Toward a formal definition of water scarcity in natural-human systems

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[1] Water scarcity may appear to be a simple concept, but it can be difficult to apply to complex natural-human systems. While aggregate scarcity indices are straightforward to compute, they do not adequately represent the spatial and temporal variations in water scarcity that arise from complex systems interactions. The uncertain effects of future climate change on water scarcity add to the need for clarity on the concept of water scarcity. Starting with a simple but robust definition—the marginal value of a unit of water we—highlight key aspects of water scarcity and illustrate its many biophysical and socioeconomic determinants. We make four central observations. First, water scarcity varies greatly across location, time, and a multitude of uses that are valued either directly or indirectly by society. Second, water scarcity is fundamentally a normative, anthropocentric concept and, thus, can and should be distinguished from the related, purely descriptive notion of water deficit. While such an anthropocentric perspective may seem limiting, it has the potential to encompass the vast range of interests that society has in water. Third, our ability to understand and anticipate changes in water scarcity requires distinguishing between the factors that affect the value or benefits of water from those affecting the costs of transforming water in space, time and form. Finally, this robust and rigorous definition of water scarcity will facilitate better communication and understanding for both policymakers and scientists.

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1. Introduction

[2] Water scarcity may appear to be a simple concept, but it can be difficult to apply to complex natural-human systems. Aggregate measures such as "physical water scarcity" and "economic water scarcity" have been used to evaluate future constraints on water availability at national and regional scales [*Rijsberman*, 2006]. Aggregate scarcity indices, while often easy to compute, have limited ability to represent the spatial and temporal variations in water scarcity that arise from complex system interactions [see, for example, *Franczyk and Chang*, 2009]. The uncertain effects of future climate change on water scarcity and natural resource sustainability have brought into focus the need for clarity on the concept of water scarcity.

[3] The purpose of this commentary is to highlight key aspects of water scarcity that alternative measures such as aggregate indices do not explicitly recognize. We propose a simple but robust definition of water scarcity and illustrate it with examples of the many biophysical and socioeconomic factors that interact within a broader system to determine water scarcity. Based on our conceptual framework and definition of water scarcity, we highlight four central observations. First, to a greater extent than with many other goods, water scarcity varies greatly across location, time, and a multitude of uses that are valued either directly or indirectly by society. This means that precise measures of

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water scarcity will often be elusive in practice, though this is a reflection of the complex role of water in natural-human systems, rather than a feature of our definition of scarcity per se. Second, scarcity is fundamentally a normative, anthropocentric concept and thus, can and should be distinguished from the related, purely descriptive notion of water deficit. While such an anthropocentric perspective may seem limiting, it has the potential to encompass the vast range of interests that society has in water. Third, our ability to understand and anticipate changes in water scarcity often requires distinguishing between the factors that affect the value or benefits of water from the costs of transforming water in space, time, and form. Fourth, a more robust and widely applicable definition of water scarcity may facilitate clearer communication and understanding across disciplines regarding water research and policy.

2. Water Scarcity in a Natural-Human System

[4] Our definition of water scarcity can be stated generally and succinctly as the marginal value of a unit of water. The term "marginal" refers to a small change—specifically, a one-unit change—in the quantity of a resource such as water. The term "value" is based on human preferences and judgments, which we discuss more later. We focus on the quantity of water in this paper, although with modifications our definition of scarcity applies to other properties of water such as temperature and purity. By emphasizing the value of water at the margin (that is, for a given incremental change in the availability of water), we allow individual units of water to have different values. For example, the first unit of water applied to a parched field will have a higher value than the one-millionth unit. As such, rather than a single number, scarcity is better thought of as the range of a single-valued function defined across a domain of water units.

[5] Our conceptual framework is built upon notions of value dating to *Smith* 1776 as well as contributions by *Dupuit* 1844 and *Marshall* 1879. While these early authors emphasized values arising from market transactions, it is now well established that the things society values frequently exist without markets [*Maler*, 1971, 1974]. Indeed, many early examples of legislative efforts to account for nonmarket values involved water, such as the 1920 River and Harbor Act and the Flood Control Act of 1936 [*Hanemann*, 2006]. Our intention here is to elaborate and expand upon this foundation by explicitly encompassing and detailing the interconnections and complex relationships involving components of both natural and human systems, and how they can enlighten our understanding of water scarcity.

[6] The application of marginal analysis to water resources and water policy has a long tradition in economics [see *Howe*, 1979; *Young and Haveman*, 1985; *Griffin*, 1998]. This approach has been recently extended to integrated hydroeconomic models [e.g., *Cai*, 2008; *Harou et al.*, 2009; *Rosegrant et al.*, 2000]. Our aim here is to build on those foundations by identifying the ways in which a complex natural-human system shapes the meaning and interpretation of water scarcity for research and for policy. Although each individual component of this framework is well understood within the relevant scientific discipline, and many of the interactions among components have been studied in detail, their integration and particular implications for water scarcity deserve more detailed examination.

[7] The four major components of our conceptual model have intentionally been simplified as (1) climate, (2) the biophysical system, (3) human values and actions, and (4) humanly devised assets of technology, infrastructure, and institutions. By climate we mean the characteristic weather conditions including temperature, precipitation, solar radiation, humidity, and winds. The biophysical environment includes both the biotic and abiotic components of the environmental system (natural and managed vegetation, aquatic and terrestrial wildlife, geology, soil, people, etc.). Human values and actions refer to the behavior and choices made by individuals and society collectively. Humanly devised assets of technology, infrastructure, and institutions represent investments in physical and human capital aimed often at improving our ability to satisfy human preferences. Rather than attempting to represent in a diagram some of the (nearly infinite) specific connections and feedback linkages that exist between the major elements of the model, we instead will discuss in section 4 an illustrative set of these linkages, including some with surprising and even counterintuitive implications for water scarcity.

[8] Generally, it is well understood that water scarcity arises at a given location and point in time when there is a limited amount of water, insufficient to fully satisfy all competing uses. For example, scarcity may arise in the biophysical system if human consumptive uses divert instream flows that adversely affect fish populations and aquatic habitats. In this case, scarcity could be measured as the value of allocating an additional unit of water to fish (or equivalently, the loss in value from decreasing the allocation to fish by one unit). This scarcity measure depends on human values, but it also depends equally on climate and hydrology, biology and ecology, and on existing technologies, institutions, and infrastructure. Together, these interacting natural and human components of the system determine the timing, location, and magnitude of water scarcity.

