explicitly account for "human agency" (farmer behavior, agency decision-making, institutional structures, pricing policy) and discuss the nuances of possible solutions. However, the very richness of case study research is also a disadvantage. Because each case study is endowed with a unique set of historical, social, economic, political, and biophysical constraints, comparison is difficult. Consequently, case studies suffer from limited generalizability; finding common causal pathways *across* cases remains a challenge.

[9] Attempts to conduct comparative studies or meta-analyses of complex case studies are plagued by the limited number of highly heterogeneous cases studied. This limits the usefulness of standard statistical procedures or may preclude the use of statistical inference altogether. The data

requirements for traditional meta-analyses are quite stringent; to pool data from different studies, each investigator must have standardized data on the same variables, using similar instruments, in comparable settings [*Rudel*, 2008].

[10] In most natural sciences studies, complexity is controlled by experimental design or statistical techniques, something that is not available to scientists who study natural systems with multiple feedbacks. There are no established methods on how to go about synthesizing results in such studies. Investigators may focus on the same topic, but the study objectives and the dependent and independent variables differ across studies. Often there are not enough cases that deviate from the dominant pattern of correlation, or analysts may find two or more variables so confounded that they cannot disentangle them empirically [*Rudel*, 2008]. Additionally, standard statistical analyses are poorly equipped to deal with conjunctural causation—cases in which outcomes occur from combinations of conditions. In conventional statistical analyses, such conditions would be represented by interaction terms; however, researchers using such methods would find that the number of explanatory variables would quickly exceed the number of cases. Moreover, traditional meta-analyses cannot easily combine qualitative and quantitative causal factors.

3. Qualitative Comparison Analysis

[11] In addressing these analytical and methodological problems faced by scientists concerned with the study of complex human–environment interactions at regional to global scales, *Young et al.* [2006] make the case for a portfolio of approaches. Among the set of complementary methodological approaches, use of qualitative comparison analysis (QCA) is suggested [*Ragin*, 1987], a technique that uses Boolean algebra to implement rigorous meta-analyses of a limited number of qualitative case studies. QCA aims to synthesize the causes and outcomes of environmental problems while retaining the complexity and richness of case study research [*Scouvart et al.*, 2007]. It also seeks to bridge the gap between traditional qualitative and quantitative approaches by combining some of the advantages of both strategies. QCA works best for sets that range from 6 to 70 cases [*Rihoux*, 2003].

[12] QCA works by grouping cases into sets that exhibit similar causal configurations that contribute to the observed outcome. In QCA, the independent variables are coded from the case study literature to be present or absent (1, 0) or, in fuzzy-set logic, partially present (between 0 and 1). QCA then relies on algorithms drawn from Boolean algebra to sort cases into minimized sets of factors that, in combination, cause a particular condition. The Boolean algorithm works by iteratively eliminating dependent variables to yield "prime implicants": minimal formulae showing parsimonious configurations of conditions that can explain all the case outcomes. QCA aims to establish some degree of generalization of conclusions in the face of complexity. It is important to note that QCA examines the data differently than regression-based statistical analysis does. QCA does not aim to determine the net effect of various independent variables on a single dependent variable across all cases [*Ragin and Rihoux*, 2004]. In fact, QCA does not take on the burden of establishing correlation or causality at all. Instead, the causality is assumed to be established *within* the case studies. The Boolean algorithm sorts the cases to find common causal pathways. A major advantage of this approach is that the method permits multiple conjunctural causations; i.e., it recognizes that certain outcomes are driven by simultaneous occurrence of certain factors. QCA differs from index-based approaches by being systematic about which variables are included. In this way QCA avoids the problem of an arbitrary choice of variables or weights that are common to other index-based approaches.

4. Implementation of QCA

[13] To address the research questions laid out in this study, we first had to clarify the systems and outcomes of interest. Unlike previous applications of QCA in the context of natural resources, such as deforestation where the presence or absence of a problem is relatively obvious [*Scouvart et al.*, 2007], water resource researchers do not have a single definition of what constitutes a "water problem." As *Cook and Bakker* [2011] show, even specific framings of a problem such as water security are highly diverse and inconsistent and vary with context and discipline.

[14] We considered the following propositions: (1) The availability or nonavailability of water to satisfy human needs is influenced by both natural processes as well as social and engineered ones. (2) Human beings care about the "services" or wellbeing derived from water use [*Gleick*, 2003]. (3) Both direct anthropogenic water use and indirect ecologic use (via ecosystem services) contribute to human wellbeing. (4) Increasing anthropogenic water use often results in decreasing water availability to ecosystems, so there are trade-offs in wellbeing from different types of water uses. (5) Increasing current water use may deplete water available to future generations; hence, trade-offs exist between current and future wellbeing. (6) Water is a stochastic resource and therefore the wellbeing derived from water may be variable. To accommodate these concerns, our meta-analysis focused on case studies dealing with coupled human–water systems. The outcome of interest was both present and future human wellbeing derived from both direct and indirect use of water.

[15] In this study, we implemented QCA in four steps:

[16] Step 1. Candidate studies of water resources problems were identified. A case study was defined as a set of papers, published by a *single research team*, that met our criteria on interdisciplinarity, subject focus, and methods.

[17] Step 2. The papers describing each case were analyzed to identify "outcome" variables that were identified by grouping cases into "syndromes."

[18] Step 3. Explanatory variables (causal conditions) were coded as binary variables (1 indicating presence, 0 indicating absence).

[19] Step 4. The causal factors for each syndrome were determined using QCA. Each of these steps is described below.

4.1. Case Selection

[20] A "case" was defined to be a research study at the basin/watershed scale (1,000 km^2 to 1,000,000 km^2) focused mainly on water quantity issues. Water quality was addressed only to the extent that it impacts the quantity of water suitable for human use and maintenance of river ecosystem

