An Economic Perspective on Water Security

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Introduction

Ensuring water security is a key challenge for society in the twenty-first century given the risks posed by inadequate access to safe drinking water, growing water extractions, and the impacts of climate change and weather-related shocks. The concept of water security is used by corporations, policy makers, development banks, and multilateral organizations (Sadoff et al. 2015), and it has been explicitly adopted as an objective of national water policy and investment. The World Bank has established a vision for "A Water-Secure World for All," which guides a lending portfolio of 170 projects of approximately $30 billion (as of 2019) and has three pillars: sustaining water resources, delivering water services, and building resilience (World Bank 2019). There has also been a sharp rise in academic research on water security since 2000, including among economists.

Despite this increased attention, water security has many different meanings, and its implications for economic research on water policy are not clear. This article presents an economic perspective on water security. We argue that water security is an important concept that deserves more attention from economists because it highlights fundamental challenges associated with the economics of water, including the difficulty of valuing and managing water across multiple policy objectives (Hanemann 2006; Garrick, Hanemann, and Hepburn 2020).

We will show that the issue of water security offers three key lessons for economists working on water policy and management. First, economic researchers can develop more effective policy responses by diagnosing and addressing the root causes of water insecurity in terms of market and institutional failures. Second, policies that promote water security—meeting basic water needs, promoting more equitable and just allocation of water, or reducing water risks—deviate from conventional measures of economic efficiency and thus require a renewed emphasis on institutions. Third, achieving the multiple objectives associated with water security

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will require multiple policy instruments, supported by appropriate property rights and institutional mechanisms to coordinate across sectors, political borders, and levels of governance.

The remainder of the article is organized as follows. First, we review the concept of water security and present economic perspectives on its definitions and measurement. Then we examine the economic causes of water insecurity and its consequences: water misallocation, infrastructure financing deficits, and water risks. Next, we present an economic framework for assessing the costs and benefits of water security and then review the challenges of implementing such a framework in practice. In the penultimate section, we discuss ways to develop more effective property rights and polycentric water institutions. The final section discusses directions for future research in this area.

The Evolution of Economic Thinking about Water Security

Economists have long recognized the complexities of water and its many dimensions. Water has attributes of a public good, a common pool resource, and a private good (Hanemann 2006). Moreover, it is subject to pervasive externalities as a result of the interconnected nature of the water cycle and water systems (Meinzen-Dick 2007). Thus, the "seemingly simple issue of system identification[1] is . . . at the root of some of the most serious conceptual problems in contemporary water research" (Ciriacy-Wantrup 1967, 179). An economic perspective on water security can help to both define water management problems and determine the costs and benefits to consider when comparing potential policy solutions. This section discusses how water security has been defined and measured and the evolution of economic thinking about water security.

Defining Water Security

In one of the more widely cited definitions of water security, Grey and Sadoff (2007, 547–48) argue that water security requires ensuring the "availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies." In this context, contemporary debates about water security have focused on four interrelated issues: water availability, vulnerability to hazards, meeting human needs, and sustainability (Cook and Bakker 2012). In 2013, the United Nations proposed a definition of water security aimed at providing a "holistic outlook" on the importance of human development and ecological health (UN Water 2013, 1).[2] Achieving this holistic vision has proven elusive, and with billions of people lacking safe drinking water supplies, there has been a shift in emphasis from water *security* to water *insecurity*, defined as the "lack of adequate and safe water for a healthy and productive life" (Wutich 2019, 1). This focus on water *insecurity* makes the economic consequences

[1]"System identification" refers to the challenge of defining the boundaries of a water management problem.

[2]This builds on the "Ministerial Declaration of The Hague on Water Security in the 21st Century" (Hague Declaration 2000, 1), which defined water security as "ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy productive life and that the vulnerable are protected from the risks of water-related hazards."

of inadequate and unsafe water supplies more explicit (Young et al. 2019). Examples include compromised livelihoods, reduced economic productivity, and declining human and ecosystem health (including mental health; Brewis, Choudhary, and Wutich 2019; Hyland and Russ 2019).

In the remainder of this discussion, we present definitions of water security from an economic perspective, focusing primarily on cost-effectiveness (least-cost path for achieving a given risk threshold), economic efficiency (maximization of net benefits), and equity (distributional justice and the fairness of processes and outcomes).

Definitions of water security often include multiple, sometimes competing, objectives. For example, the outcomes identified in Hague Ministerial Declaration (2000) involved three different objectives: "managing risk" cost-effectively, "valuing water" to maximize net benefits, and ensuring equity. This definition also specifies a set of constraints, including cost recovery, affordability, and sustainability, that require a better understanding of the costs and benefits associated with meeting these constraints.

Over time, definitions and measures of water security have more explicitly identified their economic objectives, starting with cost-effective risk management and expanding to economic efficiency and equity (Hall and Borgomeo 2013; OECD 2013; Whittington, Sadoff, and Allaire 2013). A primary focus for national and local policy institutions has been risk management, which has its own body of research. For example, Hall and Borgomeo (2013) use a risk-based framework that distinguishes indicators of hazards from indicators of vulnerability and exposure, with outcome measures including the frequency of water shortages, violations of water quality standards, aquatic species populations, agricultural output, and flood damages. Investments are then assessed according to their cost-effectiveness in achieving different thresholds for risks that are associated with these events (Hall and Borgomeo 2013, 7).