[9] Water scarcity can arise from a change in a system's hydrology, or it can also be caused by human actions. People's choices, made in response to the institutions that influence their behavior, can create water scarcity, often as an unintended side effect of their actions. Similarly, public infrastructure such as water storage and conveyance systems affects water scarcity by altering the timing and location of water availability, an important topic we return later.

[10] An incremental change in the allocation of water to one use within the system can cause an increase or decrease in water scarcity for one or more other uses. If an increase in water allocation to a given use would be valuable to society, then the scarcity of water for that use is positive. Although we have emphasized, thus far, marginal changes in water quantity, one can evaluate large (nonmarginal) changes in water allocation as well. In this case, it is important to keep in mind that the marginal value of water (its scarcity) is unlikely to remain constant for large changes in quantity.

[11] This general framework for understanding water scarcity can capture the complex interactions and feedbacks in the natural-human system. This includes the recognition that water is both a private good for individual

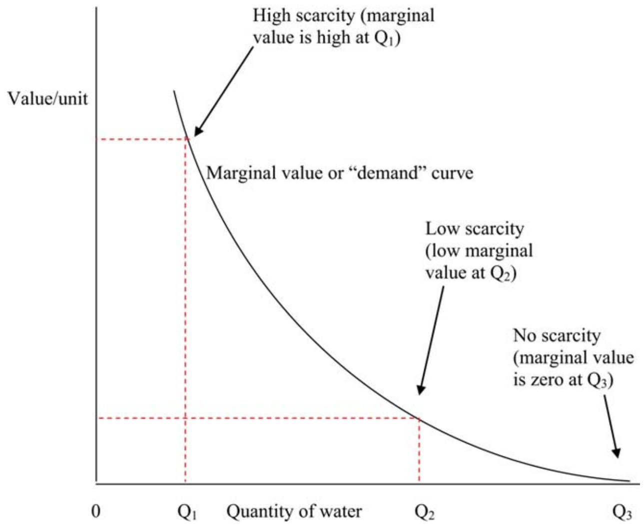

Figure 1. Scarcity as the marginal value of water at the level provided.

consumptive uses and a public good providing a wide range of vital ecosystem services and amenities. The framework also represents the ways in which some water uses have negative and positive external effects on others, such as when one person's decision to pump groundwater increases pumping costs for others and may dry up nearby streams, or when dams or forest harvest practices alter the timing and magnitude of streamflow. Finally, this framework is flexible enough to handle special cases, such as those involving absolute scarcity, or to describe water scarcity in terms of stocks (e.g., the volume of water in a lake) and flows (e.g., rate of streamflow), form (quality), and state (solid versus liquid).

[12] Scarcity can be illustrated graphically for relatively simple cases (see Appendix A for a general mathematical model). For a given allocation of water to a particular use, the marginal value (or scarcity) of water may be high, low, or zero (Figure 1). Indeed, water can have a negative marginal value when there is an overabundance—the opposite of scarcity—as in the examples of crop damage or flooding. The quantity of water available for that use is the supply of water (an amount Q_1 or Q_2 in Figure 1), whereas the marginal value function represents the demand for water. Were water allocated through a competitive market, supply would reflect the marginal cost of delivering a given quantity of water. Figure 2 is a simplified representation of how water scarcity might be affected either by a change in the amount of available water (the quantity of water available declines from Q_2 to Q_1, perhaps due to precipitation decline) or by a change in the demand (a shift in the curve from demand A to demand B). A shift in demand may be due to changes in population, income, or land use, due to changes in human valuation of ecosystem services, or due to the introduction of a new technology. A shift in the quantity of water can occur, for example, from a change in climate, an upstream dam, or irrigation diversion, or from the use of other resources, such as when the logging of a rainforest decreases long-term water availability because the water-energy cycle has been fundamentally altered.

[13] While water scarcity depends on the value placed on water at a given level of use, it is important to see that scarcity can also be influenced by the costs of providing or acquiring water. In Figure 2, if demand shifts from A to B, the effect on scarcity will be a dramatic rise from MV_1 to MV_2 if the quantity is fixed at Q_1. By contrast, this shift in demand will have no effect on water scarcity if the quantity of water can expand from Q_1 to Q_2. This might reflect the case where the water supplier (e.g., a municipal water company) can provide additional units at a constant cost and thus, simply increases the quantity of water without raising the price of water. Indeed, water can be extremely scarce for a community in an arid region if the costs of accessing water are high, while by contrast the residents of a fast-growing city experience no increase in water scarcity because the marginal cost of acquiring additional supplies is constant.

3. Key Aspects of Water Scarcity

[14] We have drawn attention to a number of basic observations, including that water scarcity can vary greatly by time and place. Scarcity is, thus, not an absolute measure but rather a relative metric that changes with the spatiotemporal setting. This implies that water can become relatively more scarce in a rainforest than in a desert because of the ways that each natural-human system has evolved to rely on different amounts of water. Scarcity can exist, or rise sharply, when water availability declines relative to recent or historical use regardless of whether a region is water rich or water poor.

[15] In the remainder of this section, we address four additional aspects of water scarcity: anthropocentric valuation, substitutions, the role of infrastructure and technology, and the role of institutions.

3.1. Anthropocentric Valuation

[16] Scarcity, as the term is commonly used, involves a human value judgment. Thus, water "scarcity" is fundamentally different from the related notion of water "deficit" or "shortage." Water scarcity reflects human preferences,

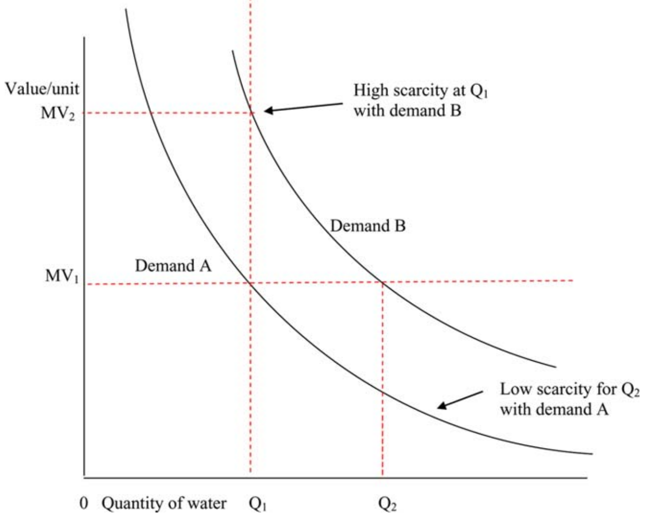

Figure 2. Changes in scarcity with increased demand and reduced supply.

and it occurs when there is insufficient water available at reasonable cost to fulfill human wants and needs.

