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On Developing a Sustainable Solution Space to Resolve Water Crisis in Arid Environments

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Abstract: This paper examines different meanings of water crisis and their implications to understand, explain and sustainably manage conflicting water needs and demands for arid environments. It proposesa Sustainability Solutions Space (SSS) for decision making by providing a framework that requires the convergence of principles and pragmatism. It emphasizes the rigor of scientific rationality while bounded by pluralistic and interpretive notions of societal impact. Such a framework can provide a consistent set of SSS targets considering multifacetednature of interactions among different sustainability indicators. The proposed strategydoes not pre-define but identify scenarios and solutions that are informed by the context and lie within a SSS. Such a framework acknowledges that the complexity of water conflicts is neither generalizable nor specifiable. Contingent resolution through adaptive learning is the approach needed to address such problems. Identification and operationalization of the SSS is an iterative and negotiated process. It shows how the use of SSS is different than conventional planning and management and provides an illustrative example of identifying SSS using historical data and climate change scenarios from Saudi Arabia.

Key words: Complexity · Water Conflicts · Sustainability · Principled Pragmatism · Water Diplomacy

INTRODUCTION

Many Faces of Water Crisis: In any conversation of a water crisis, termslike "waterstress", "water scarcity", "wateraccess", and"waterrisk" are used often interchangeably. This makes it hard to diagnose the exact problem and determine the appropriate response. For example, climate change projections from a range of climate models suggest that almost half of the world's population will be livingin areas of high water stress by 2030 [1, 2]. Water stress is now extreme in Africa and the Middle East, with the most adversely affected areas in the arid regions of the Gulf [3].

Beyond their sometimes confusingterminology, water crisis warnings prompt questions regarding access, availability and allocation of water in the arid regions: Howmuch freshwater is available? How is water availability likelytochangein this region? How certain are scientists about their projections? What can science tell decision makersaboutthepoliciesthey should enact to minimize the adverse effects changing climate in the arid regions? Morepointedly, cansciencehelp to sustainably manage water in the arid region?.

One of the most commonly used measures of water scarcity is the "Falkenmark indicator" or "water stress index" [4]. This index defines water scarcity in terms of the total renewable freshwater that is available for each person each year. If the amount of renewable water in a country is below 1, 700 m^3 per person per year, that country is said to be experiencing water stress; below 1, 000 m^3 it is said to be experiencing water scarcity; and below 500 m^3, absolute water scarcity. *Water stress* occurswhen annual renewable freshwater resources drop below 1, 700 cubic meters per person. To get an idea of the size of that volume of water, 1, 700 cubic meters is enough to fill a swimming pool which is 50 meterslong and 25 meters wideto a depth of 1.36 meters. That may seem like a huge volume at first, until one considers that this figure contains much more than the basic need to sustain one person for an entire year: the 50 liters per day required for drinking, preparing food, adequate bathing and sanitation. These basic, day-to-day immediate water needsadd up to just a little more than 1 percent (18.25 cubic meters) of all that is needed form odernlife. Muchmorewaterisconsumed by other processes and sectors including agriculture, industry and ecosystems.

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If annual renewable water supply drops below 1, 000 cubic meters perpersonannually (equivalentto2, 740 litersper day roughly725gallons), then *waterscarcity* occurs [5]. Water access, on the other hand, as defined by the World Health Organization [6], requires that 20 liters of water per person per day be available from a source within one kilometer of where it is needed for essential survival: the minimum amount required for drinking, cooking and minimalpersonalhygiene.Meanwhile, *water risk* refers to the probability and related consequences of a water-related disaster occurring, such asdrought, flood, pipelinefailure, contamination, or similar occurrences that affect the availability or quality of water. (Quality is important. After all, water may be available but not drinkable or otherwise suitable for use.) Water stress, scarcity, access and risk are different problems that affect different groups in differentplacesindifferentways, depending on how the water will be used at the end point something may be good enough for watering plants or washing clothes but not for human consumption. Therefore, it is important to distinguish which of the se different kinds of problems characterizea specific watercrisis.