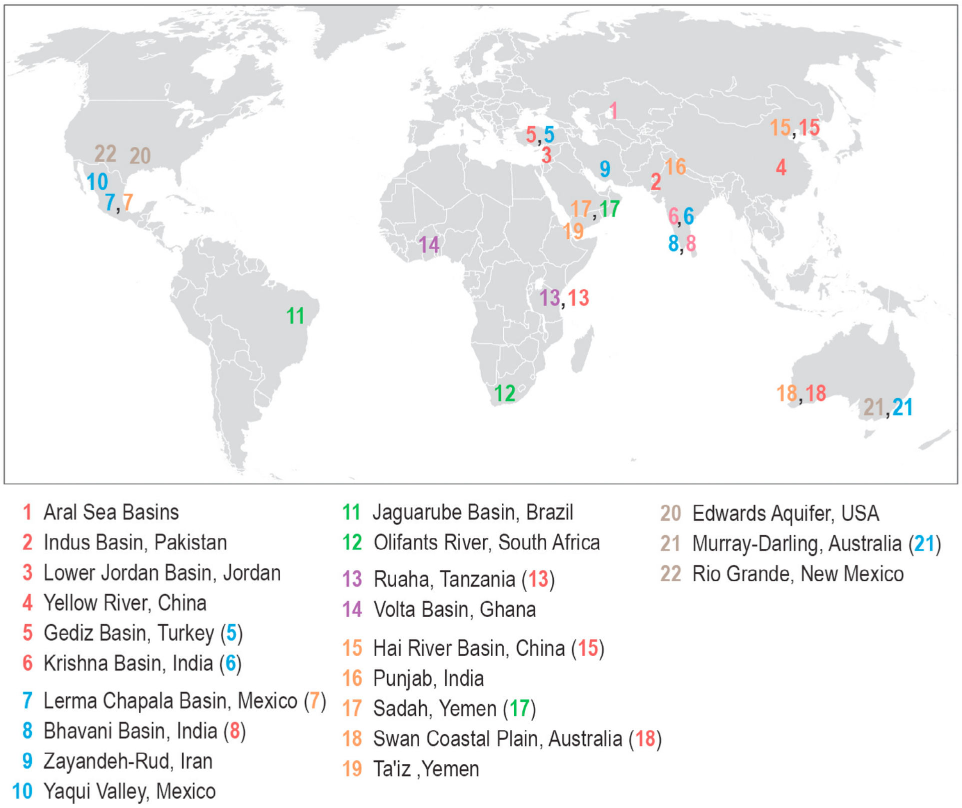

Figure 1. Location of the 22 case studies used in the meta-analysis. The region numbers are grouped and colored on the basis of the symptoms they exhibit as discussed in section 5. Red = Ecologic Destruction, green = Resource Capture by Elite, blue = Drought-Driven Conflict, purple = Unmet Subsistence Needs, orange = Groundwater Depletion, grey = Reallocation to Nature.

health. A set of search and selection criteria were used (Appendix A) to ensure that the factors considered in the case studies were based on empirical observations rather than model assumptions.

[21] We selected only cases studied by interdisciplinary teams because such teams are more likely to examine the multidimensional aspects of water resources problems. In traditional disciplinary studies, the causal factors examined tend to be limited to variables favored by a particular discipline [*Rudel*, 2008]. Given that our outcome of interest was human wellbeing derived from water use, and not the availability or use of water itself, we concluded the multiple dimensions of coupled human–water systems are best examined by multidisciplinary teams that consider a range of scientific, engineering, economic, political, cultural, and institutional factors. Therefore, a case study was required to have at least one original peer-reviewed research article (to ensure quality) published after 1980, conducted by an interdisciplinary team including at least one natural scientist and one social scientist. A single author was also considered acceptable if he or she had published an edited volume that included a synthesis of multiple studies. Finally, a case study was defined to be time-specific—coded at a particular point in time—when the conditions within the case were relatively stable. This is an important point, because the availability and use of water resources in a region could change significantly with a single infrastructure project or legal ruling. Thus, not all the cases occurred at the same time. For example, the Jaguaribe Basin, a case discussed in this paper, was coded for the period *before* a relatively successful IWRM program was implemented. In part, because the IWRM implementation is still ongoing and the outcomes are not stable, we were unable to conclusively describe the current situation in the basin. Similarly, the Rio Grande Basin and the Edwards Aquifer cases were coded on the basis of literature that analyzed these cases *after* the rulings of two high-profile Endangered Species Act lawsuits that significantly altered the basin trajectories.

[22] The publications, authors, and citations used in this study are presented in supplemental text S1.[1] Brief details of the case studies are provided in Appendix B. The case study locations are shown in Figure 1.

4.2. Independent Variable or Outcome Coding

[23] To meet our goal of developing a typology and tracing the causes of water problems, defining the dependent variable proved to be challenging. Actually, no single-outcome metric clearly describes all cases. To account for the multisymptom nature of water resource problems, we built on the concept of syndromes of environmental outcomes,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011WR011087.

Table 1. Outcome Indicator Variables

Outcome Variable Type	Outcome Indicator Variable
Current average human wellbeing as affected by direct human (urban/agricultural) and indirect (ecosystem) water use	Persistent lack of access to minimum quantity of water for drinking and hygiene needs for much of the population
	Persistent lack of access to minimum quantity of water to satisfy subsistence livelihood needs for much of the population, resulting in extreme poverty
	Highly unequal distribution of access to water: some have plentiful water supply while others have none
Current variability in human wellbeing as affected by direct (urban/agricultural) and indirect (ecosystem) water use	Temporary lack of access to minimum quantity of water for drinking and hygiene needs
	Temporary lack of water for livelihood needs, resulting in sudden but temporary declines in income and wellbeing
	Consistently high quality and sufficient drinking water supply for most of the population
	Consistently sufficient supply to meet current agricultural water demand
Future human wellbeing as affected by direct (urban/industrial/agricultural) and indirect (ecosystem) water use	Long-term decline in quantity of water stock available to future generations (groundwater levels or lake area)
	Aquatic ecosystem decline
	Long-term trend decline in quality of water stock available for future generations (large-scale groundwater or surface water contamination)
	Long-term recovery of previously depleted water stock
	Aquatic ecosystem recovery

that is, "constellations of natural and civilizational" trends and their interactions, which produce measurable impacts on the earth system [*Ludeke et al.*, 2004; *Manuel-Navarrete et al.*, 2007]. For the present study we defined syndromes of water resource utilization as an association of recognizable features, symptoms, phenomena, or characteristics of these systems that often occur together, such that the presence of one or more features alerts the researcher to the possible presence of the others. Our outcome (or dependent) variable was a categorical variable describing the syndrome(s) that best characterized a particular case.

[24] We identified 12 binary variables that describe changes in water availability and use that influence current and future human wellbeing (Table 1). To group these variables into syndromes, we assembled a series of hypothetical combinations of outcome vectors, using only consistent combinations of output variables; that is, a case could not simultaneously show ecosystem recovery and ecosystem declines. For example, a hypothetical combination might be Syndrome A = [1, 1, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0]. Each case study output vector was compared with Syndrome A. A case was considered to exhibit Syndrome A if the sum of the squares of the difference (or the Euclidean distance in the feature space of outcome variables) between the outcome vector of a case and that of another vector was smaller than some cutoff threshold or minimum distance criteria. Syndromes that accommodated too many or too few cases were dropped. This left us with six identifiable syndromes. Most of the cases belonged fully to one syndrome. A few cases exhibited a combination of syndromes.

4.3. Dependent Variable or Causal Factor Coding

[25] We identified and dichotomized explanatory or causal variables (factors) because QCA relies on principles of Boolean algebra to simplify complex sets of binary data in a logical way [*Ragin*, 1987]. The criteria used to code the cases are presented in Appendix C. For instance, regarding the Ruaha Basin Case Study, *Lankford et al.* [2009, p. 190] stated: "The Rufiji basin Water office, designed a water rights system by setting a fixed quanta for the water right (e.g., 250 l/s). Yet intakes are not monitored as there is no evidence for the existence of flow measurement structures." We coded this statement as follows: Enforcement of surface water right = 0. We used binary values (1 or 0) to code the presence or absence of factors. Fuzzy-variable coding, in which values between 0 and 1 are used to indicate partial presence or absence of factors, was not chosen in this case for two reasons. First, most articles lacked sufficient detail and commonality of reporting to make fuzzy-variable coding possible. Second, for most variables there was very little ambiguity on whether the factor was present or not.

[26] To reduce the large number of coded variables to a more tractable number, we organized the variables in two ways: chain-logical causation (i.e., one or several underlying factors driving one or several proximate factors, which results in the observed outcome) and concomitant occurrence (i.e., the independent operation of factors that result in a single observed outcome) [*Geist and Lambin*, 2002]. In Figure 2 the explanatory variable Effective Groundwater Control (1 = Effective Control, 0 = Ineffective Control) was coded by using chain-logical causation and concomitant occurrence.