[17] These preferences may relate to the satisfaction of essential human needs, such as the need for drinking water. However, society also values water indirectly, as when people wish to ensure sufficient water to sustain a wetland ecosystem or streamflows sufficient to protect rare aquatic species from extinction.

[18] In contrast, a water deficit may involve an insufficient quantity of water for a specific biophysical process, but whether such a deficit also represents water scarcity will depend on the values placed by society on that particular process. As such, water deficit can exist without scarcity, but with few exceptions, water scarcity involves a water deficit.

[19] While such an anthropocentric perspective may seem restrictive, it can encompass the vast range of interests that society may have in water. Human interests include the demand for water to support people's livelihoods, provide for amenities, and serve moral interests. However, this anthropocentric view does not imply that water is scarce only when it impinges directly on human consumptive use. Rather, and more broadly, water is scarce in relation to the values people have for it, values that may arise due to concerns about biodiversity loss, ecosystem functions, the desire for free-flowing rivers for recreation and habitat, or the aesthetics of a waterfall or glacier. These human values must also reflect humans' ethical commitments, obligations toward stewardship, notions of equity and fairness, and concerns for future generations.

[20] This is the main view one finds in the literature on the subject, where philosophers see ethical reasoning of all types as an anthropocentric enterprise, even while recognizing differing anthropocentric starting points in the regard they accord the human species [e.g., *O'Neill*, 1997]. Indeed, rather than being intrinsic, moral values for nature are commonly understood to be derivative, implying that the preservation of nature ought to be motivated by instrumental values [*Oksanen*, 1997]. It is worth noting, however, that reliance on human values has a potential limitation because they can only reflect how much we understand, both individually and collectively, about complex natural systems.

[21] Intrinsic value is clearly an important notion; it guides humans, for example, to make judgments about right and wrong behavior. Yet, the idea of intrinsic value itself still comes from people. How would we know what those nonhuman values are? How would such values inform the choices and trade-offs we make which, in many cases, will necessarily benefit one species at the expense of another? How would we, for example, weigh the consequences of a water deficit that causes the death of a person and one that causes the death of a cockroach?

[22] Water scarcity, however, must encompass people's spiritual beliefs and convictions related to the uses of water. For example, in India, the value and scarcity of beef are influenced by Hindu beliefs about sacred cows; in the Pacific Northwest, the value of instream water reflects in part spiritual beliefs held by some Native American tribe's about salmon. Both examples are anthropocentric, in that the values stem from human cultural beliefs. Water scarcity does not apply only to water as a commodity or factor of production. It can accommodate a wide range of notions about the role, uses, and value of water, including "plural normative views" [see *Hamlin*, 2000; *Feitelson*, 2012]. This means that water's value can reflect private as well as public uses, wants as well as needs, practical as well as spiritual purposes, and direct as well as indirect uses. Of course, because individuals' views and values frequently differ, social valuation involves aggregating individual preferences just as society's decisions involve reconciling disagreements through voting, courts, and other processes.

3.2. Substitution

[23] The relationship between scarcity and the availability of substitutes is fundamental to our conceptualization of scarcity. Substitution is a means by which the natural-human system adapts to changes in the spatial and temporal patterns of water's states, stocks, or flows. Comparing two situations that are otherwise similar, the scarcity of resource R will be relatively lower in one situation if there are good substitutes available at reasonable cost (e.g., bricks can substitute for wood to provide shelter, but bricks cannot substitute for water to quench thirst). For human consumptive uses of water, groundwater (if available at reasonable cost) may substitute for surface water, and bottled water may substitute for tap water. For nonconsumptive uses, streamflow in river X may or may not be a close substitute for streamflow in river Z to provide fish habitat; wetland V may or may not be a good substitute for wetland W for bird habitat.

[24] In our framework, substitutions can include the way that humans switch to other resources, locations, or time periods. For example, human migration is a way to substitute the resources available in one area for those in another area, when the cost of moving the resource instead is prohibitive. Nonhuman species also make these kinds of substitutions, such as with mammal and bird migrations or fish that find ways to substitute cool water from a spring for water that has become too warm in a lake.

[25] Where substitution possibilities are limited or too costly, we can expect thresholds, points at which scarcity rises sharply when reductions in water availability have significant consequences such as species mortality or crop failures. In such cases, the marginal value curve, like the one depicted in Figure 1, would become vertical as the quantity declines. The measure of water scarcity in these cases, however, still depends on human values: the loss associated with species mortality will depend on how humans value the species; a crop failure may lead to a loss of human life or a modest inconvenience depending on the circumstances of the affected communities. A limiting case arises when no substitution is possible or is prohibitively expensive. A person dying of thirst in the desert may have no possible substitutes for water. In this case, the marginal value of water to this individual is infinite, and water is said to exhibit absolute scarcity [*Baumgartner et al.*, 2006]. The fact that water is necessary for human survival does not, however, imply that in every spatiotemporal setting it is scarce in an absolute sense, or even that it is scarce at all.

