A dynamic framework for water security

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Abstract

Water security is a multi-faceted problem, going beyond mere balancing of supply and demand. Early attempts to quantify water security relied on static index based approaches that failed to acknowledge that human action is intrinsic to the water cycle.

Human adaptation to environmental change and increasing spatial specialization in the modern world necessitate a more flexible and dynamic view of water security.

Starting from first principles, and through application of simple water balance concepts to human-impacted water systems, we first develop a set of indicators for water insecurity. We then offer an approach to model these indicators as outcomes of coupled human-water systems to anticipate watershed trajectories under human impacts, predict water insecurity and inform appropriate action. In this way, far from being a static index, water security signifies a “safe operating subspace” within a three dimensional space that maps physical resource availability, infrastructure and economic choices.

1. Defining water security

Water security poses one of the biggest challenges of the 21st century. As populations grow, humanity faces the prospect of uncertain future water supplies both due to climate change and increasing demands on water [52]. On the one hand, too many people still do not have access to water to meet basic hygiene and livelihood needs. On the other hand, as human demands for water increase and ecosystem services become more valued, there is increasing competition for scarce water resources; not only between humans and the environment, but also between different sectors of the economy and different sections of society [24]. The concept of water security has arisen in response to this multi-faceted nature of the global water crisis.

The core idea underpinning water security is the need to balance human and environmental water needs. Indeed, the United Nations Sustainable Development Goals for water (SDG6) explicitly sets targets for each. The problem is that there is no single working definition of water security; there are many [9] and the framings veer between “broad” versus “narrow” and “academic” versus “applied” [2].

This makes the field of water security an evolving one. The launch of a new journal on Water Security is timely and presents an opportunity to reflect on how water security might be better quantified and measured. Moreover, no matter which definition we pick, at the core of the endeavor is a simple question. What makes some places (by whatever definition) “water secure”, while others suffer from water insecurity? Is it environmental determinism; some places are hydrologically well endowed while others are not? Is it cultural choices; some cultures have learnt to use the available water resources wisely? Is it economic choices; some economies are dependent on ecotourism and therefore on a pristine environment, while others are agricultural “breadbaskets” and are therefore inherently more water intensive? Is it infrastructure; some places have engineered their way out of scarcity, while others have not? Or is it governance; some places are able to enforce controls on abstractions, whereas the absence of enforceable limits, or inability to enforce them, causes other regions to overexploit water resources?

We briefly review the literature on water security with a view to understanding the framing of the problem. We then present an approach to water security that can address the multi-faceted nature of the challenge. In particular, we make the case that water security is a dynamic concept and must be defined, measured and understood as such. The review of water security presented here has many parallels with a companion review paper in this inaugural issue of the Water Security journal that similarly proposes a dynamic framework for the analysis and prediction of flood risk [3].
2. Water security as an index, a snapshot at a place and point in time

The conventional approach to water security as conceptualized and implemented by international agencies (e.g., United Nationals Development Program, UNDP; Global Water Partnership, GWP) is to set standards on how much water needs to be available to meet health, livelihood and ecosystem needs, come up with appropriate indices, and then track progress against them. This approach builds on a long history of developing indices to track imbalances between supply and demand. While the term “water security” itself has gained prominence only recently, the concept of measuring and quantifying risks/vulnerability/stress in water resources has been around for a long time. Early definitions of water security were human-centric. Several excellent reviews on measures and indices for water already exist [5,7,31].

The Falkenmark water stress index, defined as the per capita annual renewable freshwater available, was an early attempt to understand the relationship between human needs and environmental constraints; regions with less than 1000 m³ per capita per year were defined as “water scarce” [12]. The Falkenmark Index captured hydrological constraints on water supply but demand was based on what humans need rather than what they actually withdraw. Another index called the Water Resources Vulnerability Index, defined as the ratio of total annual withdrawals to available water resources, accounted for withdrawals. A country is considered severely water scarce if the ratio of withdrawals to available water exceeds 40% [31].