[27] Figure 2 also shows how two pathways can lead to ineffective groundwater control: Either groundwater is overallocated (i.e., existing laws/rules legally permit too much extraction) or the groundwater limits are set appropriately but the law is poorly enforced. These two factors can be concomitant.

[28] Groundwater overallocation is caused by the presence of one of four underlying factors (chain causation): (1) Current law follows the Rule of capture, which allows abstractors to take as much as they want; (2) groundwater is controlled by pricing, but the price is set well below the marginal social cost of extraction, so that extraction far exceeds sustainable levels; (3) abstractors need a license/permit to extract, but too many groundwater permits have been issued; or (4) rights to groundwater are double-counted—that is, the rights to the same physical unit have been granted as both a surface water right and a groundwater right. A basin would be judged to be overallocated if *any one* of the factors—Rule of capture,

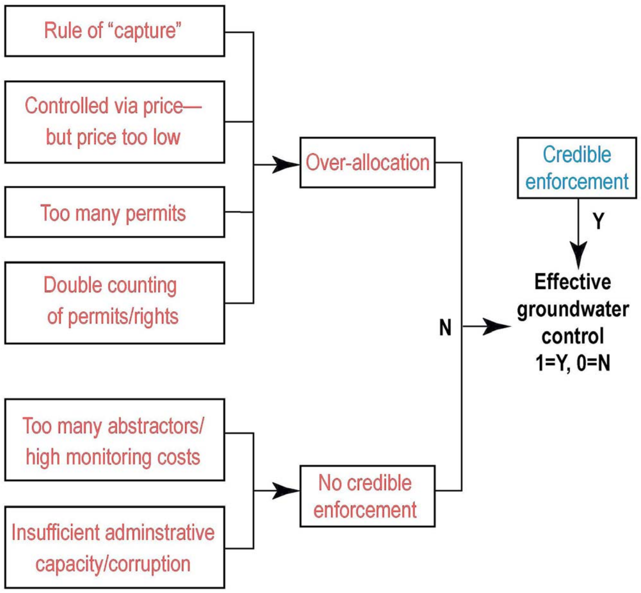

Figure 2. Example showing causal variable effective control over groundwater. The coded variables indicate two paths to ineffective groundwater control, each of which could be attributed to several underlying factors (chain-logical causation). Thus, either groundwater was overallocated (i.e., existing laws/rules permitted too much extraction) or the groundwater limits were set appropriately, but the law was poorly enforced.

Pricing too low, Too many permits, or Double-counting of rights—is coded as being present.

[29] Ineffective control over groundwater may occur even if there are appropriate laws on paper but they are poorly enforced. Poor enforcement of existing groundwater abstraction laws occurs for several reasons: The impossibility of tracking down millions of dispersed abstractors makes it too expensive to meter, and blatant misconduct or corruption of the enforcers actively or implicitly allows abstractors to exceed their permitted volumes. A basin would be judged to have no credible enforcement if *any one* of the factors causing poor enforcement were present.

[30] This aggregation of causal pathways was repeated for 38 coded variables, which represented such fundamental social and biophysical processes as climate change, population dynamics, social/cultural movements, legal rulings, or technological innovation [*Geist and Lambin*, 2002]. By iteratively combining the 38 coded variables, we arrived at a small set of immediate or 8 "proximate" causal variables, shown in Table 2. These eight variables fall under four categories: resource availability, human and ecological demand, access infrastructure, and governing institutions.

4.4. Tracing Causation

[31] Once the complete list of outcome variables (syndromes) and causal variables or factors was determined, we applied the QCA algorithm to trace the causes of each of the observed resource utilization patterns. Because QCA relies on principles and algorithms of Boolean algebra to simplify complex sets of binary data [*Ragin*, 1987], the basic requirement is therefore to dichotomize the dependent variable (or outcome) and the causal variables. Once dichotomized, data can be organized into a truth table, where each line corresponds to a logical combination of values (1 or 0) on the conditions with a given outcome value (a configuration). For n conditions, there are 2^n logically possible configurations and lines in a truth table. QCA implements a Boolean minimization procedure, which stipulates that two expressions producing the same outcome while differing by only one condition can be combined into a single, shorter expression by excluding this now-irrelevant latter condition. The output of the Boolean minimization procedure is a formula describing each outcome in the most parsimonious way. The QCA output consists of a list of terms. Each term represents one causal pathway determined by a set of factors that must occur simultaneously to generate the set of outcomes. The outcome will occur if any of the causal pathways is present.

5. Results

5.1. Syndromes

[32] We found that all 22 cases could be categorized under one of six syndromes, syndromes that correspond to differing levels of water utilization by urban, agricultural, and ecosystem "users." The six syndromes are Groundwater Depletion, Ecological Destruction, Drought-Driven Conflicts, Unmet Subsistence Needs, Resource Capture by Elite, and Water Reallocation to Nature.

[33] Some syndromes were associated with a problematic state of the coupled human–water resource systems due to a gradual decline in the water stock or ecosystem function that could result in a *long-lasting, steep drop in future* human wellbeing—*unsustainability*; or a high degree of variability causing *temporary, steep drops* in human wellbeing in some periods—*vulnerability*; or *persistently low levels* of human wellbeing for some portion or even all of the whole population—*chronic scarcity* (Figure 3). Other syndromes represent *successful adaptations* to difficult conditions.

[34] The first two syndromes (Groundwater Depletion and Ecological Destruction) were associated with a systematic decline or degradation of the natural resource base over time, caused by depletion of a nonrenewable freshwater stock or irreversible damage to system processes. In these cases, the concern would be the *unsustainability* of the sociohydrologic system and hence human wellbeing. Future generations would be unable to sustain current levels of human wellbeing either the decrease in the quantity of water available or the irreversible destruction of critical ecosystem functions.

[35] For regions characterized as Drought-Driven Conflict, the problems arose in critical periods (usually multiyear droughts) when some communities or ecosystems suffered severe losses in wellbeing, or even life. This syndrome is driven by the renewable but variable component of freshwater. These cases were characterized by the temporary drying of reservoirs, lakes, streams, or wetlands that often resulted in conflicts over how the burden should be shared among stakeholders. The concern in the Drought-Driven Conflict syndrome is the *vulnerability* of the sociohydrologic system, resulting in temporary, but steep, drops in human wellbeing that might trigger war, famine, or riots.

[36] In Unmet Subsistence Needs regions, the concern was not resource availability. Rather the concern was that some or all communities were unable to secure a minimum threshold quantity of water to meet their domestic and livelihood needs. Such communities permanently suffer from

Table 2. Proximate and Underlying Causal Factors Driving Water Resources Outcomes