3.3. Technology and Infrastructure

[26] For centuries, the ability of humans to transport, store, and purify water has served to dramatically reduce

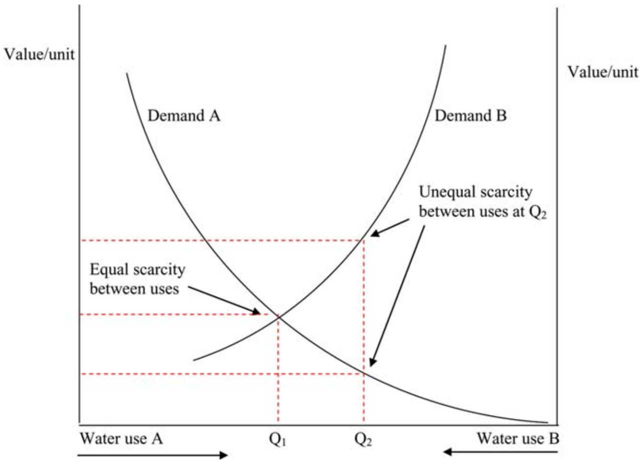

Figure 3. Scarcity of water allocated between two uses.

water scarcity. In ancient times, aqueducts brought water to cities and altered human settlement patterns. Reservoirs, irrigation canals, and hydropower dams are further examples of human inventions that have dramatically altered the location and timing of water availability. In the United States, federal reservoir projects have dominated public policy decisions related to water provision due to their size and influence [*Griffin*, 2012]. Reservoirs can reduce excess quantities of water at times when water scarcity is negative (e.g., during a flood event) and increase water quantity at times when water is scarce (e.g., during late summer). Reservoirs also have inadvertently made water scarcer at particular times and in particular locations, often adversely affecting natural systems in ways that were unrecognized or underappreciated at the time of construction [*Doyle*, 2012]. In addition, engineered changes in water systems such as large-scale irrigation projects often lead to associated investments and changes in human settlements that create direct and indirect reliance on these systems. Cities like Las Vegas, Nevada, exist in locations that would not otherwise support large populations [*Gober*, 2010]. Indeed, in some cases groundwater-dependent households and aquatic species have established themselves where water is available, thanks only to seepage from relatively inefficient irrigation technologies.

3.4. Institutions

[27] "Institutions" refers to the humanly devised mechanisms that influence human choices and how resources are allocated; examples include property rights, national sovereignty, markets, regulations and policies, as well as social-cultural norms. Water scarcity is profoundly influenced by the institutions that determine how water and other resources (e.g., land) are allocated among uses. The system of property rights, including the absence of property rights, as well as regulations affecting land and water use influence how water is allocated and, thus, where scarcities emerge in the system. A widely studied example is the system of water rights in the western United States based on the prior appropriation doctrine [e.g., *Tarlock*, 2002].

[28] Economists describe a particular resource allocation as "efficient" when the marginal value of a resource (net of acquisition or transaction costs) is equalized across competing uses [e.g., *Griffin*, 2006; *Jaeger*, 2005]. In many circumstances, this will imply that the total value of water use is maximized. Figure 3 illustrates how water can be allocated between two competing uses. At Q_1, the marginal value of water to uses A and B is equal, implying the same degree of scarcity for each use. At Q_2, on the other hand, marginal values are not equated, and water scarcity is greater for use B than for use A. In this case, the total value of the available water can be increased by reallocating it from the less to the more scarce use. Of course, in many settings the costs of reallocating water from A to B through transport or storage may eliminate the potential gains from trade.

[29] Water markets are a mechanism that can further this kind of reallocation, although markets typically play a small role in allocating water. Economists have long noted that water largely fails to meet the requirements for a smoothly functioning market system [*Young and Haveman*, 1985]. These characteristics include its bulkiness which makes it costly to transport or store in large quantities; its mobility, or tendency to flow, evaporation, seep, and transpire; variability and uncertainty in quantities; the sequential and interdependent use between upstream and downstream users; and its relationship to public goods such as species habitat, recreation, municipal demand, flood control, and power generation. As a result, alternative kinds of institutions have long been utilized to allocate water. In practice, however, institutional solutions are also costly and imperfect, especially when the natural system is complex.

[30] Institutions can both mitigate or magnify scarcity. The Upper Klamath River Basin has seen water conflicts involving irrigators, Endangered Species Act (ESA)-listed fish, tribal rights, commercial fishers, ranchers, and other interest groups. A severe drought in 2001 resulted in extreme water scarcity costing irrigators millions of dollars. However, an analysis of the 2001 drought conditions indicates that these losses were primarily due to the lack of adjudicated water rights among irrigators, rather than ESA-related restrictions on water diversions [*Boehlert and Jaeger*, 2010]. Had water rights been fully adjudicated, water trading under Oregon law could have reduced the losses to irrigators of the ESA requirements by an estimated 57% ($10 million), without reducing the allocation of water to protect fish habitat.

[31] Another example involves the commercial salmon fishery that depends on freshwater spawning habitat. In streams with low summer flows, an increase in streamflow at the right time and location could be expected to have a large value in terms of harvestable salmon. But where fisheries suffer a "tragedy of the commons" in the absence of property rights, or where ineffective government institutions sustain an overexploited and overcapitalized fishery, the actual value to society from reducing water scarcity in spawning streams may be zero. This could easily be the case if increasing streamflow over a period of time were to increase the number of fish which in turn would lead to an increase in effort (and costs) to catch these fish. In this case, ineffective institutions for fishery management produce a situation where an increase in water for salmon habitat would not increase society's net benefits from

harvestable salmon. According to our definition, water is not scarce in this case; however, it is important to see that what prevents water from generating additional social value is an institutional inefficiency. Indirectly, a defective institution limits the marginal value of water for the salmon fishery.

[32] This particular example represents an exception where even without a water deficit, acute water scarcity can arise. This can occur, for example, when weak institutions and poverty limit individuals' access to a resource such as water or food. Indeed, in the case of food, *Sen* 1981 has demonstrated that historically significant famines have not resulted from an absence of food, but rather from poverty and unemployment, high food prices, and poor food distribution systems. Scarcity of water for direct human use is subject to the same risks in many poor countries: inadequacies in infrastructure have led to high rates of waterborne diseases and extremely high levels of child morbidity and mortality. In this case it is the scarcity of water in a particular form (safe, potable water) that creates scarcity and human suffering.

3.5. Variability of Water Scarcity

[33] The imperfections of real-world institutions may be more apparent when they relate to water, than for cases involving other resources. As suggested earlier, water scarcity varies relatively more across location, time, form, and state than does the scarcity of many other resources. The reasons for this, as acknowledged in the literature [e.g., *Young and Haveman*, 2005] include (a) the mobility of water (it moves around, flows, seeps, evaporates), (b) the "essentialness of water" to sustain life, (c) the variability of water availability in space and time, (d) the high cost of transporting or storing large amounts of water because of its bulk relative to its value per unit weight, and (e) water's key role in complex natural-human systems. To a greater degree than for other basic resources, such as wood or salt, we are familiar with circumstances where water can effectively have an infinite value (such as when individuals may die from thirst) or a zero or negative value (such as when flooding occurs).

