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Thank you for the opportunity to submit this revised manuscript.

C.A. Scott

Do ecosystem insecurity and social vulnerability lead to failure of water security?

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ABSTRACT

Achieving water security for humans and ecosystems is a pervasive challenge globally. Extensive areas of the Americas are at significant risk of water insecurity, resulting from global-change processes coupled with regional and local impacts. Drought, flooding, and water quality challenges pose significant threats, while at the same time, rapid urban expansion, competing water demands, river modifications, and expanding global markets for water-intensive agricultural products drive water insecurity. This paper takes a social-ecological systems perspective, aiming to identify examples and pathways towards resilient ecosystems and social development. It draws on lessons from two science-policy network projects, one focusing on water scarcity in arid and semi-arid regions of Argentina, Chile, Brazil, Peru, Mexico and the United States; and the second addressing river and lake basins as sentinels of climate variability and human effects on water quantity and quality in Canada, the United States, Argentina, Colombia, Uruguay and Chile. Together, these 'complementary contrasts' provide an analytical basis to empirically examine stakeholder engagement, knowledge co-production and science-policy interaction supporting decision-making to achieve water security. The paper identifies four tenets for decision-making based on water-security-focused global-change science in the Americas: 1) Decision makers should focus on protecting ecosystems because water security (along with food and energy security) depend on them; 2) Water-use and allocation decisions ought to be made considering future environmental and societal vulnerabilities, especially climate projections; 3) Holistic approaches (at basin or other appropriate levels) are best suited to ensure social-ecological system resilience and reduce vulnerability; and 4) It is essential to support local/traditional livelihoods, and underserved populations to achieve equitable water security and ecosystem resilience.

I. INTRODUCTION

'Water security' has been framed in societal terms. Ecosystems may receive passing mention in conceptual definitions but, operationally, environmental water use tends not to be included in conventional water-security assessments. Conversely, environmental flow and natural flow-regime understandings of ecosystem function tend to externalize human water use and management. This leads to a growing, though not necessarily inherent or obvious, tradeoff between ecosystem and societal water security. In addition, the level of vulnerability of a social group is not only determined by the geophysical conditions and the severity of climate stresses, but also by non-climatic factors, including the interactions between different policies (Dilshad et al. 2019). In this regard, water policies interact with political processes, which can result in enhanced vulnerabilities in disadvantaged groups (Zuniga-Teran et al. 2020). We understand social vulnerability, in the same sense as proposed by IPCC (2007), to include three dimensions: (1) exposure to climate variability and extremes, (2) sensitivity to climatic change; and (3) adaptive capacity, defined by access to and control over resources. Unless conceptual and operational approaches more explicitly account for both environmental and human uses of water, water insecurity is likely to continue increasing.

We conceptualize that water security is the dynamic interaction between social and ecological systems in response to hydroclimatic and human drivers (Scott et al. 2013). There are multiple social factors that influence water security including institutional capacity, collaboration among stakeholders, allocation of resources, political stability, infrastructure, and policies, to name a few that are of primary importance to this work (Varady et al. 2016). Environmental quality and biodiversity, too, influence the ecosystem resilience inherent in water security. Clearly, these and other variables occur over spatial and temporal gradients in real-world contexts. The indicators for water (shortage to excess, predictable to extreme), ecological dynamics (stressed to robust) and social vulnerability (poverty and exclusion to wealth) all change as a result of internal dynamics and external factors. Water scarcity is an underlying chronic threat that will intensify in the future. Although acute episodes of flooding and other threats from water abundance will increasingly capture public attention, scarcity will continue to provide a compelling need for sound water management through effective institutions and resilient infrastructure. The impacts of water scarcity can be seen in pollution and reductions in environmental flows that affect the biota, sediment, and nutrient dynamics of ecosystems. These conditions are in turn affected by climate change and variability via modified precipitation and evaporation, timing and location of snow and glacial inputs, groundwater flow and quality, and land use and its effects on surface and subsurface hydrology.