The OECD (2013) developed a framework for addressing water security that combined two economic objectives: cost-effective risk management and maximization of net benefits. More specifically, that "targets for water risks should be achieved as cost-effectively as possible," and the "acceptable level of water risk for society should depend upon the balance between economic, social and environmental consequences and the cost of amelioration" (OECD 2013, 5). Achieving this balance involves "the systematic assessment of the expected costs and benefits of options to manage water risks and to properly evaluate risk-risk trade-offs" (OECD 2013, 5). In short, making these trade-offs requires defining and measuring the costs and benefits of enhancing water security.

Measuring Water Security

Over the past 30 years, substantial progress has been made in identifying and measuring specific dimensions of water security, reflected in indicators of water scarcity, water footprints, access to safe drinking water, and flood risk. At least 80 ways of measuring and assessing water security have been identified, broadly clustered into those that deal with household experiences and those that deal with resource availability, or some combination of the two (Octavianti and Staddon 2021).[3] Yet efforts to integrate these different indicators into a composite measure

[3] A full review of metrics of water scarcity and other forms of water-related risks is beyond the scope of this study. For details, see Grafton (2017) and Octavianti and Staddon (2021).

of water security have been described as a "babel of competing indicators" that often conflate physical, economic, managerial, institutional, and political aspects (Howlett and Cuenca 2017, 235). Indeed, there is a persistent disconnect between the aspirations for a "systematic assessment of the expected costs and benefits" (OECD 2013, 5) of different policy options and the reality of decision-making. This disconnect is due in part to the lack of explicit focus on the economic objectives addressed by indicators of water security.

In the discussion that follows, we review several prominent efforts to measure water security. We examine whether and how economic objectives (e.g., efficiency, equity) have been defined and integrated into different indicators. Until relatively recently, various indexes were constructed to measure water security without explicit consideration of costs and benefits. Vörösmarty et al. (2010) concluded that nearly 80 percent of the global population faces threats to water security, and their analysis considered net benefits in terms of the "reduced threat" of water insecurity associated with infrastructure development. Policy organizations and development banks compare national-level outcomes concerning water security using multidimensional indexes (Asian Development Bank 2016).[4] But such indexes rarely consider the economic costs and benefits associated with different values for the index or particular components in the index.

Economists have generally emphasized the importance of measuring water security in terms of economic efficiency. For example, in a study on the "economic value of moving to a water secure world," Whittington, Sadoff, and Allaire (2013) include economic efficiency as an explicit economic objective in their analysis. This study is a first step in moving from qualitative descriptions of the economic objectives of water security to actually quantifying net benefits. Addressing efficiency issues can also help to identify policies and investments that strike a balance between the "need to increase the upside potential' (i.e., economic benefits) associated with adequate water quantity and quality and the "need to reduce society's exposure to water-related risks" (i.e., negative externalities; Dadson et al. 2017, 6426).[5]

Grafton (2017) argues that water security cannot be reduced to a single scale of costs and benefits and that net economic benefits should be only one of many indicators. Indeed, equity, justice, and fairness are central themes of research on the political economy of water security, which highlights the winners and losers associated with different policy approaches (Zeitoun et al. 2016). The political economy of water security focuses in particular on distributive justice in terms of the "fairness in outcomes" coupled with an emphasis on the rules, norms, and associated interactions that produce these outcomes (Wutich, Beresford, and Carvajal 2016, 15). In addition, the fields of economic anthropology and economic geography have promoted justice as a normative criterion for comparing policies and institutions that are aimed at addressing inequalities of water access and reliability (Wutich and Beresford 2019).

Water Security and Economic Growth

Paralleling efforts to measure water security have been efforts to model the impacts of water insecurity on economic growth. Econometric studies have used cross-sectional analyses of climate or water variables and economic growth to examine the impact of climate variability and water availability on gross domestic product (GDP) growth (Brown and Lall 2006;

[4]See Lautze and Manthrithilake (2012) for an example of such a multidimensional index.
[5]Also see Grey and Sadoff (2006).

Brown et al. 2011, 2013; Khan, Morsuch, and Brown 2017; Russ 2020). For example, Brown et al. (2011, 633) found that in sub-Saharan Africa, there was a "consistent negative effect of persistent dry conditions on economic growth," with a 1 percent increase in drought area associated with a 2–4 percent reduction in GDP growth. In a later study, Brown et al. (2013, 2) argue that the "lack of water security [in Africa is seen as] an impediment to growth." However, it has proven difficult to demonstrate the link between water security and economic growth (Roson and Damania 2017), due in part to the multiple channels through which water influences the economy as well as the potential for economic diversification to offset the impacts of weather-related shocks (Damania 2020).