The above approaches were criticized for only accounting for “physical water scarcity”; for example, they did not account for inadequacies in water infrastructure. By these measures, a country in sub-Saharan Africa, which is entirely populated by rain-fed cultivators and herders with renewable water resources above 1700 m³ per capita per year (in the form of green water) would not be considered water insecure, even if, due to the absence of any water infrastructure, the population barely had access to 30 L (of blue water) per capita per day. Indeed, typically in the world’s poorest countries, due to lack of infrastructure, populations are at risk because they have very little access and control over water.

To account for the key role of infrastructure, International Water Management Institute (IWMI) introduced the concept of “economic water scarcity” to identify countries, where less than 25% of water from rivers was withdrawn for human purposes, and where significant improvements in water infrastructure are needed to meet human needs [36]. The “Water Poverty index [45] is another similar attempt to account for the role of infrastructure.

In most of these early indices, the emphasis was on development of water resources to meet human needs. As it became clear that indiscriminate development was destroying critical ecosystem services and biodiversity, the need to account for ecosystems, and hence a new definition of water security, emerged. One popular definition by the Global Water Partnership defines water security as follows: “Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced” [17].

Operationalizing this definition necessitates a departure from the conventional maps of “place based indices” because the impacts of human water uses on the environment are often displaced in space and time. Frequently, it is dams or cities upstream that cause the drying of wetlands or pollution downstream. A seminal paper on water security by Vörösmarty et al. [51] addressed this challenge. The study used river networks to redistribute human and ecological stressors from headwaters to the ocean, exploiting the spatial connectedness of river systems across the world [51]. The results showed how rising ambient loads during early-to-middle stages of economic growth were followed by environmental controls and decreased threats to ecosystems as societies became wealthy.

Despite the increasingly nuanced handling of human and environmental water needs many definitions and attempts at quantification have been inadequate in several ways. First, most of these indices focus on specific spatial scales and largely ignore cross-scale feedbacks across people, groundwater and surface water. Researchers and practitioners work at different scales ranging from the household to community to basin to nation. Because water is a mobile, common pool resource, achieving water security at one scale may jeopardize water security at a different scale. A sizeable body of literature provides evidence for these cross-scale feedbacks and trade-offs. One study of urban water resilience in Chennai [44] showed that as urban households invested in wells, they became individually more water secure in the short-term; but the region as a whole became less resilient and more water insecure in the medium to long term. The irrigation-efficiency paradox is another example [30,35,38,49]. Investments in drip irrigation improve incomes and allow farmers to expand irrigation at the farm scale, but often make the whole less resilient. Similarly, many communities in India and Africa have constructed soil and water conservation structures to boost artificial recharge. While these have been demonstrated to improve agricultural productivity and incomes locally, they have been shown to reduce flows into downstream reservoirs/lakes during dry years, thus making communities downstream more water insecure [16].

Second, traditional approaches to quantification of water security fail to account for the increasing spatial specialization in the modern world: what humans consume and what they produce are increasingly unrelated. A one-size fits all approach does not work any longer. Most previous definitions of water security were based on an implicit but flawed assumption that populations everywhere depend on local water resources to satisfy their needs for food, energy and other goods and services. But in the modern world, most humans do not depend on local resources. The very idea that every watershed or political unit should have a certain water availability per capita is anachronistic, but still seems to persist in the literature. Previous approaches were also fundamentally flawed in attributing the entire water footprint of the population to the watershed or basin in which they resided. In reality, most water intensive crops such as rice and sugarcane are grown in a handful of canal command areas.