Management responses in water-scarce contexts tend to emphasize ‘hard path’ infrastructure (dams, inter-basin transfers, irrigation systems, wastewater treatment under urbanization, etc.). However, there is growing recognition of the need for, and potential of, demand management and other ‘soft path’ solutions to water insecurity resulting from chronic water scarcity. At a minimum, hard path infrastructure should be accompanied by soft path measures as a holistic approach to address water insecurity.

In more water-abundant conditions, changes in water flow along rivers tend to modify ecosystem function. River flows and water quality are affected by dredging and mining as well as the impact of dams and other artificial structures. Sediment transport associated with water flow also has profound implications for ecosystem dynamics in natural lentic (lake and wetland) and lotic (river flow) systems, as well as in infrastructure (irrigation canals). Human modification of these systems impact what is delivered to estuaries and the coast. Water-scarce conditions pose threats to in-stream flows and ecosystem function, too, particularly when surface water is diverted for agriculture, urban supply and other human uses. Increasingly, reliance on groundwater to supplant surface water is resulting in aquifer depletion, salinization and associated problems.

The social-ecological systems (SES) approach, pioneered by Gunderson and Holling (2002), Berkes et al. (2003), and others is particularly useful in addressing human and ecological processes related to water resources and water security in particular. The SES framework has been widely applied (Ostrom 2009), including in the study areas featured in this paper (Vilardy et al. 2011; Milman and Scott 2010). In particular, we draw on SES and resilience-based understandings of water security (Scott et al. 2013) originally framed for water-scarce conditions by extending these to address water excess and water quality challenges directly linked to ecosystem processes and social vulnerability.

II. COMPARATIVE ASSESSMENT OF WATER SECURITY CASE EXAMPLES

This paper assesses societal and ecological dimensions of water security through the comparison of results of two recently completed science-policy network projects supported by the Inter-American Institute for Global Change Research (IAI). Both projects were based on SES principles, including attention to thresholds and their definitions, precautionary approaches recognizing the irreversibility of many SES processes, adaptive mechanisms in the face of water insecurity, and crucial human-ecosystem resilience dynamics and outcomes. Direct human impacts on water resources and climate variability and change are both powerful drivers of water insecurity. Consequently, actions to pursue water security need to be taken that address water use, demand, allocation and quality degradation along with adaptation to broader climate drivers.

The first science-policy network project is dubbed AQUASEC, for the IAI water-security virtual center of excellence. This effort coordinated research and policy engagement, and addressed water scarcity in arid and semi-arid regions of Argentina, Chile, Brazil, Peru, Mexico, and the United States. The team generated over 150 peer-reviewed scientific publications. AQUASEC is assessed in greater detail in “Dialogic Science-Policy Networks for Water Security Governance in the Arid Americas” (Lutz Ley et al., 2020), a separate paper appearing in this special issue. The second project, called SAFER, focused on river and lake basins as sentinels of climate variability and human effects on water quantity and quality at sites in Canada, the United States, Argentina, Colombia, Uruguay and Chile. The AQUASEC and SAFER teams together generated over 300 peer-reviewed publications. Both projects were conceived and implemented as interdisciplinary (melding social and natural sciences) and transdisciplinary initiatives (involving stakeholders in the process), in which fundamentals and interactions of societal and policy engagement were given the highest priority.

The SAFER and AQUASEC project teams, resource users and policy stakeholders emphasized decision-making to enhance water security guided by bidirectional interactions – science-for-policy and science-from-policy. Scientific results were presented in such a way as to support management decision-making at the system level, usually the watershed or river basin scale, accounting for stakeholder input throughout the knowledge co-production process, most critically starting from the outset. Although, in all cases, taking into consideration the views of the stakeholders directly involved or affected by the variability of the basins (Zilio et al., 2020). In this sense, we examined how social vulnerability is a condition that produces greater water insecurity. In some cases, during the process of our applied research, we were able to help empower local communities to develop their own solutions to be transferred to decision makers rather than waiting for solutions that may not be the most adequate in the local context.