Economic Causes of Water Insecurity

Achieving water security requires matching uncertain water supplies with multiple demands, including both consumptive and nonconsumptive uses of water. It also involves managing the risks posed by pollution, the degradation of freshwater ecosystems, and the depreciation of natural capital.[6] Economists have long focused on the market and institutional failures that contribute to water management problems: "Problems of [water] governance . . . have an economic explanation [that] create[s] a need for collective action in the provision and financing of water supply that simply does not arise with most other commodities" (Hanemann 2006, 87). These problems stem from pervasive externalities across the water cycle, including the negative externalities associated with water extraction and pollution and the positive externalities associated with developing and maintaining capital-intensive, long-lived water supply infrastructure (Meinzen-Dick 2007; Damania 2020). Thus, addressing and balancing the multiple objectives associated with water security (e.g., safe, affordable drinking water, equitable allocation, acceptable water risks) requires addressing multiple sources of market and institutional failure.

In this section, we focus on three aspects of water insecurity—inadequate water infrastructure, misallocation, and water risk—and examine their economic causes and consequences.

Inadequate Water Infrastructure

Water security requires multiple types of infrastructure to ensure access, storage, distribution, and conservation of water. This infrastructure includes dams and hydropower, water supply and sanitation, irrigation, and green (or natural) capital (Grigg 2017). Water insecurity can stem from underinvestment in infrastructure that generates local public goods (e.g., piped water supply networks) and overinvestment in infrastructure whose negative externalities have not been accounted for (e.g., some hydropower dams and irrigation systems).

Underinvestment in water infrastructure

Water supply infrastructure for domestic and irrigation services is characterized by relatively high capital costs and long payback periods, which has resulted in chronic underinvestment.

[6]Natural capital refers to an "economy's endowment of natural resources" (Barbier 2019, 14) and, in the case of water, involves the ecosystem functions that generate renewable water resources.

Although a comprehensive estimate of the investment gap has proven elusive, several analyses illustrate its scale. For example, the capital cost of the water supply and sanitation infrastructure needed to achieve "universal and equitable access to safe and affordable drinking water for all" and "adequate and equitable sanitation and hygiene for all" has been estimated at $114 billion USD per year through 2030, which is approximately triple recent annual investment levels (Hutton and Varughese 2016, 7).

The water security challenges associated with this investment deficit vary by region. Higher-income countries have generally overcome initial impediments to infrastructure development, but they now face aging infrastructure and the need to build from scratch in some areas that were previously excluded (e.g., tribal Nations; Deitz and Meehan 2019). They must also confront the negative externalities of past investments, such as the environmental consequences of dams (Ansar et al. 2014; Jeuland 2020). Lower-income countries also tend to underinvest in basic infrastructure, including for water supply and sanitation. Sub-Saharan Africa, in particular, has been slow to make progress in meeting international standards for safe drinking water, which stems from persistent challenges in rural areas with dispersed populations and hence limited economies of scale (Hope et al. 2020). A 2009 survey of 19 countries in sub-Saharan Africa indicated that only 30 percent of rural households paid for water, which has led to unreliable and insufficient water systems because of inadequate funds for maintenance (Foster and Hope 2017).

Overinvestment in water infrastructure

Overinvestment in infrastructure may also contribute to water insecurity when negative externalities have not been adequately considered. Dam projects are among the most controversial examples, spurring the use of benefit–cost analysis to assess these large multipurpose water infrastructure projects (Pearce 1998) and their distributional impacts (Duflo and Pande 2007). Recent analyses have identified a chronic underestimation of the costs, particularly those associated with inflation, debt servicing, and social and environmental costs (Ansar et al. 2014) and the lack of consistent and comprehensive measures of the benefits of dam projects (Jeuland 2020). The debates over dams have become so heated that one economist has suggested that "no amount of methodological improvement and additional evidence will make a difference or convince dam proponents or nay-sayers to reconsider their positions" (Jeuland 2020, 64).

Misallocation of water

Enhancing water security often involves disputes about how water is allocated across competing demands: who gets water, how, and how much. In the narrowest sense, water *mis*allocation is defined as a lack of allocative efficiency and a pattern of water use that fails to maximize the net benefits across competing demands (Pujol et al. 2006). Grafton, Garrick, and Horne (2017, 2) present a broader concept of misallocation that also considers dynamic efficiency (i.e., over time) and equity "as determined by the locally established norms of distributive justice" (3). In the discussion that follows, we trace water misallocation to the incentive problems associated with water's characteristics as both a common pool resource and a public good.

Exclusion problems

Water misallocation stems from common pool resource problems: exclusion of new water users is difficult, and water consumption can be rivalrous among uses and users (Blomquist 2011). Unlike land, water moves, complicating efforts to develop, monitor, and enforce rules limiting access to shared aquifers and river basins. For example, efforts to cap water extractions can be undermined by new surface water diversions or groundwater pumping activity that intercept previously claimed and used water. As a result, water extractions exceed renewable water supplies in many major river basins and aquifers, with approximately 30 percent of human water consumption supplied from water resources that are considered to be unsustainable (Wada and Bierkens 2014). The proportion of average annual streamflows reaching the sea have declined in the Colorado, Yellow, Murray-Darling, and Orange River Basins because of water extraction and the failure to define—and enforce—cumulative limits on extraction (Grafton et al. 2013). Political resistance from existing water users has made the introduction of new metering technologies and property rights reforms contentious, even when the benefits far outweigh the costs of doing so (Garrick, Hanemann, and Hepburn 2020).