Production and consumption regions are geographically distinct [19,22]. People living in urban, industrialized watersheds or tourist destinations satisfy most of their material needs from sources external to the watershed. i.e., by importing food from elsewhere. On the one hand, virtual water transfers offset deficits in locally available water resources [1]: on the other, they allow people in different regions to live healthy, productive lives with very different endowments of water. So how do we define, measure, compare and track water security in places with diverse economies? Different regions and different groups within those regions have dramatically different needs and priorities for water. Moreover, water is only one factor of production and rarely the primary determinant of economic activity. The latter is driven by a range of factors such as the comparative advantage of land, labor, energy, government policy or simple accidents of history [50]. And while the availability of water may or may not constrain economic activity, the nature of economic activity certainly influences how much water is abstracted and how much is left to the environment.
Third, most indices are snapshots in time; they have no sense of history and offer no predictive insight. Typically, the goal of developing water security indices at a global scale has been to identify which regions need intervention but not what those interventions should be. The “so what” question remains the biggest problem with most global assessments of water security. Once we know that a place is water insecure, how do we go about addressing it? The view of water security as a static snapshot of system state at a particular place and time has been long critiqued by scholars, who argue that it does not capture the complexity of real-world systems and the different types of water use [34]. Moreover, it does not acknowledge that human action is intrinsic to the water cycle [52]. Social, institutional, engineering and economic infrastructure cannot simply be overlaid on natural processes to evaluate water availability for human uses; rather they are a major driver of change in water resources systems [23]. The cross-dependencies or coupling between human and natural systems often leads to “emergent” patterns of form, function, and dynamics, sometimes resulting in surprises that could not have been predicted from the knowledge of the behavior of individual elements [23].

The GWP definition [17] may seem inadequate to some political scientists who interpret water security differently, emphasizing the “securitization” dimension [9]. The definition also misses distributional aspects; one group’s water security may be achieved at the cost of another’s. It is impossible to identify one approach that would encompass all meanings attributed to water security. We argue, however, that the definition is nonetheless useful and despite limitations, the dynamic approach proposed in this paper can address the critiques discussed above.

3. Water security as an outcome of a coupled human-water system

To address critiques of static indices and account for both the interconnectedness between human and water systems and the vast number of pathways by which these systems co-evolve, we suggest framing water security as an outcome of a coupled human-water systems. We present this dynamic approach to water security presented in three steps. In Section 3.1, we present a set of indicators that relate human water use to water availability. In Section 3.2, we present how these indicators map to different types of water insecurity. Finally, in Section 3.3, we present a set of causal factors that drive both human water use and water availability, so that these indicators can be modeled in the context of coupled human-water systems.

3.1. Water utilization patterns as outcomes of coupled human-water systems

We first need to understand how humans use water and how this relates to what is available. It is surprisingly difficult to initiate a discussion on “water use” because the different literatures we cite here employ the exact same terms in completely different, even contradictory ways. So first some clarification of terms is necessary.

In the traditional water resources literature, water use is a generic term that can refer to either “consumptive” and “withdrawal” uses [15]. Consumptive water uses refer to uses that remove water resources from the system i.e., the water is no longer locally available (e.g., irrigation of crops and evaporation from industrial cooling are largely consumptive). “Withdrawals” refer to the water abstracted from a water body such as a dam or river, but a large fraction may be returned to that system as return flows (e.g., hydropower plants have high withdrawals, but most of the water is returned back). Traditionally, water use has been assumed to refer to blue water only, i.e., water that is abstracted from aquifers and streams [13].

Because water security is concerned with how humans meet their needs and how much water is left in a watershed for natural ecosystems, we need to broaden the definition of water use to include green and grey water use [34]. To do this, we have adopted terms from the water footprint literature. The “Consumption Water Footprint” (CW) refers to the volume of water embodied in the goods and services consumed by people living in a region [26]. The goods and services consumed may be made or grown locally or imported from outside the region. In contrast, the “Production Water Footprint” (PW) refers to the volume of water used to produce goods and services (both material and aesthetic) by people within the region [26]; the commodities produced may be consumed locally or exported out of the watershed. Both terms include blue, green and grey water use minus any return flows [13].

In our framework, all available physical water is partitioned into direct and indirect human benefits (Fig. 1). The total physical water available in a watershed is precipitation plus any imports from outside the watershed. All physical water entering the watershed must end up somewhere. It may flow out as surface flow (Q). It may be used in agriculture for the production of food, fiber, fodder or fuel (A). It may also be used for non-agricultural purposes such as urban lawns or swimming pools or thermal power plants or industries (U). The sum of A and U is the Production Water Footprint (PW) for the watershed. Additionally, water may be lost through ET occurring via natural green spaces (N), which provide indirect cultural, regulating or provisioning services. Because we want to link water security to water governance, in this paper, the partitioning of uses into A, U or N is based on the how the water is sourced and managed. Thus, evapotranspiration from an urban garden that is irrigated using piped utility water is “U”, while evapotranspiration from an irrigated corn crop is “A”. ET from an irrigated urban park is “U”, while ET from a wooded stretch in a city that’s not actively managed natural is “N”.