Factor Type	Proximate Factor (Var_Name)[a]	Underlying Factors
Resource system	Poor resource endowment **(AQ)**	Little or no aquifer storage
	External drivers decreasing surface water resource availability **(SUPP)**	Decrease in water available due to prolonged drought or climate change Upstream diversions Decrease in recharge
Water demand (human and environmental)	Increase in anthropogenic demand urban or agricultural **(DMD)**	Increase in population living in cities Increase in industrial/commercial demand Increase in water-intensive life style Shifts to high-yielding varieties/water-intensive crops Agricultural subsidies (price floors etc.) Vote bank politics Clientalist politics Food self-sufficiency mandates Expansion of agriculture due to high crop prices in global markets
	Increase in ecological water demand **(ECOL)**	Conservation movements/cultural change External interest in protecting charismatic or endemic species/ biodiversity hotspots
Governance system	Ineffective control over water rights or in-stream flows **(CNTRL)**	Overallocation of groundwater Rule of capture (no extraction limits) Too many permits granted Price set too low Double-counting of groundwater and surface water rights Poor enforcement of groundwater abstraction Inadequate administrative capacity. Corruption Minimum flow laws or cap on diversions Laws that protect specific species, areas. Infusion of federal or state funds to protect specific species or areas. Mandated releases for downstream users (e.g., hydropower) Mandated releases to comply with interstate or international compacts Lack of control over water quality— −+weak pollution enforcement or inadequate sewage treatment
	Presence of reallocation mechanisms **(REALLOC)**	Water markets Infusion of federal funding to buyout/retire agricultural land Reliable interbasin transfers Effective water efficiency programs
Access infrastructure	Insufficient and inadequate infrastructure **(NOINFRA)**	Insufficient reservoir storage Inadequate distribution Deteriorating distribution infrastructure (leaky or incomplete canals and pipes) Inadequate administrative capacity Inability to recover costs
	Extensive groundwater infrastructure **(PMP)**	Widespread rural electrification /diesel pumps Credit programs for farmer tube wells

[a]The high-level or proximate factors are shown in bold with a variable name in parentheses. The underlying factors were the ones that were actually coded in the case study; they were aggregated to the proximate factor using an OR operator; i.e., if any one of the underlying factors is present, then the proximate factor is considered present.

extreme poverty, or their human wellbeing is below a minimum threshold. These regions were characterized by insufficient investments in infrastructure; as a result, they were unable to harness the available water resources to guarantee a basic minimum quality of life.

[37] The Resource Capture by Elite syndrome is a variation of the Unmet Subsistence Needs syndrome. In these cases, the problem is not the average water abstracted for human needs but the highly skewed *distribution of benefits*: Most of the benefits are captured by a small minority. Some communities within these regions might lack access to a minimum threshold quantity of water to meet basic human or livelihood needs; even such aggregate indicators as per capita dam storage or total agricultural production appears adequate. In these regions, any interventions to address vulnerability, lack of access, or unsustainability must occur within the context of this highly uneven playing field. For instance, in the Olifants Basin, the vast majority of water resources development in the 19th century benefited commercial agriculture and mining operations owned by a tiny minority, such that 99.5% of the rural population used only 5% of the water [*Merrey et al.*, 2009].

[38] Not all the resource utilization patterns resulted in problems of unsustainability, vulnerability, or chronic scarcity. Water Reallocation to Nature regions were characterized by decreasing total anthropogenic water use, a gradual decrease in the quantity of water used by irrigated agriculture, and an equivalent increase in the allocation of water to the environment. While the actual process of transformation may vary—restoration to natural land covers, fallowing, switching to less water-intensive crops, or minimum flow mandates—the net outcome was similar. This basic idea of

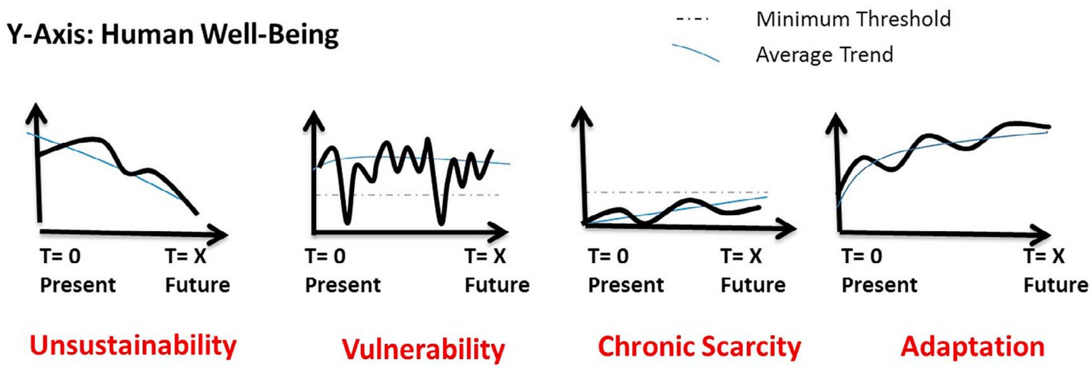

Figure 3. Typology of basin syndromes. Caveat: This typology does not focus primarily on processes, but rather on outcomes: resource sustainability, vulnerability, and scarcity. It does not account of transparency of process. Moreover, the categories are applicable in aggregate, and smaller regions or communities may be particularly vulnerable even if the basin as a whole is not.

reallocating water back from irrigated agriculture to natural ecosystems has been characterized by other scholars in different ways: a reversal in the upstream migration of water assets [*Sivapalan et al.*, 2012] and peak anthropogenic water use [*Gleick and Palaniappan*, 2010].

[39] Although Water Reallocation to Nature represents a possible adaptation to local resource constraints and increasing recognition of preserving ecosystems, the net global effect is unclear. *Allan* [1998] argued that water-scarce countries could achieve water security by importing water-intensive products instead of producing them domestically. However, recent research suggests there is no assurance that virtual water transfers occur from water-rich to water-stressed regions. Indeed, comparative advantage in crop exports is not driven by whether a region is water-rich or water-poor, but rather by the total opportunity cost of crop production, including land, labor, capital, and water [*Wichlens*, 2004]. Indeed, today perverse policy incentives cause transfers in the reverse direction [*Verma et al.*, 2009].

5.2. Tracing the Causes of Observed Resource Utilization Patterns

[40] The coding process described in the previous section resulted in a set of eight essential proximate causal variables that could not be collapsed any further: absence of a deep, productive aquifer (AQ), exogenous supply decreases via decrease in recharge, upstream abstractions or climatic changes (SUPP), increase in anthropogenic demand (DMD), increase in demand for ecological flows (ECOL), weak controls over quantity abstracted and in-stream flow protection (CNTRL), inadequate surface water infrastructure (NOINFRA), excessive groundwater abstraction infrastructure (PMP), and the presence of reallocation mechanisms such as government buyouts, water markets, and environmental water trusts to reallocate water between uses or users (REALLOC). However, recent benchmarking analyses by *Marx and Dusa* [2011] suggest that, to be robust, a QCA based on 22 cases should not allow more than six variables (i.e., causal factors). To resolve this problem, we conducted the QCA in two stages, using a stepwise procedure. First, we conducted the analysis on all eight variables to determine which factors could be eliminated; then, in the second stage, two or more factors were dropped to obtain a robust result for each of the 22 cases. In other words, depending on the outcome of the first stage of QCA, a different set of six variables was chosen for each QCA run. QCA allowed us to highlight a limited set of causal pathways (Table 3).

5.3. Multiple Causal Pathways

[41] Each syndrome exhibited multiple causal pathways (Table 3). Different biophysical conditions also could result in different outcomes. Increased groundwater pumping could lower the groundwater table and also induce recharge from a river. In this latter case, long-term groundwater decline perhaps was not observed, but the rivers dried up, destroying aquatic ecosystems. If the aquifer is shallow and surface water is plentiful, groundwater declines might occur only during prolonged droughts, when consumers pump groundwater to compensate for lack of surface water availability. In this case, the buffering capacity of the aquifer is lost and consumers may experience losses in income, livelihood, or sufficient drinking water.

[42] The multiple causal pathways for each syndrome are described below.