The commonly used Falkenmark water stress index method is straightforward, easy to use and the data needed is readily available. However, such a simplistic approach has its limitations: (a) it ignores important regional differences in water availability, only measuring water scarcity at a country level; (b) it does not account for whether or not those water resources are accessible; (c) it does not include engineered sources of freshwater such as desalination plants which increase; (d) it does not account for varying use of water for different countries, culture and context.

An alternative way of defining and measuring water scarcity is to use a criticality ratio. Gassert *et al.* [7] provided estimates of Baseline Water Stress: the ratio of total annual water withdrawals to total available annual renewable supply. This water stress index incorporates all the domestic, industrial and agricultural water use per person for any given region. Two variables determine baseline water stress: water supply availability and demand for that water. Baseline water stress provides a robust measure of the level of competition among users and depletion of the resource. Focusing on competition and depletion makes this indicator an effective way to measure the hydrological context at the catchment scale, but does not attempt to evaluate water quality, water governance, or the level of investment in the water sector. Baseline water stress measures total annual water withdrawals expressed as a percentage of the total annual available renewable water resource. Higher values indicate more competition among users: (4-5): Extremely high stress (>80%); (3-4): High stress (40-80%); (2-3): Medium-high stress (20-40%); (1-2): Low-medium stress (10-20%); (0-1): Low stress (<10%).

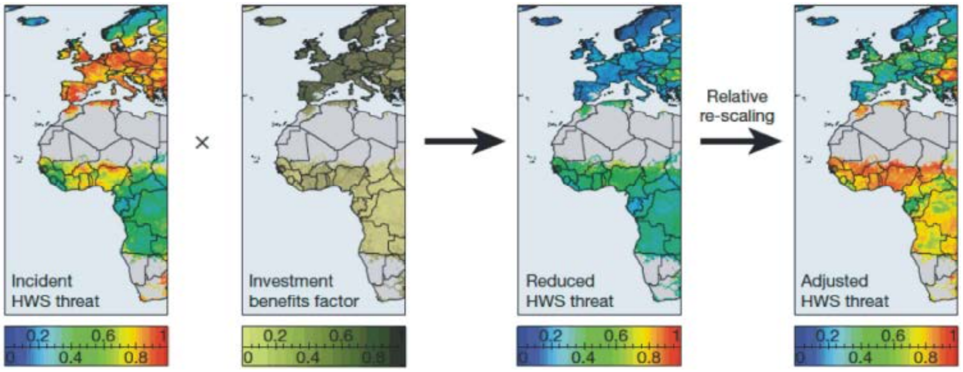
Because of its naturally arid setting- and due to its large and growing number of users and unsustainable management practices and -the Gulf regionhas become one of the most physically water stressed regions in the world. Four Gulf countries - Bahrain, Qatar, Kuwait and Saudi Arabia - have been named the most vulnerable countries and are at “extreme risk” of interruption to their water supply, topping a list of 186 nations [3]. The Gulf is an example of a region where natural water stress is already severe. The complex web of infrastructure and governance structures around the region over the last few decades made this as one of the most water stressed regions in the world. Gassert *et al* [7] rankings do not include the effects of management and infrastructure, instead focuses on objective measures of underlying hydrological conditions. But the overall picture is clear: imbalance between supply and demand has put the region under severe water stress (Table 1; adapted from Gassert *et al*. [7]).

A third measure of water scarcity developed by the International Water Management Institute (IWMI). This approach attempts to address the problems listed above by including: each country’s water infrastructureand measuring the adaptive capacity of a country by assessing its potential for infrastructure development and efficiency improvements.While the IWMI measure of water scarcity is more realistic, it is primarily expert opinion driven and requires significant amounts of time and resources to estimate. This approach also fails to consider the input from affected stakeholders and the ability of societyto adapt to changing water situations.