Rivalry and water scarcity

The difficulty of excluding new water users is problematic because of rivalry among competing uses. For example, the "consumed fraction" of a water diversion is unavailable to other users within a given season or location.[7] However, rivalry is almost always partial because of "return flows," as water used for irrigation, drinking, or industrial purposes is not fully consumed and can become available to downstream users or recharge groundwater. This dual nature of water use—partly rival, partly nonrival—makes it difficult to define property rights and address externalities as water supply and demand change (Blomquist 2011; Hanemann and Young 2020).

The "marginal value of a unit of water" is an indicator of water scarcity when water use is rivalrous (Jaeger et al. 2013). As scarcity intensifies and the marginal value of water varies across competing uses, there are potential gains from reallocation. Despite this potential, many water-scarce regions have failed to reallocate water at expected levels. Estimates of the potential gains from reallocation consistently find that the benefits are not evenly distributed and that high transaction costs constrain these potential efficiency gains (Leonard, Costello, and Libecap 2019). For example, although groundwater trading would decrease the costs of complying with groundwater restrictions in the Republican River Basin of Nebraska by up to 90 percent, the cost savings are unevenly distributed across wells, counties, and institutions, which constrains uptake (Palazzo and Brozović 2014).

Freshwater ecosystems and free riding

Enhancing water security depends on conserving or restoring freshwater ecosystem services and the natural capital associated with aquifer and river health (Barbier 2019). Many of these

[7] Pérez-Blanco, Hrast-Essenfelder, and Perry (2020) define the consumed fraction as water transpired and evaporated by plants.

benefits are public goods and are associated with free-riding problems that lead to an undersupply of conservation efforts. Solving these problems requires addressing the exclusion issues discussed earlier (see also Koehler, Thomson, and Hope 2015) and encouraging those who benefit from improved freshwater ecosystems to invest in their conservation (Damania 2020). This institutional failure has led to the depletion of water stocks, a form of natural capital, which has substantial economic impacts. For example, groundwater depletion in Kansas resulted in an estimated reduction in wealth of $110 million per year between 1996 and 2005 (Fenichel et al. 2016). Without effective institutional responses, rivers and aquifers may approach tipping points and thresholds beyond which their functioning is impaired.

Water Risks

Water security has become increasingly associated with managing and mitigating water risks[8] that involve negative externalities, such as the economic impacts of weather-related shocks (e.g., droughts or floods), the costs of water shortages, or the effects of pollution on the environment and public health (Damania 2020). In this context, Grey et al. (2013, 4) define water security as a "tolerable level of water-related risk to society." The uneven distribution of water risks across regions, gender, and socioeconomic characteristics contributes to poverty and inequality, which highlights the importance of considering infrastructure and institutions that address water security in the broader context of development policies (REACH 2020). In the remainder of this section, we identify the major consequences of water risk, as well as their rough magnitudes and distribution.

Consequences of water risk

Water risks cause negative externalities through multiple channels—such as water shortages, poor water quality, and flooding—which has made it difficult to develop global, comparable measures of these impacts and their monetary value. To address the issue of water security from a risk perspective, the OECD and the Global Water Partnership convened a task force on water security in 2013. The task force identified several types of water-related risk and their impacts: inadequate water supply and sanitation, flooding, water shortages (including droughts), and ecosystem degradation (Sadoff et al. 2015). Inadequate water supply and sanitation are found to lead to economic losses associated with the time spent collecting water or traveling to defecation sites—estimated at $260 billion annually and concentrated in South Asia and sub-Saharan Africa (Hutton 2012). The annual expected direct economic losses from flooding are estimated at $120 billion per year and concentrated in North America, where asset values are high; without adaptation, the damages from coastal flooding are projected to quadruple, while riverine flood risk could more than double (Sadoff et al. 2015). Water shortages have economic impacts on multiple sectors, with direct impacts on irrigation in particular. Enhanced water reliability for existing irrigators was estimated to generate welfare gains of $94 billion in 2010 (2010 USD; Sadoff et al. 2015). The economic

[8]Water risk is associated with the potential for undesirable outcomes related to water (Hall and Borgomeo 2013).

impacts of water shortages in cities and regions with more diversified economies are harder to measure, as they occur through multiple channels, such as increased incidence of diarrheal diseases and power outages (Damania 2020). Finally, the effects of pollution pose a risk to growth (Damania et al. 2019), but the full range of impacts, particularly the economic costs of ecosystem degradation, are among the most difficult to estimate because of the nonmarket values associated with functioning freshwater ecosystems.

Transboundary aspects of water risk

There has been growing concern that negative externalities associated with water risks are not fully internalized into decisions as a result of the transboundary nature of water resources and their related infrastructure and supply chains (Dell'Angelo, D'Odorico, and Cristina 2018). Many discussions of water security focus on water systems shared by multiple sectors and political jurisdictions. In the world's transboundary international river basins, for example, upstream development and diversions pose downstream externalities, as well as free riding problems (Duflo and Pande 2007; Olmstead and Sigman 2015). In the Nile basin, the development of the Ethiopia Grand Renaissance Dam has spurred tense discussion about promoting coordination of infrastructure operation between Ethiopia, Egypt, and Sudan to reduce the potential negative downstream externalities associated with filling the dam (Wheeler et al. 2020).