In pre-historic times, all of the available annual renewable water resource ended up as discharge or evapotranspiration via natural vegetation; very little was captured by humans. As societies developed and became interconnected, production and consumption become increasingly disconnected. Thus, while PW and CW coincide in primitive societies, they tend to diverge in modern societies.

Fig. 1-i represents a water utilization pattern in a hypothetical hunter-gatherer community. In such a landscape, humans do not alter watershed processes much and human water footprints tend to be very small. As societies clear forests and transition to settled agriculture, a small portion of the rainfall endowment gets allocated to rain-fed agriculture. Subsistence agriculture communities are on average just able to meet their own needs. So their water footprint equals the water used to produce goods and services in the watershed (Fig. 1-ii). While the populations living in these regions have sufficient food and water in average rainfall years, during drought years, because they are dependent on local resources, consumption would have to drop sharply, leading to famine.

As societies invest a portion of their wealth in infrastructure, they are able to “capture” a larger and larger fraction of rainfall and also import water. People increase both their production and consumption water footprints and become food self-sufficient (Fig. 1-iii). If infrastructure expansion continues, they may eventually begin to generate food surpluses. At this point, PW will begin to exceed CW. If the community continues to invest in infrastructure so that more and more of the rainfall endowment is allocated to production, then stream flows to the ocean will decline to such levels that wetlands and other aquatic ecosystems could be significantly impacted (Fig. 1-iv). This may also occur through
groundwater development. Indiscriminate well drilling and the absence of controls over groundwater extraction (by either licensing or pricing) allows farmers to increase water use beyond the annual renewable resource by depleting groundwater (Fig. 1-v).

If the CW for the watershed is far greater than the PW, it implies that the watershed is a net importer of virtual water. Physical water imports, I, allow a watershed to increase the “rainfall-pie.” I can be comprised of natural water inflows from upstream watersheds or infrastructural transfers [22].

The three right most bars (Fig. 1-vi to -viii) represent patterns that may be observed in developed economies with complete spatial specialization of economic activity. For instance, Fig. 1-vi depicts an urban watershed, where piped water is imported into a primarily urban watershed.

In Fig. 1, we have implicitly assumed the spatial unit to be a watershed only because it is easy to compute a water balance at the scale of a watershed. However, there is no inherent reason why the figure could not be applied to political units; it would merely be harder to calculate the physical inflows and outflows across system boundaries. Moreover, Fig. 1 is scale independent because the axes are ratios. Overall, we would expect smaller watersheds to be more homogeneous (all urban or all agricultural), while large river basins would have a mix of all water use types.

Boundary issues, however, do challenge our conception of water security, due to the additional challenge of the need to understand both local and non-local sources of water. To really understand water security, we would need to define the system boundary as the spatial domain of all local and non-local water receipts. For example, recent research examined local and non-local water resources dependencies for Flagstaff, Arizona in the United States [33] and the United Kingdom [18]. However, it is not clear how the quantification of water security would change if a larger or smaller urban area or watershed were to be considered. In fact, different spatial units (i.e., watershed, county, city, country, etc.) would lead to different understandings of water security, since not only do local water resources change with each spatial resolution, but so does reliance on virtual water imports. An important area of future research is to evaluate the spatial scaling properties of water security. We leave this for future work.

3.2. Linking water utilization patterns to a typology of water insecurity

The different water utilization patterns in Fig. 1 result in different types of water insecurity. For instance, in Fig. 1-ii, the main problem is sufficiency; users do not have access to sufficient quantities of (safe, affordable) water to live a healthy, productive life. In Fig. 1-iv, the problem is often that over-allocation of resources makes the system vulnerable to drought. Since a large fraction of the water is allocated to productive water uses, there will inevitably be conflict between human and ecosystem needs during drought years. In Fig. 1-v, the problem is long-term unsustainability, because the productive water uses exceed what is available. Depletion of groundwater means that future generations will not be as well off as the current one.