As the following Figure (adapted from Vorosmarty *et al*. [8]) shows, the way water scarcity is defined has direct and sometimes contradictory, implications on how serious the issue is perceived for different interventions and different choice of indicators. By using a criticality ratio, Vorosmarty *et al*. [8] estimate the level of water scarcity based on a number of stressors (Incident HWS - Human Water Security - Threat). Multiple stressors were combined using relative weights - estimated from expert assessment - to derive cumulative HWS. Stressors were expressed as 23 geospatial drivers organized under four themes (catchment disturbance, pollution, water resource

Table 1: Baseline Water Stress in the Gulf and Neighboring Countries

		Score (Standard Deviation)			
Rank	Name	All Sectors	Agricultural	Domestic	Industrial
1	Bahrain and Qatar	5.00 (0.00)	5.00 (0.00)	5.00 (0.00)	5.00 (0.00)
17	Saudi Arabia	4.99 (0.18)	5.00 (0.05)	4.93 (0.56)	5.00 (0.07)
18	Kuwait	4.96 (0.17)	4.97 (0.17)	4.97 (0.17)	4.90 (0.28)
25	Yemen	4.67 (0.80)	4.69 (0.75)	4.63 (0.92)	3.92 (1.80)
46	Iraq	3.48 (1.01)	3.54 (0.95)	3.37 (1.22)	3.05 (1.24)
102	Egypt	1.33 (1.55)	1.33 (1.55)	1.10 (1.29)	1.56 (1.78)
119	Sudan	0.91 (1.05)	0.93 (0.99)	0.90 (1.61)	0.72 (1.40)
127	Ethiopia	0.61 (0.72)	0.64 (0.70)	0.43 (0.83)	0.61 (0.67)



development and biotic factors). This HWS threat indicator, however, does not include the impact an investment in technological development can have on improving water security. They then estimate an "investment benefits factor" to include investment capacities of each country. They then include the investment benefits factor to the measure of water scarcity to estimate an adjusted measure of water scarcity when technological and investment capacity is taken into account (Adjusted HWS Threat).

Above Figure shows the shifts in spatial patterns of relative HWS threat after accounting for water technology and investment benefits. Incident HWS threat is converted to reduced threat which is then rescaled into adjusted HWS threat. Color spectra depict measures of threat (increasing, blue to red) and investment benefits (increasing, light to dark).

A Closer Look at Water Crisis: Scarcity to Sustainability: A key lesson is that any single indicator may give a misleading impression about water scarcity and sustainability. It is therefore important to be clear how the indicator is defined and which aspects of water scarcity it measures and to recognize that one measure by itself is not enough to provide a trackable measure of sustainability. For example, Egypt has a very low water stress index (1.33) compared to Saudi Arabia (4.99); yet, on an average, both countries receive less than 100 mm rainfall over the year. Thus, this most commonly used water stress index is not physically linked with one of the most important hydrologic variables (rainfall) and can't be used to develop a trackable measure of sustainability.

Environmental Impact Assessment, Integrated Assessment and other currently used approaches provide significant inputs for managing water resources in a sustainable way; yet, they need to be reframed to respond to three key questions Who decides (e.g. experts, decision makers, affected communities)? What indicators to use? How to link indicators to trackable sustainable outcome? Our proposed Sustainability Solutions Space (SSS) for decision making addresses these questions by providing a framework that will require the convergence of principles and pragmatism. It will emphasize the rigor of scientific rationality but will be bounded by pluralistic and interpretive notions of societal impact. Such a framework can provide a consistent set of SSS targets considering the systemic relations among the indicators representing a particular problem context. This tool will allow the decision makers to have a roadmap for sustainable decisions and makes them aware of the synergistic and contradictory effects their decisions may generate. We hasten to add that a roadmap alone will not solve all the sustainability problems; however, it will make the choice of routes, mode of transportation and passengers in the journey easier.

Sustainability Solutions Space (SSS): We will characterize, test and track SSS by building on the safe operating space for humanity developed through the planetary boundary limits [9, 10] and societal concerns [11, 12]. Our proposed SSS was motivated by an approach initially suggested by Wiek and Binder [13] for decision making by addressing systemic, normative and procedural requirements of sustainability assessment within the context of urban and regional planning. In contrast to usually used global measures, our proposed SSS will be defined by using the carrying capacity of a natural system as a ceiling and socio-economic conditions as the foundation for a given problem context. What is new in this framing is that the plurality of interpretations of sustainability is contextualized with the facts on the ground by bringing in the capacity and constraints imposed by the chosen system. The proposed strategy will not pre-define but identify scenarios and solutions that are informed by the context and lie within a SSS. Identification and operationalization of the SSS is an iterative and negotiated process that will include (i) a set of guiding principles that can be operationalized for specific outcomes within a chosen problem context (guiding principles), (ii) a system model with interactions and feedback to assess different scenarios and options for the given problem context (scientific principles) and (iii) a negotiated process to integrate input from relevant stakeholders and to synthesize guiding and scientific principles for a chosen problem context (principled pragmatism).