International borders are not the only boundaries that are relevant for tracking the negative externalities posed by water risk. Urbanization is leading to growing competition for water between cities and rural areas, resulting in the externalities of urban demand being felt in distant rural regions.[9] Global supply chains are also linking distant regions, thus extending water risks far beyond local or regional impacts. For example, although trade in food and other commodities can enhance economic welfare, it has also been associated with "environmental cost-shifting" (i.e., negative externalities) that may allow richer countries to address their water resource constraints by imposing burdens on poorer countries, such as oil-rich, water-scarce countries in the Middle East outsourcing food production to northern Africa (Dell'Angelo, D'Odorico, and Cristina 2018).

An Economic Framework for Analyzing Water Security

With this background on key concepts and issues related to water security, we next present an economic framework for analyzing water security that focuses on the benefits and costs of different policy and institutional options. First, we examine how various definitions of water security align with economic efficiency. Then we explore the relationship of these definitions to the concept of integrated water resources management (IWRM). Finally, we discuss the challenges of implementing an economic framework for water security in practice, including issues related to defining costs and benefits and the management of water systems across multiple jurisdictions.

[9]These impacts of urbanization are exemplified by water valuation disputes such as those between Los Angeles and the Owens Valley (Libecap 2007).

Water Security and Economic Efficiency

When thinking about water security, economists tend to focus on efficiency as a benchmark: that is, maximizing the incremental costs and benefits of various actions involving water management. However, assessing the efficiency of policy options depends on how water security is defined and which costs and benefits are included. The key point here is that most definitions of water security can be compared to a standard definition of economic efficiency, at least in principle. For example, the definitions of water security presented earlier can be viewed in terms of the constraints they impose on the net benefit maximization problem, the values associated with particular characteristics of water (such as cleanliness or availability), or the geographic area over which net benefits are assessed. In these cases, researchers can estimate the extent to which these particular definitions of water security depart from a standard measure of economic efficiency that maximizes the sum of producer and consumer surplus.

Clarifying the domain for maximizing efficiency

The breadth of issues included in definitions of water security highlights the need for economists to clarify the domain (or boundaries) of the problem they are studying. If water security is defined in terms of acceptable risks, the domain for maximizing net benefits would need to be narrower than the domain for general efficiency maximization. This narrower domain for maximization naturally follows from the definition in Grey and Sadoff (2007, 547–8), which refers to "acceptable" levels of water-related risks. Thus, the domain could include a number of risks, such as shortages, drought, floods, water-borne diseases, and ecosystem degradation.

The concept of water security has parallels with food and energy security. Economists may assess the value of a more secure energy supply by estimating the impact such a supply could have on gross national product or consumer welfare. They might also consider cost-effective options for promoting food or energy security within a given budget.

Minimizing costs versus maximizing net benefits

From the perspective of normative theory, there are two approaches for framing the water security problem that can incorporate various economic features of the problem. The first is to minimize the costs of achieving a given set of objectives. The second is to maximize net benefits subject to constraints. Both approaches have the advantages of simplicity, flexibility, and the ease with which one can see the connection between costs and benefits. As has been noted by several economists (e.g., Lave 1981), other things equal, the cost minimization approach is generally easier to implement than net benefit maximization because it does not require an explicit estimation of a benefit function.

However, the net benefits approach easily allows specification of the many characteristics of water that make it a unique economic good. For example, in his argument that water has both private and public good aspects, Hanemann (2006, 71) distinguishes between the water in a reservoir, which could be sold as a private good, and the capacity of the reservoir, which has some public good characteristics. In principle, both of these characteristics could be included in the benefit function. Moreover, the net benefit maximization framework provides a clear benchmark for comparing different policies. However, this assumes that both the benefit and cost functions can be operationalized, which, as we will discuss later, poses serious challenges.

Net benefits maximization and integrated water resources management

At a theoretical level, the net benefit maximization framework for assessing water security is virtually indistinguishable from the concept of integrated water resources management. IWRM has been the subject of discussion for decades, dating at least as far back as the 1950s and the concept of "integrated river basin development" and its notion of river basins as the "backbone . . . of a unified system of multiple-purpose . . . projects to promote regional growth" (White 1957, 157). In the same report where it first cites water security, the Global Water Partnership (2000, 15) provides a widely accepted definition of IWRM:

> a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Based on this definition, the concept of IWRM can be recast as a constrained net benefit maximization. This suggests that, in theory, the IWRM problem and the water security problem are *equivalent*, although they may not be equivalent in the specific benefit function that is used. For example, the benefits associated with reduced risks of flooding may vary, depending on whether one views these risks through the lens of water security or IWRM. The key point here is that the *structure* of the two formulations is very similar, if not the same.

One possible difference between IWRM and net benefit maximization is that IWRM focuses more on *process*, whereas water security focuses more on inputs and outputs (Asian Development Bank 2013). To the extent that the process can link inputs with outputs and that the process is not a good that itself has value, this difference appears unimportant for structuring the analytical problem to be solved. That is, in economic terms, the process of achieving water security can be thought of as part of a production function that defines benefits and costs.