Thus a composite view of water insecurity requires us to consider all the three components presented in Fig. 1: water resource utilization (the red box), human demand or consumption (the grey dotted line) and human development (the gradient from left to right).

a) The fraction of the available resource is being utilized or the water resources utilization intensity [14,45]. Water used by humans to produce food and other goods and services (PW) as a fraction of available water resources (P + I). Again both PW and P + I are expressed in volumetric terms so that the ratio PW/(P + I) has no unit. The ratio represents the fraction of the available water resources endowment that is being utilized by humans, i.e., it captures the resource con-

Fig. 1. Apportionment of available physical water resources across humans and nature. P is precipitation, I refers to physical water entering the watershed from outside either naturally or via infrastructure. A refers to water use in agriculture, U refers to water use for non-agriculture uses, Q is flow out of the basin, and N is water used by natural ecosystems. Production Water Footprint (PW), shown as the red box, is the total water abstracted from the watershed for purposes directly beneficial to humans, while Consumption Water Footprint (CW) use, shown as a grey dotted line, refers to the total water embodied in products consumed by people living in the watershed. (i): Hunter-Gatherers, (ii): Subsistence Agriculture, (iii): Self-sufficiency, (iv): Ecological Destruction, (v): Groundwater Depletion, (vi): A large city with inter-basin imports, (vii) Agricultural Breadbasket, (viii): Tourism dependent economy like a national park. Note: the left-most bar represents the main inputs to the system consisting of precipitation and imports.
strait. As $PW/(P+I)$ creeps closer to 1, the amount of water left for nature, both evapotranspiration through natural vegetation or ecological flows, decreases. It is even possible for $PW$ to exceed $P+I$ in cases of severe groundwater depletion.

b) The capacity of populations to invest in technology to store, distribute and access the water or purchase food and other commodities on the global market. Places may either invest in their own infrastructure or may obtain a higher fraction of their agricultural water requirements from external sources, an implicit “infrastructure sharing” across borders [21]. We use GDP/capita as a proxy to capture this ability of societies to invest in “trade and technology” denoted as $TT$.

c) Spatial heterogeneity in production and consumption is captured by the ratio of the production water (PW) and their consumption water (CW) footprints. This ratio is inspired by the internal and external water concept proposed by Hoekstra and Mekonnen [19]. However, we suggest a ratio (rather than the difference in [19]) to make it scale independent. Both PW and CW are expressed in volumetric terms so that the ratio has no unit. We would expect this ratio, $PW/CW$, to be very different depending on the predominant economic activities in the region. In an agricultural or water-intensive industrial belt, $PW/CW \gg 1$, whereas in an urban area with mostly service sector jobs, we would expect $PW/CW \ll 1$.

When these three variables are plotted against each other (Fig. 2), we can map out certain spaces (the blue hashed areas) as water insecure; if a watershed has too high a CW but does not produce enough and has too little money to pay for water infrastructure or buy food on grain markets, it is likely to be water insecure. A community living in a watershed may allocate physical water stress defined as $PW/(P+I)$, by decreasing human abstraction of water or increasing imported water $I$. As societies become wealthier ($TT$ increases), they initially increase human water abstraction and environmental protection [42].

Increasingly, coupled human-water systems models are beginning to use agent-based models to simulate two-way feedbacks between the human and water components of systems. Such models may be able to capture the relationships between governance systems, agent behavior, and resource availability to predict water insecurity. The challenge is that, typically, models hold agent motivations and the governance or operational rules constant over the modeling period. Although a few models have begun to allow rules to change endogenously [40] these still seem to be operational level changes rather than fundamental constitutional changes. In the short to medium term, this is a very reasonable assumption. But what if the socio-political system itself and the corresponding set of operational and constitutional rules themselves change over longer time frames? Models maybe able to predict historical water insecurity, but not how watersheds become less water insecure over time. This requires a more flexible modeling approach.

3.3. Developing a causal framework to model water insecurity

The idea of a new framework that includes these multiple facets to understand water security is itself not novel. Indeed, several authors have compared them [29] or combined them to develop a composite index [45]. The main contribution we offer in this paper is a dynamic view of water security. Once we understand what drives societies to utilize water resources in a particular way, we can model and anticipate their occurrence. The goal in this paper is not yet another index of water security that is based on published data, but rather coupled human-water systems models that can generate the indices and trajectories as emergent outcomes.