It will provide a solution framework that highlights the notion of learning by doing and adaptive feedback loop between duality of notions (e.g. facts and values; numbers and narratives; explicit and tacit; quantitative and qualitative). Such a framework acknowledges that the complexity of water systems is neither generalizable nor specifiable. Contingent resolution through adaptive learning is the approach needed to address such problems.

How is SSS Different than Conventional Planning and Management?: With the rise to prominence of water sustainability challenges on the global stage, concerns over long-term water scarcity, security and sustainability have become closely associated with many national and international initiatives supported by a wealth of academic literature.Despite its increasing sophistication, most of this literature remains wedded to searching for a generalizable theory building on the conventional notion of causality with (implicit) assumptions that engaging an array of methods, tools and governance structures will yield a universal cure. Conventional planning and management approach usually adopts a generic template presuming that rational argument forms the basis of policy actions with following steps: defining the problem; specifying goals; and generating options to realize goals. Such an approach takes planning by bureaucratic professionals and discretion of experts as the modus operandi. It also remains silent about the complexity introduced by the politics and assumes simple problem structure with well-defined cause-effect relationship and rational argument forms the basis of policy action. Such anapproach accepts the rational steps of planning as a necessary condition andthe search for finding an optimal sustainable solution space continues. The search for such a space has been a central focus in social science literature including economist's indifference curve, Pareto optimality, Bernard's zone of indifference and Simon's bounded rational space and satisficing criterionare often cited examples. These approaches - and their variants - seek to specify the boundary within which rational action can vary and assume that despite variationsit is possible to pursue and remain focused and achieve the overall goal. In reality, however, specifying the variables that defines the boundary andidentifying threshold values of the boundary when system dynamics changes (for example, system changes from simple to complex) has been and continues to bea difficult challenge (say, specifying Simon's criterion of satisficing for different complex systems). These assumptions are rarely challenged and the search for a generic SSS continues. When faced with failure, it has become commonplace to assert that *"context matters"*.

To addressquestions-*why*, *when* and *how* context matters-we hypothesize that complexity thinking can help. A key attribute of systems that are complex is the notion of emergence. Emergent patterns are neither deterministic nor random; neither perfectly predictable nor totally unpredictable; neither reducible from the macroscale nor transformable from the microscale. Emergence is the effect a complex system creates. We further hypothesize that inadequacies of past attempts to address water sustainability challenges are largely a product of our inability to focus adequately on emergence. Water systems are the product of complex linkages among natural, social and political forces. Traditional efforts to observe and analyze through cause-effect rationality do not account for the notion of emergence and thus produce inaccurate diagnoses. It is from our ability to diagnose emergent patterns, rather than relying on strict notions of causality, that we will be able to draw lessons that can help us identify probable local solutions to water resource challenges. We view this as an adaptive and iterative process. Our understanding of a particular water system needs to be informed by a history of studying other complex systems and drawing lessons based on observed patterns. While the best available information may be used to arrive at the diagnosis and suggested interventions, we accept that our prospective understanding of the system will almost always remain incomplete and we need to actively engage stakeholders to seek their input in light of uncertainty and contextual conditions.

We do not think development of a detailed water resources planning and management model and asking generic "what if" questions will lead to any actionable insight for a given water problem. Because effective resolutions to water resource challenges in arid regions can emerge from convergence that takes science, policy and politics into account. Candidate solutions evolve from rigorous scientific study and a pragmatic awareness of the context, capacity and constraints of the chosen problem context. In this process, stakeholders are engaged to bring in plurality of values to bear on these proposed solutions with the hopeful outcome that an effective and socially acceptable intervention can be negotiated.