However, in a critique of IWRM, Biswas (2004, 248) argues that "in the real world, the concept will be exceedingly difficult to be made operational." In this context, there is growing recognition that the same issues that arise in measuring the impacts of policy interventions that support IWRM also arise in measuring the impacts of policies designed to improve water security (Gerlak and Mukhtarov 2015).

Challenges of Implementing an Economic Framework for Water Security in Practice

There are two main challenges to implementing the preceding economic framework for defining water security and evaluating policies for enhancing water security. First, it is a challenge to specify and measure costs and benefits in practice. Second, multiple jurisdictions and institutions are responsible for managing water systems.

The challenge of what to include in cost and benefit functions

When evaluating how policies affect water security, policy makers and researchers need to be clear about which types of costs and benefits should be included in a net benefit maximization or which types of costs to include in a cost minimization. Whittington, Sadoff, and Allaire (2013) suggest including benefits derived from using water to support ecosystem services; energy production; municipal and industrial water activity; and agricultural production and costs that are associated with floods, droughts, and water-borne diseases. However, there may be disagreement about what should be included in the benefit and cost functions. For example, in the western United States, there is a multiplicity of uses and values as well as conflict over which should be deemed "beneficial" (Blomquist 2011).

Another challenge is that the researcher needs to determine the geographic boundary for the analysis. Because water is an input to many production processes, its consumption will often be affected by trade within and across countries (e.g., Debaere 2014). A country that is short on water may, for example, choose to import goods that are water intensive. Thus, the researcher will need to consider the importance of such trade flows when deciding whether to include them in the analysis.

A key issue in measuring the costs and benefits of water management policies is uncertainty. In principle, the net benefit maximization function could incorporate uncertainties, including probability distributions over the demand and supply characteristics of the water system. In practice, however, other approaches may be needed if, for instance, benefit or cost functions cannot be known with any degree of certainty, as in the case of the effect of climate change on water security.

If the benefit or cost function is not easily specified, an alternative is to measure inputs to the production of water security, such as the size and quality of investments in activities aimed at improving water management.[10] Still, to the extent that there is not a clear relationship between investment and results, it may be difficult to implement the economic framework for water security in practice.

The challenge of multiple institutions and jurisdictions

A second challenge that researchers need to address when measuring the potential impact of policies on water security is that water systems are often managed by multiple authorities with different responsibilities. In particular, the agencies and institutions that are responsible for constructing and managing water supply infrastructure are often not the same as those that are responsible for allocating the supplied water across competing uses and users. Moreover, institutions are often defined by political jurisdictions rather than water basins. For example, the Colorado, Murray-Darling, Orange-Senqu, and Yellow Rivers are all divided into national and/or subnational jurisdictions (Schlager and Blomquist 2008; Grafton et al. 2013).

Institutions for Water Security

Although it is now widely accepted that there is no silver bullet for addressing water security challenges, there are two clear implications of the preceding discussions. First, addressing

[10]For example, it may be possible to use a water security index that calculates the capacity of institutions and infrastructure to provide services that promote water security (Hall et al. 2014).

the multiple objectives associated with water security requires multiple policies and capable institutions (Damania 2020), as well as mechanisms for coordinating them (Meinzen-Dick 2014). Second, an analysis of "second-best" policy options will be needed because institutions and jurisdictions have different interests and property rights are always incomplete because of hydrological, social, and economic linkages (Blomquist 2011). In the rest of this section, we discuss how economists can better integrate institutions into their analysis of policies for enhancing water security.

Multiple Types of Water Institutions

Institutions are "the prescriptions that humans use to organize all forms of repetitive and structured interactions" (Ostrom 2005, 3), or the "rules of the game" (North 1991). Enhancing water security involves multiple types of interactions (e.g., allocating water, financing infrastructure, managing risks) and hence requires multiple types of institutional arrangements. Institutional arrangements are needed to (1) plan for, finance, operate, and recover the costs of capital investments in water supply infrastructure; (2) address the negative social and environmental externalities, including the resolution of conflicts across competing uses and objectives; and (3) allocate water supplies across competing uses, including monitoring and enforcement (Grafton 2017). Grey and Sadoff (2007, 550) illustrate the wide range of institutional arrangements required to enhance water security. They define water institutions "broadly to include organizations and capacity, as well as governance, policies, laws and regulations and incentives, addressing issues ranging from water allocation, quality, rights and pricing, to asset management and service delivery and their performance." Economists and other researchers have developed a large body of research on designing and reforming institutions that can not only strengthen institutional performance in terms of multiple criteria (efficiency, effectiveness, equity) but also address coordination problems associated with transboundary issues (Meinzen-Dick 2014; Villamayor-Tomás et al. 2019).

Designing Institutions to Enhance Water Security

Inadequate water supply infrastructure, intensifying competition for water, and growing water risks create several challenges for designing water institutions, including (1) assigning governance tasks at the right levels of decision-making (i.e., degree of centralization or decentralization); (2) distributing tasks between the private and public sector and across jurisdictions (i.e., degree of coordination); and (3) building capacity for monitoring, enforcement, and conflict resolution. Because of the externalities discussed earlier, fully decentralized responses to water security challenges can cause unintended and undesirable consequences, such as when farm-level water-use efficiency improvements reduce return flows that support downstream water users (Ward and Pulido-Velasquez 2008; Grafton et al. 2018). Some guidance for balancing decentralized decision-making with regional, national, or international coordination can be found in the principles of subsidiarity and nesting. Subsidiarity involves assigning or retaining governance decisions at the lowest institutional level that has the capacity and legitimacy to make them, while nesting involves coordination to address economies of scale or cross-border externalities (Marshall 2009).