[34] In the Pacific Northwest, for example, where streamflow is vital for protecting fish habitat, a 10 cfs addition to a dewatered stream reach in midsummer can have enormous benefit to fish populations, whereas the same increment to a high flow mainstem river in winter would have negligible value because of a lack of scarcity. For example, in the Upper Klamath River Basin in Oregon and California, USA, water is allocated among multiple uses including agriculture and fish habitat. A recent study estimated the marginal value of an acre-foot of water for farmers, when ESA-imposed streamflows and lake levels were maintained, varied from $1 in September to $48 in June in an average year; and under drought conditions the June value went as high as $274/acre-foot [*Boehlert and Jaeger*, 2010].

4. Effects of Complexity and Feedbacks

[35] Although our definition of scarcity is conceptually simple, the natural-human system to which we apply it is, in most cases, extremely complex. The dynamic interactions among different components of the natural-human system, the multitude of often poorly understood feedbacks, and significant time lags result in a system that is certain to produce unexpected results. In fact, indirect feedbacks among different components of the natural-human system can either offset or exacerbate the initial effects of a water deficit on water scarcity. Because of the complexity of the system, the relationship between system component evolves and changes in scarcity can at times run counter to expectations, obscure cause-and-effect relationships, and make it difficult to predict scarcity. A better understanding of these dynamic interactions is an important step toward developing sustainable water management policies that can reduce water scarcity and vulnerability. Current modeling efforts suggest that climate change impacts are global and local in scale [*Knight and Jäger*, 2009] and likely to produce changes in precipitation events, system yields due to streamflow changes [*Moradkhani et al*., 2010; *Najafi et al*., 2011], extreme events including floods [*Chang et al*., 2010; *Halmstad et al*., 2012] and droughts [*Madadgar and Moradkhani*, 2012; *Jung and Chang*, 2011], and ecohydrologic factors [*Praskievicz and Chang*, 2011; *Moradkhani et al*., 2010]. The complexity and feedbacks in these systems make predicting water scarcity a daunting task.

[36] In snowmelt-dominated basins in the western United States, for example, there has been a shift in the timing of peak streamflow to earlier in spring, primarily driven by an increase in winter and spring temperatures [*Stewart et al*., 2005], and declines in late summer streamflow [*Chang et al*., 2012]. Formal detection and attribution studies show that human influence is responsible for 60% of the climate-related trends in historical streamflow and snowpack in the western United States from 1950 to 1999 [*Barnett et al*., 2008]. Some climate change scenarios for the U.S. Pacific Northwest using global general circulation models suggest a temperature-induced shift from snow to rain and earlier snowmelt [*Mote and Salathe*, 2010]. Similarly, in the Colorado River Basin, future projections in changes in runoff using a more topographically complex regional climate model are dominated by a combination of winter snow cover change, increase in spring temperature, and decrease in summer precipitation [*Gao et al*., 2011].

[37] For Oregon's Willamette Valley, these observations suggest that the region will remain a "water-rich" region overall. Scarcity, however, may increase substantially when changes in water availability are differentiated intraseasonally: increased winter and early spring runoff produces a water surplus in those seasons (and thus minimal or zero reduction in scarcity), whereas the concomitant declining snowpacks and decreased late spring and summer runoff produce a water deficit later in the year that could increase scarcity due to adverse effects on farmers, fish, and other species [*Chang and Jung*, 2010]. In this case, scarcity will remain if substitution possibilities (e.g., substituting spring runoff for summer runoff via reservoir storage) are limited or very costly.

[38] Extreme water scarcity can arise in some situations where either biophysical or socioeconomic relationships create "tipping points" or thresholds where small changes in water availability can have compounding feedback effects on interacting components of the natural-human system. One example of this may be drought stress in forests such as those in the U.S. Pacific Northwest, where it is

likely that warmer temperatures and consequent reduced and earlier melting snowpack will lead to increased water stress and frequency of drought in forests. Drought stress increases the forest's vulnerability to changes in the frequency, intensity, and spatial extent of disturbance from fire, insects, and disease. When water availability drops below some threshold level necessary to sustain healthy trees [*Coops and Waring*, 2011], the measure of water scarcity at this water deficit threshold (the marginal cost to society of slipping below the threshold) must include the compounding and potentially irreversible chain of events of forest loss due to fire, insects, and disease, that in turn, can be followed by other impacts such as landslides, debris flows, floods, or dramatic increases in stream turbidity and sediment transport [*Westerling et al*., 2006; *Moody and Martin*, 2009; *Allen et al*., 2010]. This example represents a case where the value of maintaining forest moisture above a particular biophysical threshold has potentially enormous value to society and thus represents a point below which water scarcity becomes extreme.

[39] Similar kinds of threshold effects could arise where changes in water temperature result from reduced flow and increases in air temperature, increasing the spatial and temporal extent of warm waters beyond a threshold level [*van Vliet et al*., 2011]. This can trigger algal blooms and a subsequent sudden collapse of fish populations, potentially resulting in lost recreational, aesthetic, or existence values related to that water body.

[40] Water scarcity can also be affected by a system's vulnerability to shocks, stresses, and disturbances [*Turner et al*., 2003; *Leurs*, 2005; *Schiller et al*., 2001], such as when cumulative effects of water deficits over multiple periods produce threshold effects. For example, high climate variability often contributes to regional water scarcity by increasing the frequency of extreme drought events [*Risley et al*., 2011; *Jung and Chang*, 2011; *Madadgar and Moradkhani*, 2012].