Emerging results from both projects demonstrate that ecosystem health is a basic indicator – a necessary though not sufficient condition – of water security, as this relates to both social and ecological systems. Specifically, water quality, availability, equity of access, and social vulnerability are indicators of human water security. At the same time, water quality and seasonality of flows are essential for ecological water security, recognized as a core 'value' of ecosystems. Maintaining a dynamic equilibrium between water conditions and aquatic ecosystems is essential. Modifications of or perturbations in these conditions disturb all the interactions within the ecosystem as well as ecosystem services to society. Water is invariably the first element in the ecosystem to feel any perturbation to the system. Thus, water bodies can be considered sentinels of any change impacting the broader SES. Reverting to earlier SES states requires work or energy exertion by the system and the returning path can be the same as, or different from, the forward path, depending on the type and level of the perturbation. However, if the disturbance is strong enough to cross some specific threshold, the system may not be able to return and will need to find a new equilibrium condition.

Figure 1 depicts the locations of study as described in this paper. What follows is a comparative quantitative analysis of the sites, supported by analysis and description of case evidence that allows for discussion of factors enhancing or impeding water security.

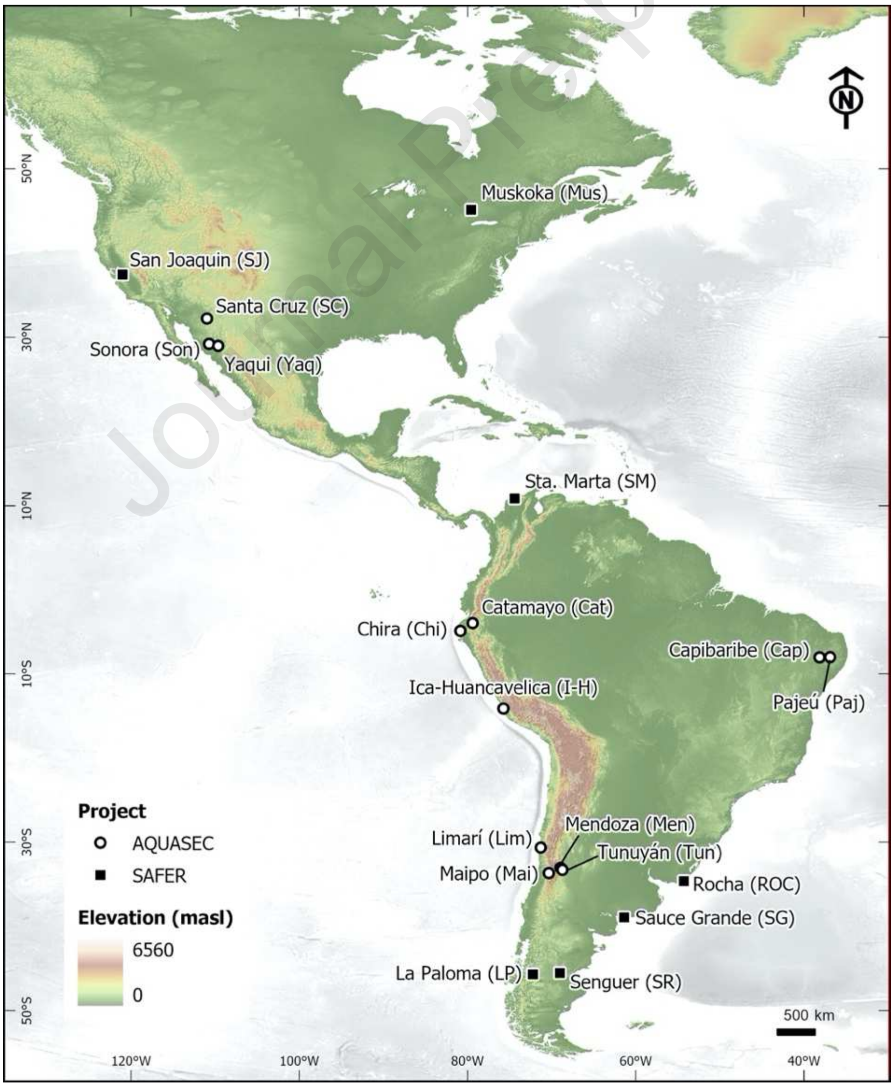

Figure 1. Map of SAFER and AQUASEC sites

Extending a diagnostic approach used previously for SAFER and Ramsar sites (Harmon et al. 2018), we can illustrate the spectrum of hydroclimatic, environmental, socioeconomic and governance-related conditions encompassed by AQUASEC and SAFER sites (Figures 1 and 2).