A now-mature field of research has systematically assessed the conditions and design criteria associated with improved performance (whether in terms of efficiency, equity, or other criteria). Although universal principles and guidance have proven elusive, several studies (Ostrom 1993; Cox, Arnold, and Villamayor-Tomás 2010; Araral 2013; Ma'Mun, Loch, and Young 2020) have identified how institutions can be tailored to local conditions and the relevant externalities. For example, it has long been recognized that common pool resources like water require clear boundaries that define the resource and access to it (e.g., via limits on extraction). However, water security often includes objectives that cross boundaries, which raises questions about who should be involved in allocating and financing water. We next examine these institutional design issues in the context of property rights to water and transboundary coordination.

Property rights to water

Property rights to water and other natural resources are institutional arrangements that establish rights and duties or obligations (Meinzen-Dick 2014). Young (2014) identifies several principles to consider when designing rules associated with allocating water, including the need to (1) design water rights to have separate instruments for distinct objectives; (2) account for hydrological interdependencies between groundwater and surface water; (3) reduce the transaction costs of reallocation (including trading and other "second-best" means of reallocation); (4) assign risks to individuals (i.e., internalize the costs and benefits of their water use decisions); and (5) ensure the robustness of the water rights system over time. Implementing these principles has proven difficult in practice. In a review of the literature on water markets, Leonard, Costello, and Libecap (2019) identified two fundamental reasons for these difficulties: transaction costs and the distributional conflicts associated with establishing and exchanging property rights. In this context, Blomquist (2011) has argued that water rights need to be as multidimensional as the resources they govern, involving a "bundle" of rights that address issues of access, withdrawal, decision-making, management, and trading in relation to different types of water uses and conflicts between uses. Even in regions with private, tradable property rights, such as Australia or Chile, there are multiple layers of property rights in which individual access and withdrawal are conditioned by public regulation and/or collective decision-making rights governing how water is managed and reallocated (e.g., collective rights held by irrigation districts). Reliance on collective rights reflects an increasing awareness that group-level policies can address environmental challenges effectively (Kotchen and Segerson 2020) and can sometimes be more efficient than individual rights or complementary to them.

Polycentric water institutions

Neither decentralized solutions nor centralized regulation alone have proven to be sufficient to enhance water security across its many dimensions. With this issue in mind, Meinzen-Dick (2007) refers to the need for an institutional "tripod" that includes roles for governments, markets, and communities. These institutional arrangements are polycentric in nature, which means that there are multiple centres of decision-making (Ostrom, Tiebout, and Warren 1961; Ostrom 2010; Pahl-Wostl and Knieper 2014). Polycentric institutions vary in terms of their distribution of authority and rights and the coordination mechanisms in place. The potential for these institutions to function as a coherent system in the context of decisions about water infrastructure provision and allocation depends on there being informal and formal mechanisms to ensure transboundary and multilevel coordination (e.g., monitoring, financing, conflict resolution). River basin organizations and regional authorities have attempted play these coordination roles. The appropriate coordination mechanisms will depend, at least in part, on the benefits of coordination and the transaction costs of doing so (Feiock 2013). Informal institutions may be sufficient for addressing some coordination problems (such as joint monitoring and information sharing) related to the management of shared infrastructure or coordination of some water uses (Villamayor-Tomás et al. 2019).

Reforming Institutions

Values and preferences regarding water security objectives evolve over time, as do the institutional arrangements for defining property rights and coordinating across sectors and jurisdictions. Thus, although past policies and infrastructure investments may have addressed the priorities of their time, they may prove ill equipped to address changing objectives (Libecap 2011; Briscoe 2014). In particular, Saleth and Dinar (2004) find that water institutions may fail to keep pace with social, environmental, and economic changes as a result of powerful political interests and the transaction costs associated with institutional reform.[11] Indeed, stakeholders that benefited from past decisions may resist what would otherwise be viewed as beneficial changes . When short-term responses constrain future changes, there is a loss of option value because of decreased flexibility to shift course (Marshall 2013).

The effective design of institutional responses to water security challenges requires an explicit focus on sequencing, such as improving the allocative and productive efficiency of existing water supplies *before* pursuing new supply options (Gleick 2018). This suggests that the first step in reforming institutions to respond to water security challenges should be to make adjustments that work within the prevailing governance structures and institutional environment (McCann and Easter 2004). Path dependency will bias responses toward incremental measures, such as improving the operation of existing water supply infrastructure and working within the existing framework of rules and incentives to allocate water across competing demands and mitigate water risks. Short-term responses to water security challenges may also involve development of small-scale supplies (e.g., groundwater pumping), information campaigns to spur voluntary water conservation, or reallocation of water rights within the existing regulatory framework. For example, short-term responses to drought and flood risks may rely on decentralized adaptation through measures such as crop-switching by farms, supply chain management by firms, and rainwater harvesting by households.