[41] One consequence of the complexity in these systems is that it limits our ability to fully understand and measure water scarcity, which in turn limits our ability to make informed policy decisions. A variety of integrated modeling approaches have shown promise for estimating water scarcity by attempting to capture the complex interactions between water and the economy, drawing on multiple disciplines and applying the tools of benefit-cost analysis [*Draper et al*., 2003; *Brouwer and Hokfes*, 2008; *Pulido-Velazquez et al*., 2008; *Ward*, 2012]. Efforts of this kind have contributed to our understanding of water scarcity in settings ranging from agriculture [*Cai et al*., 2003a, 2003b], to the protection of habitat for endangered species [*McCarl et al*., 1999], to the effects of biofuel production [*de Moraes et al*., 2012], to optimal management of groundwater pollution [*Pena-Haro et al*., 2011], to tradeoff between irrigation and endangered species protection under drought [*Ward et al*., 2006a, 2006b], and to potential impacts of climate change and water management [*Hurd and Coonrod*, 2012; *Varela-Ortega et al*., 2012]. One approach, "holistic water resources-economic optimization modeling," seeks a greater degree of integration of both hydrologic and economic systems so that a more consistent, endogenous treatment of the coupled human-natural interrelationships is achieved [*Cai*, 2008]. Overall, these approaches represent tools for more effective analysis and decision making for water policy at a regional scale and enable estimation of the marginal value of water [*Cai et al*., 2008].

[42] Uncertainty affects nearly every domain where people—individually and collectively—make choices and evaluate the consequences and values of their actions. In such settings, and particularly in the case of water, there is only imperfect and incomplete information—on the part of scientists as well as society as a whole—with which to evaluate the complex linkages in the system that give rise to water scarcity. Indeed, more information, in the form of scientific research findings or public education, can and does alter our understanding and valuation of water scarcity. In addition, the complexity of these systems and associated feedbacks can create uncertainty in settings where the stakes may be high. Future studies aimed at addressing water scarcity could benefit from the kinds of guiding principles that have been put forward generally in the context of ecosystem service valuation [*Daily et al*., 2000]. These guiding principles include the careful identification of possible alternatives (including recognizing all potential substitutes), identification and measurement of the impacts for each alternative (including endogenous responses), and translating the consequences of each alternative, when compared to the status quo, into comparable units (e.g., monetary units when possible).

[43] Of course, measuring or estimating water scarcity raises many of the same complex questions found in the general literature on valuation of nonmarket goods and the use of benefit-cost analysis [see, for example, *National Research Council*, 2004; *Arrow et al*., 1996]. As with other resources, the direct use value of water will be more apparent and easier to quantify than its nonuse value or its value in contributing to the production of other ecosystem services. For present purposes, we simply acknowledge that measuring scarcity where markets are mostly absent, and where nonuse values are important, presents real challenges.

5. Indices of Water Scarcity

[44] Taking a different approach, alternative metrics have been developed to provide indicators of water scarcity at the national or regional level. Water scarcity indices have included the Falkenmark Indicator, the Social Water Stress Index, Water Footprinting, Life Cycle Assessment, Watershed Sustainability Index, and many others [see *Brown and Matlock*, 2011; *Ridoutt et al*., 2009]. These indices have the potential advantage of being easy to compute with available national-level data. Some observers see them as being "at the forefront of political and corporate decision making" [*Brown and Matlock*, 2011; see also Rijsberman, 2006]. However, even advocates of these aggregate indices recognize their limited ability to represent how water scarcity varies spatially and temporally as a result of complex system interactions. Critics observe these "top-down" or "variable-oriented" studies have overlooked human agency and the role of institutions and thus cannot point to implementable solutions to water crises [*Srinivasan et al*., 2012].

[45] Indeed, much of the recent evolution of proposed indicators in this literature has reflected a recognition that

early indicators such as the Falkenmark Indicator and Social Water Stress Index inadequately accounted for many of the sources of heterogeneity that affect the demand for and availability of water for human and nonhuman purposes. Still, the most widely used metric is the Falkenmark "water stress index" which proposes 1700 m^3 of renewable water per capita per year as a threshold water requirement for household, agricultural, industrial, energy, and environmental needs. Countries whose renewable water supplies fall below this threshold are said to experience "water stress," those below 1000 m^3 are said to experience "water scarcity," and those below 500 m^3 are said to experience "absolute scarcity" [*Falkenmark et al*., 1989].

[46] The Falkenmark Indicator has serious limitations, however, including "(a) the annual, national averages hide important scarcity at smaller scales; (b) the indicator does not take into account the availability of infrastructure that modifies the availability of water to users; and (c) the simple thresholds do not reflect important variations in demand among countries due to, for instance, lifestyle, climate, etc." [*Rijsberman*, 2006].

[47] Attempts to improve on Falkenmark include *Ohlsson's* [1999] modification to account for society's ability to adapt to water stress through economic and technological means. Others have tried to develop a more accurate measure of the demand for water rather than a fixed requirement per person. This has led in the direction of measuring water withdrawals or use, rather than demand (which will ultimately vary with cost or price). This led *Alcamo et al.* [1997] to define a "criticality ratio," the ratio of water withdrawals for human use to total renewable water resources." These measures also have significant limitations because they do not account for (a) the share of water resources that could be made available for human use, (b) the share of water withdrawals that are consumptively used (or evapotranspired) versus the amount that could be available through recycling or return flows, and (c) differences among societies in their capacity to cope with water stress [*Rijsberman*, 2006].

[48] Recognizing these limitations, the International Water Management Institute (IWMI) attempted to analyze demand based on consumptive use in order to take account of existing water infrastructure as well as future adaptive capacity, including potential infrastructure development and irrigation efficiency and management [*Seckler et al*., 1998]. Countries not projected to meet estimated water demands by 2025 were labeled "physically water scarce"; countries with sufficient renewable resources but requiring significant investments in infrastructure to make water available to people were labeled "economically water scarce" [*Rijsberman*, 2006]. Even at this modest level of detail, however, the intricacy and resulting complexity of this approach have deterred other researchers from using it. Moreover, this IWMI approach is still an aggregate, national measure that does not provide insights into whether individuals have safe or affordable access to water to meet their needs [*Rijsberman*, 2006].