5.3.1. Groundwater Depletion

[43] This syndrome was associated with the presence of a deep, productive aquifer that could potentially be depleted (AQ), ineffective control over groundwater use and the absence of in-stream flow protection (∼CNTRL), and the absence of reallocation mechanisms (∼REALLOC). However, the first pathway was driven by decentralized agricultural pumping, as observed in Yemen, Punjab, and the Hai River Basin. In Yemen, in a well-documented groundwater "basket case" [*Shah et al.*, 2000, p. 1]. the rights of downstream users were historically protected by the law of runoff, which prevented conversion of the open grazing land into agriculture. A push to privatize open grazing land allowed farmers to also develop groundwater for irrigated agriculture, thereby changing a resource previously restricted per tribal law, to an open access resource [*Lichtenthaler*, 2003]. At the same time, groundwater-irrigated agriculture in Yemen was spurred by cross-border Saudi Arabian demand for high-quality grapes and livestock, coupled with wider access to

Table 3. Causal Pathways Identified for Each Syndrome

Syndrome	Cases	Causal Pathway Description	Conjunctural Conditions[a]
		Unsustainability Syndromes	
Groundwater Depletion Groundwater decline over study period	Hai River Lerma-Chapala Punjab Sadah Swan Coastal Plain Taiz	Groundwater decline caused by decentralized pumping by farmers and urban dwellers. The underlying drivers were inadequate controls over groundwater use and the absence of reallocation mechanisms to buy out farmers or import water across basins.	~AQ DMD ~REALLOC PMP
Ecological Destruction Ecosystems, wetlands, or lake areas declined over the study period.	Aral Sea Bhavani Gediz Basin Indus Basin Krishna Basin Lower Jordan Ruaha Basin Tellow River Zayandeh-Rud	Expansion of centralized infrastructure to meet new growth in demand accompanied by industrial and/or sewage pollution. There is no protection of in-stream flows and no reallocation mechanisms in place to avoid the continuous appropriation of water from nature to agricultural and urban uses. Rampant decentralized abstraction of groundwater and exogenous shocks to the system via, e.g., climate change or upstream diversions or a decrease in recharge, resulting in loss of wetlands or aquatic ecosystems and salt water intrusion.	DMD ~SUPP ~CNTRL ~REALLOC ~NOINFRA SUPP NOINFRA PMP
		Vulnerability Syndromes	
Drought-Driven Conflict No long-term trend in water resources or human wellbeing but significant decreases during droughts	Gediz Basin Krishna Basin Murray-Darling Yaqui Valley Yellow River	These cases were driven by the inability to reallocate water between stakeholders, thus causing conflicts over how water should be allocated to satisfy human and natural needs. Conflicts are driven by the inability of the aquifer to act as an effective buffer or by increased demand. In all cases, reallocation mechanisms and control over groundwater and surface water were weak.	~REALLOC ~CNTRL ~NOINFRA & (AQ*DMD | ~AQ* ~PMP)
		Chronic Scarcity Syndromes	
Unmet Subsistence Needs Underdeveloped basins where very little water is being extracted for human needs. Some portions of the population may not have enough access to meet their subsistence needs.	Ruaha Basin Volta Basin	These cases are characteristics of underdeveloped economies with little irrigated agriculture, little surface water or groundwater abstraction infrastructure, and typically weak controls over water resources. Demand is stable or increasing very slowly.	~DMD ~CNTRL NOINFRA ~PMP
Resource Capture by Elite[b] The average water use may be sufficient to meet the needs of the entire population, but some segments of the population suffer from chronic scarcity.	Jaguaribe Basin Olifants Basin Sadah Basin	These cases are characterized by a highly skewed initial distribution of water rights.	–[b]
		Adaptation Syndromes	
Water Reallocation to Nature Increasing demand is met by reallocation to higher value uses, usually from agriculture to ecosystems or urban uses.	Edwards Aquifer Murray-Darling Rio Grande	These cases are characterized by the reallocation of water from agricultural to urban or in-stream uses. This syndrome is driven by decreasing demand for human uses and increasing demand for ecosystem uses. Strong in-stream protections are in place, supported by adjudicated and enforced surface water rights and functioning surface water infrastructure.	~DMD ECOL CNTRL REALLOC ~NOINFRA

[a]Legend: ~, Factor not present; SUPP, Exogenous shocks on water supply quantity; REALLOC, Effective reallocation of water across sectors/areas; CNTRL, Effective control over groundwater, surface water, in-stream flow; DMD, Increasing net demand for water; PMP, Widespread access to pump sets; NOINFRA, Insufficient and functioning surface water infrastructure; AQ, Shallow unproductive aquifer; ECOL, Increasing ecological consciousness.

[b]We did not attempt to trace causation for Resource Capture by Elite regions; the causes tend to be rooted in the unique history of each basin.

pump technology. This led to steep declines in groundwater levels in Yemen.

[44] The second pathway involved decreases in recharge because of plantations and paved surfaces. Pine plantations leading to a reduction in groundwater recharge were documented in the case of the Swan Coastal Plain Aquifer in Australia [*Bekesi et al.*, 2009]. This particular pathway was driven by the Swan Coastal Plain case, in which rapid growth in urban demand (and absence of agricultural pumping) were significant features. Here too, groundwater resources were not effectively controlled.

5.3.2. Ecologic Destruction

[45] This syndrome occurred via two causal pathways. The first pathway involved unrestrained expansion of

surface water infrastructure, which meant that many rivers no longer reached the sea, and resulted in the destruction of aquatic ecosystems and wetlands. For instance, the Aral Sea crisis, a classic case of unsustainable water resources management, has been attributed to massive mismanagement by Soviet era planners in promoting water-intensive cash crops in the upstream reaches of the Amu Darya and Syr Darya basins. The massive shrinkage of the inland lake severely impacted local climate, ecosystems, and human health [*Micklin*, 2007]. Similar large-scale infrastructure investment in the Yellow River occurred without much opposition during the Chinese Cultural Revolution; as a result, much of the lower reaches of the Yellow River have become permanently dry today.

[46] The second pathway involved massive growth in demand, spurring decentralized groundwater pumping and abstraction from small, local, surface water bodies with consequent ecosystem losses. This pathway was typically associated with poor controls over groundwater and widespread presence of electrified pump sets, accompanied by increasing demand. This was observed in the Lower Jordan River case, where flows into the Dead Sea dropped over time as increased groundwater pumping significantly decreased base flows into the Jordan River. The Krishna Basin is also an example of ecological destruction driven by decentralized water abstraction.

5.3.3. Drought-Driven Conflicts

[47] This syndrome occurred usually in surface water–dependent systems overlying unproductive aquifers. Two separate causal pathways were driving this syndrome. (1) There was an increase in demand for water both from cities and agriculture. Although surface water infrastructure may be adequate to meet average demand, increasing environmental consciousness and supply shocks created conflicts in periods when less water was available to be shared among competing users. (2) Users switched to groundwater during multiyear droughts. The increase in demand during critical periods produced temporary declines in groundwater levels, eroding the ability of the aquifer to act as a buffer.

5.3.4. Water Reallocation to Nature

[48] This syndrome occurred when an increasingly environmentally conscious population along with increasing demand for water in urban areas was met by decreases in consumptive water use by agriculture (by either land fallowing or a switch to less water-intensive crops). In general, this outcome was observed in developed countries where only a small fraction of the population was dependent on irrigated agriculture and where minimum flow requirements were specified in deciding licensing for surface water and groundwater rights.