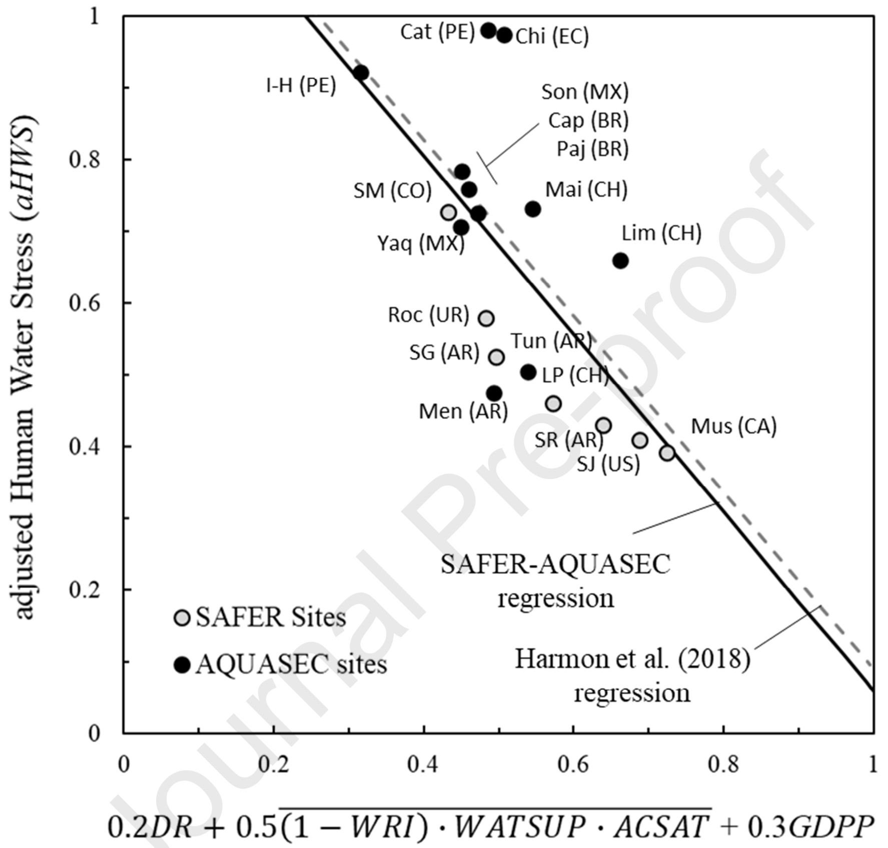

Figure 2. Regression between adjusted human water stress *aHWS* (Vörösmarty et al. 2010) and aggregated climatic, water resources, sanitation, and wealth indicator for the SAFER-AQUAEC sites (slope -1.24, intercept 1.30, R^2 0.44); for comparison, prior regression line from Harmon et al. (2018) for SAFER-Ramsar sites (slope -1.23, intercept 1.32, R^2 0.85). Note: The Santa Cruz River Basin [SC (US-MX)] is excluded from the analysis in this figure due to the lack of spatial data for that basin (Riverthreat *aHWS* product).

The following are the indicators in the regression formula: DR, drought severity based on average drought length and soil dryness; WRI, return flow index based on % of available water previously used and discharged as wastewater; WATSUP, water supply based on fraction of nation's population with access to improved drinking water; ACSAT, access to sanitation based on fraction of a nation's population with access to improved sanitation; GDPP, based on gross domestic product per capita).