[49] A related indicator of sustainable water use, the Water Footprint Index (WFI), has been proposed by *Hoekstra et al*. 2009. The shortcomings of the WFI highlight one reason why water scarcity is a particularly complex concept. The WFI was inspired by "carbon footprinting" that measures the carbon emissions associated with a person or activity. The concept of a carbon footprint, however, recognizes that carbon emissions everywhere have essentially the same value (or cost) to society because CO_2 mixes quickly in the atmosphere, and thus, its effects on the climate do not depend on the time or location of emissions. By contrast, the marginal effect of conserving a unit of water can vary greatly across small distances or time steps. This contrast highlights the difficulty of summarizing water scarcity at an aggregate scale and underscores the complex role that water plays in natural-human systems.

6. Scarcity and Policy

[50] Much of our interest in water scarcity stems from the idea that we can intervene with a change in policy, or investment in public infrastructure, to address complex problems faced by society. It is when considering possible interventions that policymakers, stakeholders, engineers, economists, and others need to better understand, evaluate, and measure water scarcity as a basis for decisions about public works or public policy. What collective action response can minimize or avoid the consequences of increased scarcity, especially when those consequences are believed to be particularly harmful or costly? Such cases may arise if the consequences of water scarcity are irreversible (e.g., species extinctions) or where the costs are concentrated on vulnerable individuals or groups. Our exploration of the definition, dimensions, and complexity of water scarcity, as well as the methods used to measure it, leads to a number of key observations:

[51] (1) To the extent that there is a "myth of abundance" for "water-rich" systems like the U.S. Pacific Northwest, high water scarcity may arise due to declining water availability, rising demand for water, the high cost of moving, storing, or transforming water to meet demand, or all of the above. The ecology of water-abundant regions evolves in ways that depend on continued abundance and synchrony between water availability and ecosystem requirements. Similarly, human systems evolve to take advantage of, and thereby rely on, water abundance, as in the example of the hydropower-dependent Pacific Northwest or the rice-producing regions of Southeast Asia. The cost to society of a given reduction in water availability can be higher in a water-rich region than in a water-poor region.

[52] (2) Human actions leading to water deficits in ecological systems may pass a threshold where large ecological consequences inflict high costs on society. While a diversion of water from ecological uses to human consumptive uses may solve water deficit problems and benefit our society in the short term, degradation of the ecosystem could have a large and cumulative long-term effect on society. Indeed, the long-term social costs of such changes could harm future generations due to irreversible losses of water-related ecosystem services and species extinction.

[53] (3) Scarcity can be pronounced for specific segments of society, such as the very poor, even when water is relatively abundant in proximity to those affected. Some of the early indices of water scarcity produced maps showing vulnerabilities related to water scarcity concentrated in the low-income countries of Africa and South Asia. Large vulnerable populations no doubt exist in many of these

countries. However, rather than being caused by a lack of available water, the vulnerabilities found in less developed countries are often due to poverty itself, coupled with a lack of adequate institutions and infrastructure.

[54] (4) Where water serves public purposes, its scarcity should reflect its value to all individuals. Differences and changes over time in individuals' preferences and values augment the complexity of evaluating water scarcity. For example, when some people place a high value on leaving water instream for aquatic ecosystem health, while others see value only in diverting water to produce food and jobs, how should we sum, or weight, these divergent individual preferences in order to arrive at a collective judgment of their relative importance?

7. Concluding Comments

[55] Water scarcity has been defined here as the marginal value of a unit of water. This definition, along with a conceptual framework and illustrative examples, highlights water scarcity's extraordinary variability across spatial and temporal domains. This is a direct result of the distinctive nature of water itself: water is necessary for life, but difficult to transport in large quantities (to mitigate scarcity spatially), and difficult to store in large quantities (to mitigate scarcity temporally). That water scarcity varies greatly from place to place and day to day has mainly to do with the properties of water and its role in natural-human systems, rather than our definition of scarcity. Indeed, the strength of this definition is that it brings out this important reality about water scarcity. By contrast, were we to apply the same definition of scarcity to wood or salt, for example, we would find scarcity to be relatively more homogeneous across space and time.

[56] Water scarcity, as defined here, reflects an understanding that is highly interdisciplinary: first, the normative basis of value described earlier has its underpinnings in moral philosophy and reflects the view that ethical reasoning of all types is anthropocentric, and a moral value of nature is derivative, reflecting the instrumental value of maintaining nature [*O'Neill*, 1997; *Oksanen*, 1997]. Moreover, while the connection between nature's value and humans' aesthetic sensibilities toward nature has been made by philosophers such as Immanuel Kant [*Lucht*, 2007], similar ideas have also been stressed by contemporary biologists [e.g., *Orians*, 1998].

[57] Second, the framework for identifying different categories of human values related to water and natural systems (i.e., direct use value, indirect use value, nonuse value), as well as the methods for measuring and aggregating these values (i.e., revealed preference, stated preference), has been developed by economists working closely with other disciplines [*National Research Council*, 2004].

[58] Third, although the natural sciences do not provide an independent framework for making normative value judgments related to scarcity, society's judgments about the value of water depend fundamentally on the information that science provides us about how a water deficit or surplus may affect the natural-human systems. The examples described earlier have emphasized the implications of water deficits for a large range of human values.

[59] Fourth, geography plays an important role: the spatial and temporal dimensions of water availability and use necessitate placing all aspects of our definition in a geographical context. This highlights the role that engineered changes in water storage and delivery have played in determining spatial patterns of water scarcity that are often independent of whether a region was originally water-rich or water-poor [e.g., *Vörösmarty et al*., 2000, 2010].

[60] Fifth, the importance of institutions to either ameliorate or exacerbate water scarcity has long been recognized in fields including law [e.g., *Freyfogle*, 2011], political science [e.g., *Ostrom*, 2009], geography [e.g., *Wolf*, 2009], and institutional economics [*Bromley*, 1992].

[61] While this definition of water scarcity encompasses a wide range of disciplines and recognizes the interconnections and complex relationships among components of the natural-human system, these strengths also point to a limitation: it is impractical to measure, or estimate, water scarcity at every point in space and time. At the other end of the spectrum, national or regional aggregate water scarcity indices offer a simpler way to produce quantitative metrics, but these are highly imperfect measures that provide limited information about spatial and temporal variations in water scarcity and thus are of limited usefulness for evaluating the consequences of scarcity.

[62] The discussion here suggests that when assessing scarcity, water resource professionals, engineers, and policymakers should consider not only the states, stocks, and flows of water but also the way that demand and the costs of water provision can fluctuate across space and time.