5.3.5. Unmet Subsistence Needs

[49] This syndrome occurred in regions where agriculture was not yet developed, so there was very little irrigation or urban demand. A key feature of these cases was the absence of both centralized surface water infrastructure and decentralized pump sets. Water rights systems (both surface water and groundwater) were rudimentary and unenforced, with in-stream rights typically not being recognized. Few mechanisms were in place to reallocate water between sectors or across regions.

[50] The meta-analysis relies on basin-scale water resources analyses, which are not well-suited to identifying causes of lack of access to water for drinking and livelihood needs in the Unmet Subsistence Needs cases, as these latter have to do with a range of political, institutional, cultural, and socioeconomic factors. However, the analysis does reinforce the importance of considering whether regions are purely constrained by infrastructure (economic scarcity) or by infrastructure and water resource combined (physical and economic scarcity); this difference is an important consideration for infrastructure funders and practitioners in the water sector. Water projects in the developing world have notoriously high failure rates [e.g., *Abebe et al.*, 2008]; many developing world drinking water projects are narrowly focused on addressing the last-mile "services delivery" problem without considering the sufficiency of water resources, often resulting in failure within a few years [*Abebe et al.*, 2008]. Viewing Unmet Subsistence Needs in context as being one of several syndromes helps frame infrastructure deficiency as only one of several factors contributing to chronic scarcity.

5.3.6. Resource Capture by Elite

[51] This syndrome occurred in regions with historical inequalities, e.g., a colonial history or feudalistic societies where large landowners traditionally owned most of the land. We did not attempt to trace causation further for this syndrome because the underlying reasons tend to be rooted in the unique history of each as described in the case studies. For instance in the Jaguaribe Basin in Brazil, an oligarchic society associated with a military regime resulted in constructing the vast majority of public infrastructure to benefit a very small number of families. In the Olifants Basin in South Africa, some 90% of the water rights were held by 5% of the people. In this latter case, the highly unequal distribution of water rights was rooted in the colonial history of white settlers in the region.

6. Discussion

[52] This study provides insights both into the nature and causes of water crises, as well as into interdisciplinary water resources research.

6.1. Syndrome Analysis

[53] Although water crises are multifaceted, the review pointed to six underlying syndromes. Fifteen of the 22 regional cases exhibited only a single syndrome, and only a single case was dominated by more than two syndromes (Table 4). The most common syndrome was Ecological Destruction, which described crises throughout the globe: in India, China, Pakistan, Australia, Jordan, and Turkey. Only two of the water crises were characterized by Unmet Subsistence Needs, but it is not surprising that both were in sub-Saharan Africa.

[54] Our study offers several insights on coupled human–water systems. First, water is accessed by multiple stakeholder groups who have different quality and timing needs. The perspective of a single stakeholder regarding water vulnerability or unsustainability of water supply is inadequate. Water is often made available to one stakeholder group at the expense of another, making it necessary to understand tradeoffs across stakeholder groups. The syndromes explicitly

Table 4. Syndromes Characterizing Regional Crises

Region	Groundwater Depletion	Ecological Destruction	Drought-Driven Conflict	Unmet Subsistence Needs	Resource Capture by Elite	Water Reallocation to Nature
Aral Sea		x				
Bhavani, India		x				
Edwards Aquifer, USA						x
Gediz, Turkey		x	x			
Hai River, China	x	x				
Indus Basin, Pakistan		x				
Jaguarube, Brazil					x	
Krishna, India		x	x			
Lerma-Chapala, Mexico	x	x	x			
Lower Jordan, Jordan		x				
Murray-Darling, Australia			x			x
Olifants, South Africa					x	
Punjab, India	x					
Rio Grande, New Mexico, USA						x
Ruaha, Tanzania		x		x		
Sadah, Yemen	x				x	
Swan Coastal Plain, Australia	x					
Ta'iz, Yemen	x					
Volta, Ghana				x		
Yaqui, Mexico			x			
Yellow River, China		x				
Zayandeh, Iran		x				

address this by distinguishing between trends in human water use and water left in natural ecosystems and between current and future generations' wellbeing. In many industrialized countries, populations are increasingly becoming ecologically conscious. Increasing demand for water by nature is typically met by decreasing consumptive water use in agriculture, as was observed in the Water Reallocation to Nature syndrome cases. This may be achieved by switching to less water-intensive crops or land fallowing. The reallocation may have occurred by retirement of water rights via government buy-outs, agricultural–urban water transfers, or water conservation programs.

[55] Second, the syndromes exhibit a range of time frames and concerns: Both long-term declines and short-term crises are related to supply variability and chronic scarcity because water resources had not been harnessed to satisfy basic human and livelihood needs. By distinguishing between short-term outcomes and long-term outcomes, the syndromes could account for the dynamics of sometimes nonrenewable (groundwater) and renewable (surface water) components of water resources. In addition to biophysical differences (e.g., surface water tends to be stochastic and renewable, while groundwater is often nonrenewable) [*Gleick and Palaniappan*, 2010], surface water and groundwater have fundamentally different characteristics in terms of how they are governed and accessed. Technologies that access either state differ in monitoring costs and enforcement costs. For example, surface water is typically stored, controlled, and distributed in a centralized manner, while groundwater abstraction and control is often decentralized. However, overutilizing surface water and groundwater resources may have very different outcomes. Overutilization of surface water resources may occur at the expense of ecosystem and downstream users (Ecologic Destruction) or may manifest only during multiyear droughts (Drought Conflict). In contrast, overdraft of a deep aquifer makes it possible to continually increase human abstraction in the short-term, thus shifting the burden to future generations (Groundwater Depletion). Finally, the syndromes recognize that water crises could arise both from too little water being abstracted by humans (Unmet Subsistence Needs) as well as too much (Groundwater Depletion, Ecologic Destruction).

6.2. Possible Additional Syndromes

[56] Our list of syndromes is based on a limited number of comprehensive studies that met a rather high bar needed to qualify as candidates for inclusion in our meta-analysis. The list of syndromes is undoubtedly incomplete. Based on our familiarity with other regional water crises and literature describing more focused and disciplinary studies, we suggest the existence of at least two additional syndromes: Open Basins and Contaminated Basins. We define Open Basins as regions that meet new needs by successfully reallocating water across regions or across sectors within the same basin with relatively little conflict. Reallocation may occur by investing in new infrastructure storage projects, creating water markets, or pursuing such soft options as pricing, water-efficient fixtures, or lifestyle changes. We define Contaminated Basins as regions suffering from widespread contamination of surface water and groundwater from both natural and anthropogenic origins, to the extent that the utility of a regional water resource has been reduced or eliminated for some or all purposes. For instance, arsenic contamination is a major problem in many parts of the world: Cambodia, Vietnam, Bangladesh, and Nepal. In many other regions of the world, human use has severely degraded or destroyed shallow aquifer systems by agricultural chemical, septic waste, and industrial fuels, solvents, and metals. The development and management of water resources in these regions is greatly influenced by the need

to mitigate human health risks created by the presence of these contaminants.

6.3. Classification Framework of Causes

[57] In traditional hydrology, human-induced activities are viewed as external drivers in water cycle dynamics [*Milly et al.*, 2008]. Although some studies have included human activity into hydrologic studies, most have been predictive models seeking to establish optimal cropping patterns or optimal institutions rather than retrospective efforts trying to better understand the causal drivers of change. Very few hydrologic studies link institutions, particularly informal institutions such as social norms and lack of enforcement or monitoring, to water resource availability and human wellbeing. These linkages are increasingly being recognized and formalized in the emerging fields of sociohydrology [*Sivapalan et al.*, 2012] and socialecological systems [*Ostrom*, 2009], which aim to characterize and investigate feedbacks between human and natural systems.