But how can we ensure that the models can throw out indicators of water insecurity?

Fortunately, previous empirical meta-analyses have found that patterns observed in real world case studies could be explained by just four sets of factors [29,42]:

(i) Culture/Economy: What societies need water for.

(ii) Resource: How much water is available; i.e., the environmental constraint.

(iii) Wealth: Whether the society has the capacity to invest in technology or buy goods (with virtual water embedded).

(iv) Governance: Whether there are rules to decide who is allowed to take out how much water, for what purpose.

For instance, long-term decline in groundwater levels has been associated with the presence of a productive aquifer, increasing demand for human needs, ineffective controls over water use and the absence of reallocation mechanisms. In developed countries an increasingly environmentally conscious population is motivated to meet increasing demand for water in urban areas by decreases in water use by agriculture (by either land fallowing or a switch to less water-intensive crops). In general, this outcome is observed in regions where there are effective controls over both water abstraction and environmental protection [42].

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![Fig. 2. Mapping resource utilization patterns to water insecurity. A given watershed may follow one of several paths in the 3-D space defined by the three axes. The red lines marked a and b present two hypothetical trajectories a watershed may follow over time. The blue hashed sub-spaces denote water insecure sub-spaces. CW and PW are the consumption and production water footprints respectively, and TT is investment in “trade and technology.”](image-url)
4. Water security as predicted by regime shifts

In recent years, there has been increasing recognition that effective management of water over long periods of time requires an understanding of the coevolving dynamics and feedbacks inherent in coupled human-water systems [39,28,46,37]. Place-based “socio-hydrology” studies have begun to study and characterize the workings of coupled systems over long time frames [20,48,25,41,10,8].

Many case studies from the across the world have identified “regime shifts” arising as a direct result of anthropogenic influences [39,11]. A common theme in these studies is that human responses are highly nonlinear. People move, lifestyles change, and values and norms change. Societies respond to the issues/concerns of the day by building infrastructure and trade, constrained by the legacy effects of their previous decisions.

To understand the concept of regime shift, we need to synthesize data from many watersheds across the globe. If we plot the trajectories of these watersheds over time, we should begin to see some common transitions. Watersheds should follow predictable water resource evolution pathways. They should diverge when there are differences in macro-economic, governance or infrastructure decisions.

In order to chart common trajectories, we present a framework inspired by the Budyko curve [6], which has revolutionized catchment hydrology. It provided a unifying framework for a field that had previously been fragmented and empirical. However, the framework is only applicable to relatively pristine catchments and there has been no comparable framework for human dominated socio-hydrologic systems. Where the Budyko curve encapsulated the climate (precipitation and radiation) controls on annual water balance of catchments, we present a framework that encapsulates controls on human water security (Fig. 3).

Fig. 3 hypothesizes possible pathways that watersheds may follow with regime shifts. It uses the same axes as Fig. 2 but the GDP/capita (TT) is not displayed for ease of visualization. Instead, increasing wealth is shown with increasingly darker colors. In Fig. 3, primitive societies would lie more or less along the PW = CW line; i.e., all production and consumption is local. As societies become wealthier, their economies specialize; some become virtual water consumers or importers and others become exporters. If they over-invest in infrastructure then agricultural or industrial production could go up, but this would occur at the cost of the environment.

Regime shifts occur because of changes in the cultural and political context of a watershed. In the context of socio-political changes, several factors determining regime shift have been identified, such as community sensitivity, memory of disasters, social cohesion and technology. For instance, Elshafei et al. [10] characterize and define “community sensitivity” to protecting the environment, which fluctuated as the environment or livelihood varied, and prompted community action (through a behavioral response variable); van Emmerik et al. [48] estimated “environmental awareness” as a cumulative measure that reflected community sentiment in the Murrumbidgee Basin in Australia as the environment degraded and prompted community action to restore the environment. Similarly, a study of the Kissimmee River Basin in Florida indicated that flood intensity decreased after channelization, which

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**Fig. 3.** Mapping regime shifts in socio-hydrologic systems. The axes represent two of the causal drivers of water security: Culture/Economy and Resource. The arrows represent the other factors: Technology and Governance.
reduced concerns about flooding [8]. But channelization led to a decrease in wetland storage; as people became concerned about ecosystem declines, priorities switched back from favoring flood protection to favoring wetland conservation. Subsequently, management strategies too followed suit. In other words, we need to understand what drives societies to shift regimes in the long term.