The approach used watershed-based human water security estimates by Vörösmarty and colleagues (2010), then aggregated drought (DR), water resources infrastructure (WRI), access to clean water (WATSUP) and sanitation (ACSAT) (all taken from Hofste et al. 2019), and national wealth (GDPP). Although the 18 cases used here exhibit more scatter than the previous results (R^2 = 0.44 compared to 0.85 in the previous case), the regression coefficients are nearly identical, reconfirming the empirical link between water security, climate, wealth and governance quality (in terms of capacity to create water infrastructure).Using the information generated in Figure 2, we classify the different sites in three water security classes: Low for those sites with values of adjusted human water stress (*aHWS)* greater than 0.7; Medium for sites with *aHWS* between 0.4 and 0.7; and High for sites showing values of *aHWS* below 0.4. Table 1 presents the results of this classification and values of average annual precipitation and flow.

Table 1. Water security class for SAFER and AQUASEC sites (river or ciénaga/lake basins)

Site, Country *(Code)*	Precipitation (mm/yr) / Flow (m^3/s)	Water Security Class
Catamayo, Ecuador *(Cat)*	681 / 110	Low
Chira, Peru *(Chi)*	80 / 142	Low
Ica-Huancavelica, Peru *(I-H)*	784 / n.a.	Low
Sonora, Mexico *(Son)*	437 / 530	Low
Capibaribe, Brazil *(Cap)*	938 / 22.6	Low
Pajeú, Brazil *(Paj)*	655 / 20.3	Low
Ciénaga Sta. Marta, Colombia *(SM)*	830 / n.a.	Low
Maipo, Chile *(Mai)*	286 / 90	Low
Yaqui, Mexico *(Yaq)*	475 / 88	Medium
Limarí, Chile *(Lim)*	140 / 15	Medium
Rocha, Uruguay *(Roc)*	1120 / n.a.	Medium
Sauce Grande, Argentina *(SG)*	1040 / 2.5	Medium
Tunuyán, Argentina *(Tun)*	200 / 28	Medium
Mendoza, Argentina *(Men)*	200 / 50	Medium
La Paloma, Chile *(LP)*	1300 / n.a.	Medium

Senguer, Argentina *(SR)*	150 / 52	High
San Joaquin, USA *(SJ)*	210 / 230	High
Muskoka, Canada *(Mus)*	1000 / 74	High

Although the analyses used to describe the hydroclimatological conditions of the sites are simple and do not account for temporal variability or spatial heterogeneity, it appears evident that water security is better represented by multivariate functions that account for infrastructure, governance and ecosystem health. Below, we also provide details of social vulnerability for several examples gleaned from the SAFER and AQUASEC sites.

III. TRANSITIONS FROM WATER INSECURITY TOWARD WATER SECURITY

In this paper, we expand on the crucial role of water security in underpinning ecosystem security in a manner that reduces social vulnerability. Not only must ecosystem integrity be included in the pursuit and practice of water security, it is a necessary first principle for promoting SES resilience. Water security, along with food and energy security, depends on ecosystem services provision (Millennium Ecosystem Assessment, 2005; Vörösmarty et al. 2010; Richardson 2010; Green et al. 2015; Vanham 2016). Even though water security as an operational concept emerged later than food security and energy security, it is of paramount importance and underlies both food and energy security as well as earth system resilience (Scott et al. 2018; Varady et al. in press). This dependence leads us to assert that water policy should increasingly prioritize preservation and protection of ecosystems and the services they provide, both in order to provide sufficient water of good quality to people and to sustain the ecosystems on which they depend. This implies a need for recognizing that human water uses are not always the only uses to defend (which can be more difficult in water-scarce and quality-impaired conditions), because preserving ecological flows is essential for the transition toward increased water security and decreased social vulnerability. Moreover, this dependence must be internalized by all SES stakeholders, not only by decision makers, if the objective is achieving progressive degrees of water security. Naturally, the path towards water security is not linear and there is no reason to believe that a certain stage of water security will always be followed by a better one.