[58] The classification framework developed in our meta-analysis suggests that in designing such interdisciplinary studies, different categories of human factors should be considered. Causal factors could be classified into four categories: (1) the nature of the demand, i.e., the relative importance of urban, commercial, and industrial demand compared with irrigated agriculture vs. the relative demand for ecological water relative to anthropogenic needs; (2) the institutions that govern who is allowed to abstract water at what price, and whether these allowances are credibly enforced; (3) the technology or infrastructure available to users to access the resource; and (4) the nature of the physical resource system, e.g., rainfall and aquifer characteristics.

6.4. Implications for Water Policy

[59] The grouping of water crises into syndromes and categorizing the syndromes based on impacts on human wellbeing can promote learning from "water experiences and experiments in distant places and times" [*Wescoat*, 2009, p. 61]. A major challenge in the water sector has been how to effectively implement initiatives founded on a set of general principles (participation, integration, coordination, gender equity) in a heterogeneous world made up of different cultures, social norms, physical attributes, availability of renewable and nonrenewable resources, investment funds, management capacities, and institutional arrangements. The absence of rigorous comparative water research frameworks has affected the success of major global water initiatives such as IWRM, the current dominant paradigm for funding water sectors. To address the diversity of conditions across and within countries, the Global Water Partnership (GWP), the global organization tasked with funding IWRM internationally, offers a "toolbox" containing 54 different "tools" including policies, institutional frameworks, participatory and regulatory capacity, ecosystem assessment, water use efficiency, conflict resolution, and many more. In the absence of a unifying framework, it has been difficult to diagnose what the objective of an IWRM intervention should be, which tools might be suitable for a specific region, and whether the implementation has been successful [*Biswas*, 2008; *Franks and Cleaver*, 2007].

[60] Given the challenge of diagnosing water crises and proposing solutions across a diversity of conditions, this study makes three contributions to freshwater resource policy analysis. First, the classification of regions into syndromes identifies both differences and similarities among regions. Syndrome analysis offers a means to better *inform policy interventions* in the water sector. Given the diverse nature of water crises, attempting one-size-fits-all policy prescriptions is futile. However, in the absence of a unified framework, crafting solutions tailored to specific regions has remained a challenge. By grouping regions based on the syndromes and focusing on likely causal pathways of water crises, water managers and policy makers can begin to guide water resource development on the basis of relevant experiences across regions facing common problems. They can better articulate the broad objectives, causal pathways, and possible solutions that might be applicable in a given region. For instance, regions facing groundwater depletion where ineffective control over groundwater is driven by poor enforcement of groundwater rules could be amenable to new monitoring technology or to participatory groundwater management programs. Regions where ineffective groundwater control is driven by overallocation of groundwater permits might be amenable to "shared learning" workshops where stakeholders might be induced to develop a common understanding of future scenarios by using modern simulation and visualization techniques to agree to lower allocation limits. Regions where groundwater is controlled but underpriced may be candidates for innovative pricing policy experiments.

[61] Second, there is a potential to *improve prediction* of the direction a basin might take, based on how basins with similar characteristics have developed. Improved predictability of an uncertain future depends on fully characterizing the behavior space of the coupled human–environment system [*Kumar*, 2011]. Despite the fact that behavior of coupled human–water systems have been shown to be controlled by broader societal choices on culture, economy, and infrastructure [*IWMI*, 2000] and institutions [*Ostrom*, 2009], these latter are rarely factored into regional water resources models. By exogenously setting such factors as demand, cropping patterns, land use, property rights, and prices, many models constrain their results artificially. Major policy analysis briefs [*The 2030 Water Resources Group*, 2010] continue to frame the problem in terms of meeting the demand–supply gap, that is, the idea that demand for water is driven by other underlying factors. Instead, the meta-analysis suggests that increased attention to the underlying sociotechnical drivers of demand and institutional structure will allow for more realistic scenario development.

[62] Third, this research offers a way *to link to the sustainability discourse* and literature. Water resources problems are particularly hard to characterize. A dual objective of meeting basic human needs but still leaving enough for the environment and future generations must be achieved under uncertainty for both surface water and groundwater (blue water) and soil water (green water) hydrologic components. As a result, efforts to link water to the literature on food security, the ecosystem, and human health have proved challenging [*Kajikawa et al.*, 2007]. By characterizing the water challenge

in terms of human wellbeing rather than water resources, we suggest a stronger link between water resources studies and well-established discussions on sustainability and resilience.

7. Summary and Conclusions

[63] Despite decades of research, the nature of the global freshwater crisis remains poorly defined and characterized, making it difficult both to prioritize and to design useful solutions. This has occurred for two reasons. Research in water has been fragmented both by discipline and by region. Without a common framework to organize relevant variables identified from theories and empirical research, diverse studies merely give rise to fragmented knowledge. We analyzed 22 interdisciplinary, water resources, subnational, regional studies from around the world. The case studies indicate that although there is no universal metric that definitely captures every type of water crises, different regions of the world show a limited suite of distinct resource utilization patterns by urban, agricultural, and ecosystem uses. This suite comprises six syndromes:

[64] Groundwater Depletion, Ecological Destruction, Drought-Driven Conflicts, Unmet Subsistence Needs, Resource Capture by Elite, and Water Reallocation to Nature. Each of these categories was associated with a set of causal factors that could be broadly classified into demand and supply changes, governance systems, and infrastructure. Our study suggests that each syndrome is generated by a limited set of causal pathways.

[65] The regional studies highlight the importance of both proximate and underlying causes of patterns of water resource utilization. Societies make choices on how to harness water resources, how much to leave to nature, and how to distribute water resources among sectors and agents in ways that reflect inherent resource limitations, cultural values, historical context, and political realities.

[66] The study suggests that to be able to predict the occurrence of water crises and to find solutions for them, water resources researchers should consider directing more attention to the underlying drivers of demand and to the institutions that govern the abstraction of water.

Appendix A: Criteria for Case Study Selection

[67] Because our initial search for the terms "water sustainability," "water crisis," "water scarcity," "water shortage," "water stress" in four commonly used search engines covering a range of disciplines did not prove useful, we broadened the set by proactively searching within the grey literature. We searched within websites of known international programs in water resources for peer-reviewed articles and reports. The following programs were considered: International Water Management Institute's Benchmark Basins, the GLOWA Project sponsored by the German government, the Global Water System Project, and the UNESCO International Hydrologic Program (IHP) on Integrated Water Resources Management. Each case was completed by looking for additional papers by the same research team by searching both by author names and basin names in the four databases as well as Google Scholar.

[68] To be included in our meta-analysis, the articles needed to meet the following criteria:

[69] 1. Empirical, data-driven. Calibrated models, statistical studies, or qualitative discussions are all allowable if supported with data.

[70] 2. Using past data or documents in attempts to find links between outcomes and causal factors. Thus, purely normative scenario analyses that compared policies or management options into the future were not included.

[71] 3. Associated with a specific time period. Because humans adapt to crises by modifying policies and laws or building new infrastructure, a water resource system could change quite dramatically with one new legal ruling or interbasin transfer project. As a result, it is necessary to specify a particular period for the case study. Thus, "The Syr Darya basin from 1990 to 2000" would be a valid case study but "The Aral Sea Disaster" would not.