5. Way forward: Towards a dynamic framework for water security

The perspectives on water security presented in previous sections capture the tension between uniformity and simplicity in choosing quantitative descriptions of water security on one hand and differentiation over space and time and complexity on the other. But in reality they merely capture coupled human-water system dynamics at different time-scales (Fig. 4).

Water security as a snapshot at a particular place and point in time has the advantage of being simple and easily scalable, but does not really consider feedbacks between human and water systems and does not help inform action. A snapshot in time does not have any predictive or explanatory power and merely provides a representation of the system state over a short period for time (say 1–5 years) over which agencies and governments manage the system.

Water security as an outcome of coupled human-natural system models accounts for human adaptability to external drivers. Under these circumstances, models can indicate how the coupled human-water system might evolve for a given governance, culture and infrastructure. For example, agent-based models that hold human values, norms and beliefs as fixed, coupled with hydrological models, can be used to make predictions about water security in the medium term (say 5–25 years), the typical planning horizon for water agencies.

Over much longer time horizons, the system might undergo regime shifts, which will require changes to model structure and governing equations of the coupled human-water system with societal changes in governance and culture. A society’s values, norms and beliefs themselves may evolve over time and these in turn may prompt changes in policy, governance and infrastructure so that, over time, the society might switch to an entirely different trajectory. Such regime shifts cannot obviously be predicted in the conventional sense that hydrologists do predictions, but anticipating these regime shifts can improve predictive insight [43]. These in turn can form the basis of citizen engagement over much longer time frames (say 25–100 years), at which large-scale infrastructure is planned.

6. Implementation of the dynamic framework for water security

The discussion so far has provided the theoretical underpinnings to defining, classifying, measuring and predicting water security. In this Section, we address implementation of these ideas towards achieving the UN Sustainable Developing Goal (SDG) targets. The UN SDG 6, which deals with water aims to simultaneously “achieve universal and equitable access to safe and affordable drinking water for all”, “ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity”, “implement integrated water resources management at all levels” and “protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes” [47].

Unlike the Millennium Development Goals, which focused on access to water and sanitation infrastructure, the SDGs are broad in their scope. Operationalizing these goals is likely to be challenging because we have to make trade-offs. Ensuring access for humans will inevitably have some impact on water-related ecosystems, and therefore we need a framework that can evaluate these trade-offs. Implementing the SDGs will entail measuring, tracking and funding goals for which we neither have clear metrics nor actionable guidelines. An additional source of complexity arises in that we do not live in a world with a single, omnipotent decision-maker.

Humans are constantly evolving and adapting in response to environmental changes and the cumulative action of the adaptive actions of millions of humans can completely alter the course of water resources systems. In its previous incarnation, Integrated Water Resources Management (IWRM) largely relied on physically-based models of the water resources system in which only parameters such as population and infrastructure were allowed to change over time. These models were very poorly equipped to address adaptive actions by people. As a result, seemingly obvious solutions had unintended consequences, e.g., the drip irrigation and virtual water paradoxes in Sivapalan et al. [38]. Moreover, IWRM implementations were stymied by the lack of a clear actionable framework [4,27], in part because the models artificially constrained human behavior to what could be modeled.

Any action towards delivering on the SDG 6goals must address the fundamental weaknesses of previous implementations of IWRM. In this paper, we suggest that SDG 6 goals essentially encompass all aspects of water security. We offer a framework to define, classify, quantify and model water security over different time-scales. There are multiple ways in which societies may be water insecure. Therefore, water security cannot be quantified by a single index. Rather water security should really be seen as a “safe operating subspace” [32] within a three dimensional space mapping physical resource availability, infrastructure and economic choices. Coupled human-water system models can then be used to anticipate future watershed trajectories, predict water insecurity and inform appropriate action.

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References