The case of Colhué Huapí Lake, in the “Bajo de Sarmiento” of the Argentine Patagonian plains (Scordo 2018), is a clear example of how bad decisions about water management can undermine the bases of water security at a local and regional level. The Colhué Huapí and Musters Lakes together form the lower section of the Senguer River basin, an endorheic system that has its headwaters in the Andean Range (González Díaz and Di Tomasso 2014). The Senguer River becomes an alluvial fan when it arrives at the “Bajo de Sarmiento”, mainly due to the low slope in the area. The main channel of the alluvial fan ends in the Musters Lake. However, 50 m upstream the lake, its flow diverges to the east, and it becomes the Falso Senguer River that discharges into the Colhué Huapí on its west coast (Scordo 2018). From the east coast of Colhué Huapí Lake, the water flows through the Chico and Chubut Rivers and discharging in the Atlantic Ocean.

Social dynamics center on the fact that around 250,000 inhabitants of the region depend on the Senguer River for drinking water. Additionally, one of the southernmost agricultural-livestock valleys in the world is located southwest of Colhué Huapí Lake and water users divert river water for irrigation. Additionally, oil drilling activities and cherry orchards take water from the Falso Senguer River, while Musters Lake is strategically vital for tourism and as a water source for the local and regional communities. All of these activities have caused Colhué Huapí Lake to become dry, with the local community seeming to be uninterested in, or unable to influence, the lake's future (Scordo et al. 2017).

Water infrastructure was developed to divert water to the more populated areas of the region. This human activity, along with climate variability, has modified the geomorphology of the surrounding area of the Colhué Huapí Lake and, for the last 80 years, precluded flow in the Chico River (Scordo et al. 2017, 2020; Scordo 2018). The current SES regime involves major changes in water flows, shifting the basin from exorheic to endorheic, accompanied by significant fluctuations in the surface area of Colhué Huapí, which was 105 km^2 in 2001, 800 km^2 in 2007 and nearly dry in 2016 (Tejedo 2003, Llanos et al. 2016, Scordo et al. 2017, 2018).

Inferring how the SES dynamics of the watershed might have evolved without human intervention is speculative. Because water demand and vulnerability are high, water infrastructure was designed to ensure the provision of some ecosystem services at the expense of others, without considering how the waterworks could affect the functioning of the basin as a whole in the long term. This myopic decision-making in the past is currently reflected in the reduced importance that local stakeholders assign to ecosystem services provided by Colhué Huapí (Scordo et al. 2018). Not surprisingly, given that the basin is located in an arid area, water resources are highly valued by stakeholders who depend critically on the ecosystem services that the Senguer River provides. However, this appears not to be reflected in their perceptions of the Colhué Huapí Lake and even the Chico River.

In contrast, the Lower Santa Cruz River Basin in Southern Arizona, U.S., appears on the path to water security. Amidst a growing demand and declining water levels in the aquifers, this region has developed innovative water management strategies to achieve water security and reduce vulnerability (Albrecht et al. 2018). These include a diversification of the water portfolio – from being solely dependent on groundwater, water utilities now have surface water from the Colorado River (through interbasin transfers), and reclaimed water to meet their water demands (Megdal and Forrest, 2015). In addition, some households in the city of Tucson within the basin opt to harvest rainwater and reuse their greywater (City of Tucson Water Department 2013). Another strategy to reduce vulnerability involved the reduction of water demand from a growing population, through a series of incentives, regulations, and other policies implemented since the 1970s (City of Tucson Water Department 2013). Further, changes in water uses, through purchase of agricultural land to obtain water rights from exurban and rural areas, allowed for the supply of this resource to the growing municipalities. This agricultural land is now being used to recharge the aquifer with Colorado River water. Also, through the Sonoran Desert Conservation Plan (1998-99), it became possible to protect important riparian and watershed ecosystems from development, ensuring their function, and consequently, enhancing overall water security. Further, innovative groundwater regulations (referred to as assured water supply rules), require land and real-estate developers to demonstrate that there is enough water in the aquifer to supply their proposed project for the next 100 years in order to obtain permission to develop. Finally, efforts to address equity issues have developed into diverse policies and economic instruments, including a block tariff structure; incentives, rebate programs, and subsidies for green infrastructure and rainwater harvesting; and collaborative planning through stakeholder engagement. These sorts of water management strategies combined with land use regulations have directed and allowed urban growth in this water-scarce region, while reducing water demand. However, climate change and prolonged drought conditions continue to threaten water security in the near future, as mountain snowmelt declines causing water levels in the main reservoirs of the Colorado River basin to decline (Zuniga-Teran and Staddon 2019).