Our proposed convergent approach of engineering and technical innovations with diplomatic pragmatism goes beyond the conventional cause-effect based machine metaphor (specialization, standardization and predictability) of science and technology to one based on complexity thinking. And our focus on going beyond "what is or what ought to be" to "what can be" will allow us to explore options and interventions that are technically feasible, economically efficient, socially acceptable, environmentally sustainable and politically feasible within a SSS.Our approach thus does not build on conventional notion of logical rationality. Instead, it highlights practical reason as a component of a rational decision-making process. In such a process, rationality is one component of integrationand the modality of such integration is negotiation rather than logic.

In an uncertain world, anything is possible. However, in reality: not everything happens. Of all possible events, only a few will actually happen with significant consequences. How do we know which few important things will happen and when? How do we plan and prepare so that we can act accordingly when those few significant things happen? More importantly, can we identify and influence what may happen, given the resources and constraints we have?How do we decide what to do when options are many, resources are limited, uncertainty is large and consensus is difficult to achieve? Many of these decisions are complex - because variables, processes, actors and institutions are interconnected and interdependent - making a range of solutions possible. But not all possible decisions are actionable. In such a process of complex decision making, rationality is one component of integrationand the modality of such integration is negotiation rather than logic. Our approach of identifying and affecting SSS is based on such a negotiated process by actively engaging three groups of stakeholders from resource, research and decision making communities.

An Illustrative Example of Identifying SSS from Saudi Arabia: Analysis of rainfall obtained from the surface observed data over Saudi Arabia (SA) indicates a large interannual variability and somewhat confusing temporal and spatial trends in rainfall over the region [14, 15, 16]. A linear decreasing trend is usually reported in the observed rainfall for Saudi Arabia (1970-2009); there is a strong decreasing trend over the recent past (1994-2009) while there is an increasing trend (1970-1994) as well. It is also intriguing to note that spatially rainfall increased in the southern Peninsula and along the Red Sea coast, while it decreased over most of Saudi Arabia during the 2000-2009 decade compared to 1980-1989. Is this increasing (or decreasing) trend related to large scale climatic variability or signs of changing climate? Are these trends related to large scale global circulation patterns like El Niño Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO)? The climate in the SA is reported to be influenced by ENSO and NAO; strength and oscillation of subtropical jet stream may also play a role in pulling hot, dry air masses of SA [16]. These results suggest a more careful temporal and spatial analysis of rainfall with an extended data set going earlier than 1970 and extending till 2018 is urgently needed.

Recently SA has experienced extreme flooding such as Jeddah flooding. Analyses of rainfall records from other regions of the world suggest a significant change in the frequency and intensity of extreme rainfall events. It is critically important to examine whether there is a change in extreme rainfall characteristics over SA. The Climate Change Group of the Prince Sultan Institute (CCGPSI) has already initiated some preliminary analysis to explore the change in the trends of the extreme rainfall. This proposed project will extend these analyses.

Future projections of rainfall patterns in water scarce and arid regions like SA are highly important for effective water resource planning and management. Yet, findings from most climate models are mixed and inconclusive. For example, using regional models, Hasanean and Almazroui [16] showed the decreasing trends of rainfall in most regions during 1978-2009 while no trend was reported for the southwest region. Chowdhury and Al-Zahrani[17] predicted an increase of rainfall by 15-25 mm/year in the central, western and eastern regions by 2050 while Al-Zawad [18] predicted the rainfall increase by 26-35 mm/year during 2070-2100. In the southwest region, Chowdhury and Al-Zahrani [17] predicted the rainfall increase of 109.7-130.4 mm/year while Al-Zawad (2008) predicted an increase of 96.7 mm/year. Recent analysis of rainfall has shown variable patterns - decreasing for some periods while increasing in other - with respect to emission scenarios and assessment periods [19].

Based on the above review of existing literature, we can identify three knowledge gaps: (a) temporal and spatial trends in rainfall over SA is inconclusive; (b) historical analysis of and changes in extreme rainfall characteristics over SA is missing; and (c) future projections of rainfall patterns from different climate models and scenarios are not adequate for future water resource planning and management. To address these gaps, we will examine two related goals: (i) Identify and quantify temporal and spatial trends in rainfall over SA with the longest data set available; and (ii)Identify a set of future climate change scenarios to provide future projections of mean and extreme rainfall patterns over SA that can aid in effective planning and management of water resources. Findings from these data analysis and modeling will be presented at the meeting to identify SSS for different scenarios.

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