[72] 4. Largely confined to a single country. Several excellent case studies on the Nile, Jordan, Danube, and the Mekong were excluded from our analysis. The problems facing international river basins were fundamentally different from domestic river basins. These cases were dominated by geopolitical factors and the relative negotiating positions of the different parties [*Wolf*, 2007]. Although our final set of cases did include portions of some international basins (Indus, Volta, Olifants, Rio Grande), the subbasins studied fell largely within a single nation, such that cross-national issues were secondary during the period of the case study.

Appendix B: Regional Studies–Location, Time Period, and Size

[73] Table B1 presents case study statistics.

Appendix C: Criteria Used in Coding Factors

[74] Table C1 lists the codes used, what each describes, and whether or not their usage is significant.

Table B1. Case Study Statistics

Region	Case Study	Period of Study	Size, km^2
Asia	Aral Sea, Kazhakistan	1990–2000	150,100
Asia	Bhavani Basin, India	2000–2005	6,500
North America	Edwards Aquifer, Texas	2000–2005	11,560
Asia	Gediz Basin, Turkey	1995–2005	18,000
Asia	Hai River Basin, China	2000–2008	320,000
Asia	Indus Basin, Pakistan	1980–1990	944,564
South America	Jaguarube, Brazil	1988–1997	75,961
Asia	Krishna Basin, India	2000–2005	253,514
North America	Lerma-Chapala Basin, Mexico	2000–2005	54,300
MENA[a]	Lower Jordan Basin, Jordan	1995–2005	18,000
Australia	Murray-Darling Basin	1995–2005	1,060,000
Africa	Olifants River, South Africa	1995–2005	54,308
Asia	Punjab, India	2000–2006	50,362
North America	Rio Grande, New Mexico	2000–2008	150,100
Africa	Ruaha, Tanzania	2000–2008	83,979
MENA	Sadah Yemen	1996–1999	213
Australia	Swan Coastal Plain, Australia	1995–2005	100,000
MENA	Ta'iz Yemen	1995–2000	930
Africa	Volta, Ghana/Burkina faso	2000–2009	398,000
North America	Yaqui Valley, Mexico	2000–2005	2,530
Asia	Yellow River, China	1998–2005	795,125
MENA	Zayandeh-Rud, Iran	2000–2008	41,500

[a]Middle East/North Africa.

Table C1. Coding Criteria

Proximate Factor (Var_Name)[a] and Underlying Factors	Code = 1 (Not mentioned OR factor cited as being insignificant → Code = 0)
Poor water resource endowment (AQ)	
Low renewable freshwater availability	Low renewable freshwater per capita
Little or no aquifer storage	The aquifer underlying the basin is highly unproductive with limited storage capacity.
Change in resource availability (SUPP)	
Multiyear drought	Continuous years of below-average rainfall are mentioned in the context of a water crisis.
No effective protections against upstream diversions	The basin is unable to control upstream diversions (usually out of jurisdiction). Data are provided to show that transboundary flows have declined significantly over time.
Decrease in recharge due to plantations	Hydrologic studies show that plantations reduced recharge significantly or to zero.
Increase in demand (DMD)	
Increase in population living in cities	Urban population doubling over a recent period of 20 years; significant immigration from the countryside or other countries
Increase in industrial/commercial demand	Specific water-intensive industries located into the region
Increase in water-intensive lifestyle	Significant increases in indoor plumbing or suburban pools/lawns mentioned
Shifts to higher yielding varieties/water-intensive crops	Increase in the area or expansion of high-yielding varieties of specific crops that need more water than historically grown crops—rice, wheat, sugarcane, cotton, maize—did
Agricultural subsidies. Vote bank politics. Clientalist politics. Food self-sufficiency mandates	Agricultural expansion shown to be driven by crop support prices, export policies, or crop input subsidies. The underlying drivers of these may be vote bank politics, farm lobbies, or government policy on food self-sufficiency.
Expansion of agriculture due to high crop prices	Policy changes resulting in absolute levels of product prices; high demand for imports from nearby wealthy countries (Mexico, Jordan)
Increase in ecological water demand (ECOL)	
Conservation movements	Specific campaigns by local naturalists towards protecting local wetlands or aquatic wetlands (e.g., protest by Turkish Society of Birds, lawsuit by Sierra Club)
External interest in protecting charismatic or endemic species/ biodiversity hotspots	Funding by World Wildlife Fund and other international nongovernmental organizations to protect an area, specifically referencing interventions to restore environmental flows to National Parks, protected areas, or wetlands.
Ineffective control over water (CNTRL)	
Overallocation of groundwater. Rule of capture (no extraction limits). Too many permits granted	Allocated licenses known to be significantly above scientifically stated “sustainable yield,” either for political reasons or by activation of “sleeper licenses” when water markets are introduced
Overallocation of groundwater. Price set too low	The only mechanism in place to control groundwater pumping is via electricity or water price—but the volumetric price is either too low or is based on a flat-rate tariff.
Overallocation of groundwater. Double-counting of groundwater and surface water rights	Groundwater licenses are determined independently of surface water licenses, ignoring the fact that groundwater and surface water are linked; in effect, the quantity of available groundwater is double-counted.
Poor enforcement of groundwater abstraction Inadequate administrative capacity. Corruption	Specific mention of instances of corruption and bribery to payoff local enforcers Mechanisms to measure and independently monitor groundwater extraction either do not exist at all or have been tampered with.
Minimum flow laws or caps on diversions	In-stream flow laws are assumed to be absent UNLESS specific reference to basin-wide caps on diversion are cited as being of importance in limiting permits.
Laws that protect specific species or areas; infusion of federal or state funds to protect specific species or areas	There are strong protections for species, such as the U.S. Endangered Species Act, which shape administrative actions by the water agencies.
Maintain releases for downstream hydropower	References to downstream hydropower plants—in terms of importance in power generation and priority accorded
Interstate or international compacts	Legally binding requirements to maintain transboundary flows to either another state or another country
Presence of reallocation mechanisms (REALLOC)	
Water markets	Functioning water markets are available to reallocate water among users in the long term or during multiyear drought.
Infusion of federal funding to buy out/retire agricultural land	Allocation of funds from the government to purchase (and retire) water rights or farmland
Reliable interbasin transfers	Completion and commissioning of projects or desalination plants that infuse significant amounts of water into the basin so as to satisfy demand or even “reopen” the basin. If interbasin projects are built, flows are reliable.
Effective water-efficiency programs	Programs in place to fund farmers/urban water consumers to purchase and install water conservation devices
Insufficient and inadequate infrastructure (NOINFRA)	
Insufficient reservoir storage	Reservoir storage is cited as being “insufficient” or poorly managed. Reservoirs are cited as going dry frequently.
Inadequate distribution (leaky or incomplete canals and pipes). Inadequate administrative capacity. Inability to recover costs	Head-end/tail-end problems. Canal system is mentioned as being poorly constructed (e.g., never built to planned capacity) and poorly managed; high leakage is cited as a problem.
Extensive Groundwater Infrastructure (PMP)	
Widespread rural electrification/diesel pumps Credit programs for farmer tube wells	Groundwater extraction mechanisms (electric or diesel bore wells) are widespread, and groundwater accounts for about half of irrigated agriculture. Conversely, the absence of electric or diesel wells may indicate a lack or unaffordability of rural electrification.

[a]The high-level or proximate factors are shown in bold with a variable name in parentheses. The underlying factors were the ones that were actually coded in the case study; they were aggregated to the proximate factor using an OR operator; i.e., if *any one* of the underlying factors is present, then the proximate factor is considered present.

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