Longer-term responses and more significant systemic changes will face larger-scale collective action challenges (and higher transaction costs). More comprehensive institutional reforms to water rights, such as capping water extractions, will also involve distributional conflicts and require political coalitions to address vested interests (Garrick et al. 2017; Garrick,

[11]In addition, path dependency—the idea that past decisions and technologies constrain future options—means that decisions made today will limit future adjustments.

Hanemann, and Hepburn 2020; but see also Zetland 2013). Insights about governing common pool resources at local levels have offered limited guidance for larger systems; however, some institutional design principles may apply, such as the importance of participation by affected stakeholders or jurisdictions, beneficiary payments for public goods, joint monitoring by trusted entities, and a range of informal and formal conflict resolution venues to deal with the negative externalities of water extraction or pollution (Cox, Arnold, and Villamayor-Tomás 2010). The application of these principles will depend on local and regional conditions, underscoring the importance of informal institutions when political systems are weak and the capacity of formal institutions is limited (Wutich, Beresford, and Carvajal 2016).

Priorities for Future Research

We believe that economics can play an important role in informing the water security debate and helping to meet water security challenges and that this will require that economic modeling and institutional analysis go hand in hand. With this in mind, we conclude with a discussion of priorities for future research.

First, the issue of how to define water security requires more attention. Economists can help provide some clarity by developing models that illustrate the costs and benefits of using different definitions of water security, thereby identifying the potential gains from treating water management in a more integrated manner and identifying when the multiobjective problem can be simplified. Such modeling could also provide insights into the distribution of the costs and benefits of policies across sectors and populations.

Second, economists should continue to conduct research on the effectiveness of different institutions for managing water security issues. In the short term, it may be difficult to change institutions or infrastructure. Thus, economists may decide to model the limited range of supply and demand options available to policy makers, say, in a drought. This means that the current institutional structure may not allow for certain more efficient solutions, such as efficient pricing or quantity instruments. This research could also consider options for improving the design of "noneconomic" instruments (e.g., traditional standards, information) for promoting water security. In the longer term, a more sustained program of research on institutional design is needed to compare policy options for reforming water rights systems and strengthening transboundary coordination (Villamayor-Tomás et al. 2019).

Third, we suggest that economists work with policy makers to design field experiments to identify key determinants of the costs and benefits of improving aspects of water security. Examples might include estimating demand elasticity, estimating the elasticity for adopting particular technologies (such as drought-resistant crops), and identifying behavioral biases in consumption and investment decisions. Behavioral economics could also play a role in improving our understanding of farmers' responses to various policy measures, such as reducing fertilizer use, and consumer responses to water conservation measures (e.g., Ferraro and Price 2013; Brent, Cook, and Olsen 2015).

Fourth, greater attention to second-best solutions is needed, as are frameworks and indicators to assess the performance of water institutions in allocating water, investing in water infrastructure, and addressing risks. Institutional analysis can guide the design and evaluation of policy responses (e.g., water rights reforms, collective choice processes) in the context of path dependencies and the associated economic, cultural, and environmental conditions.

Fifth, economists can help inform the debate about water security by ensuring that integrated water modeling includes both infrastructure and institutions, along with the latest approaches to modeling hydrology and ecosystems (e.g., Khan, Morsuch, and Brown 2017).[12] A key challenge is quantifying the gains from changing institutions or institutional structures. Examples of such efforts include estimating models of water markets (Erfani, Binions, and Harou 2014) and modeling the relationships among various dimensions of water security, such as the relationship between trade and water security. These modeling efforts also need to be combined with assessments of the political realities and technical constraints that might impede otherwise beneficial institutional changes.

Such modeling and specifications have four benefits. First, they highlight potential efficiency gains, especially those that may arise because of the interrelationships among various aspects of the water security problem. Second, they highlight the gains from better information (Raiffa 1982). Third, they highlight where important institutional changes could yield substantial benefits and where the existing institutional structure performs well. Finally, they provide insights about potential winners and losers from changes in water management policy.

Finally, there is an urgent need to learn more about how policy instruments can affect water security when water systems are stressed, such as during a drought. Unfortunately, politicians tend to respond to droughts with programs whose effectiveness is rarely measured. For example, economic losses for agriculture resulting from the drought in California were nearly $4 billion between 2014 and 2016 (Lund et al. 2018); however, the economic effectiveness of the various policy responses and their long-term implications are only beginning to be understood. The rapidly growing cities across the Global South face similar challenges of supply shocks in the context of rapidly growing demand and more limited infrastructure and institutional capacity. In such cases, the response to water system stresses cannot be separated from systemic issues related to development policy and planning.[13]

Water security challenges are likely to continue and become more serious in the future because of persistent gaps in access and the impacts of climate variability and change. Thus, it is important to develop analytical tools that will help address these issues more effectively. We hope that the discussions and economic framework presented here will contribute to the development of such tools and to the more effective resolution of water security challenges.

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[12]There is a growing trend toward optimization and a vast literature on hydroeconomic modeling to support decision-makers (Harou et al. 2009; Jaeger et al. 2017).

[13]See, for example, the Melamchi Water Supply Project serving Kathmandu (Gurung et al. 2017).

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