[63] Although there are significant obstacles to estimating water's value in complex natural-human systems [e.g., *Daily et al*., 2000], our view is that one should begin with the best possible conceptual definition of water scarcity and then search for ways to overcome the challenges. As in many other settings, individuals and societies use shortcuts, rules of thumb, and precautionary principles as prudent ways to deal with limited information. Or there may be indirect ways to identify where and when rising water scarcity will occur: where (a) the cost of providing additional water would likely increase sharply, (b) where substitution possibilities on the demand side are limited, (c) where demand is currently increasing while available quantities are diminishing, and (d) where thresholds, lags, and irreversible damages are likely to limit flexibility in responding to water scarcity.

[64] Water scarcity, as we have defined and described it here, should be viewed as but one input into society's decision-making process, one however that may help foster improved policymaking and targeted research, as well as better communication and understanding among the many groups involved in anticipating and alleviating water scarcity.

Appendix A: A Formal Derivation of Water Scarcity

[65] Suppose there is a fixed amount of water available in basin j at time t, denoted by $\overline{Q}_{jt}$, which could be allocated to N different uses (e.g., agriculture, urban, fish, wetlands, and hydropower), with W_{ijt} denoting the amount of water allocated to use i in basin j at time t.

[66] Let $U = F\left(W_{1jt}, W_{2jt}, \ldots, W_{Njt}\right)$ denote the social welfare function of water allocation, which maps individual preferences in the society to collective values for water allocations. The social welfare function may depend not only on the total amount of economic and environmental benefits derived from water uses but also on distributional impacts and social justice considerations. The function F is assumed to capture the complex interactions between components of the biophysical-human system.

[67] An allocation of water is socially optimal if it maximizes social welfare subject to water availability. Formally, the optimal allocation solves the following maximization problem:

$$\begin{aligned} &\underset{\left(W_{1jt}, W_{2jt}, \ldots, W_{Njt}\right)}{\text{Max}} && U = F\left(W_{1jt}, W_{2jt}, \ldots, W_{Njt}\right), \\ &\text{subject to} && W_{1jt} + W_{2jt} + \cdots + W_{Njt} \leq \overline{Q}_{jt}. \end{aligned}$$

[68] Let $\left(W^*_{1jt}\left(\overline{Q}_{jt}\right), W^*_{2jt}\left(\overline{Q}_{jt}\right), \ldots, W^*_{Njt}\left(\overline{Q}_{jt}\right)\right)$ denote the solution to the maximization problem. The social welfare under the optimal allocation equals

$$U^*\left(\overline{Q}_{jt}\right) = F\left(W^*_{1jt}\left(\overline{Q}_{jt}\right), W^*_{2jt}\left(\overline{Q}_{jt}\right), \ldots, W^*_{Njt}\left(\overline{Q}_{jt}\right)\right).$$

[69] *Definition of Water Scarcity and the Degree of Scarcity*: Water scarcity exists in basin j at time t if and only if

$$S_{jt} \equiv \frac{dU^*\left(\overline{Q}_{jt}\right)}{d\overline{Q}_{jt}} > 0.$$

[70] The degree of scarcity can be measured by S, which equals the additional benefit the society would be able to gain if an additional unit of water was available. Essentially, the degree of scarcity (S) is measured by the opportunity cost imposed by scarcity. Although we define scarcity relative to the socially optimal allocation, it can also be defined at any other allocation. Thus, optimization is not critical to the definition, though it helps to elucidate the notion of efficiency that we discuss later.

[71] This full definition of scarcity is challenging to implement in most cases because we have incomplete information, as well as conflicting views, for some dimensions of the function F (e.g., how to measure and establish agreed upon weights for individual or group rights and definitions of fairness or equality). In some specific settings, elements of the function F that extend beyond the simpler formulation described later have been included quantitatively or evaluated and recognized separately.

[72] To proceed with the current derivation, a simpler formulation assumes that benefits from water use are additive. Let $B_{ijt}\left(W_{ijt}\right)$ denote the net benefit from water use i in base j at time t. Allocative efficiency of water is achieved when the net benefits to society, or "aggregate surplus (AS)," are maximized from a particular allocation:

$$\begin{aligned} &\underset{\left(W_{1jt}, W_{2jt}, \ldots, W_{Njt}\right)}{\text{Max}} && \text{AS} \equiv B_{1jt}\left(W_{1jt}\right) + B_{2jt}\left(W_{2jt}\right) + \ldots + B_{Njt}\left(W_{Njt}\right) \\ &\text{subject to} && W_{1jt} + W_{2jt} + \cdots + W_{Njt} \leq \overline{Q}_{jt}. \end{aligned}$$

[73] One important rule than can be derived from this framework is that when the water is allocated efficiently, the marginal benefits (what we refer to as marginal value in the text) must be equalized for all uses, that is,

$$\frac{dB_{ijt}\left(W_{ijt}\right)}{dW_{ijt}} = \frac{dB_{kjt}\left(W_{kjt}\right)}{dW_{kjt}}, \qquad \text{for any } i \text{ and } k.$$

[74] The allocation represented by Q_1 in Figure 3 is an example of an efficient allocation between two uses. More generally, let $\left(W^E_{1jt}\left(\overline{Q}_{jt}\right), W^E_{2jt}\left(\overline{Q}_{jt}\right), \ldots, W^E_{Njt}\left(\overline{Q}_{jt}\right)\right)$ denote the efficient allocation of water resources. The aggregate social benefit from the allocation equals $\text{AS}\left(\overline{Q}_{jt}\right) = F\left(W^E_{1jt}\left(\overline{Q}_{jt}\right), W^E_{2jt}\left(\overline{Q}_{jt}\right), \ldots, W^E_{Njt}\left(\overline{Q}_{jt}\right)\right)$.

[75] For current purposes, however, the central element of this derivation is that we have the following definitions:

[76] *Definition of Water Scarcity and Degree of Scarcity*: Water scarcity exists in basin j at time t if and only if

$$\hat{S}_{jt} \equiv \frac{d\text{AS}\left(\overline{Q}_{jt}\right)}{\mathrm{d}\overline{Q}_{jt}} > 0.$$

[77] The degree of scarcity (S) can be measured by $\hat{S}_{jt}$.

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