The Colhué Huapí and Santa Cruz cases demonstrate that, in practice, ecosystem integrity is a crucial component of water security that also addresses vulnerability. Preserving and enhancing ecosystems is a priority to promote resilience. Additionally, preventative measures to maintain the health of the SES system can simultaneously improve livelihoods for under-represented and more vulnerable populations. Reducing water insecurity implies an adaptive management approach to water governance, viewed as a constantly evolving process in which the goal must be achieving regulatory efficiency through clear and well implemented norms (Bakker and Morinville 2013). In general, but particularly in developing countries, simply having rules to guide water policy is not enough to ensure compliance. Better enforcement is an essential component of a regulatory framework to drive SESs towards water security. These contrasting South and North American cases described here show the need for water-security assessments over multiple spatial and temporal scales, which are the focus of the next two sections.

IV. WATER SECURITY ACROSS SPATIAL SCALES

The selection of the unit of analysis is not a trivial issue for the identification of water-security pathways. Each SES has particular characteristics, different degrees of interaction among water users, potential interbasin transfers, and other complicating factors. In this context, working at the appropriate level is necessary to ensure SES resilience and reduce vulnerability across the system. Furthermore, habitat monitoring, and spatial species inventories are essential in evaluating the state of the ecosystem so that water policy can anticipate major water-security challenges (Vörösmarty et al. 2010).

An example in which the scale of analysis is critical is when water bodies become contaminated and pose a threat to consumers who may be supplied from distant sources. In this case, it is urgently necessary to accurately identify the stakeholders affected. An illustrative case is the mining spill of 40,000 m^3 of acid leachate discharged into the Sonora River, Mexico, on August 6, 2014. Studies of aquatic ecosystems after this event are scarce. For this reason, using a Mexican federal law as a reference, members of our team compared the data of surface water samples for the 38 sites observed during the period from August 2014 through September 2015. We created a database of numerous parameters reported monthly per site.

Finally, the sampling sites were mapped at the frequency of observations during the period under study (Díaz-Caravantes et al. 2018).

Mexican federal law provides two sets of norms for protection of aquatic ecosystems. One set establishes the water-quality guidelines for exemptions from the payment of national water rights. The other set establishes the maximum permissible limits as parameter values under which wastewater discharges are exempted from fees and water rights payments. The first set's guidelines are more rigorous than the maximum permissible limits of the second set. We found that of the 17,000 entries in the database for the 2014-2015 period, 1% exceed the maximum permissible limits; while 43% are outside the guidelines. These findings may contribute to the design of policies for the protection of ecosystems, particularly aquatic life (Díaz-Caravantes et al. 2018). After the spill, the effects on vulnerability were direct and very negative on the agricultural and commercial sectors of the Sonora River communities, as they stopped their activity for at least one year, and after five years, still they have an indirect impact on the livelihoods and increasing water insecurity of rural communities (Díaz-Caravantes et al. 2016, Elizalde 2020).

This pervasive decoupling of stakeholders, scales and policies demonstrates the challenges of poorly integrated management of water resources, which is a frequent driver of water insecurity (Margerum and Robinson 2015; Gerlak and Mukhtarov 2015; Al-Saidi 2017). Interjurisdictional issues and power dynamics add to this complexity. The Tunuyán River basin in Mendoza, Argentina, for instance, was divided into two administrative sub-basins (Upper and Lower) at the beginning of the 20th century within the framework of expansion of irrigation "oases" in arid lands. This fragmentation process was consolidated between 1965 and 1973 with the construction of the Carrizal Dam, located right between the two sub-basins. Water was allocated 18% and 82% to upper and lower sub-basins, respectively. But this arrangement came under threat toward the end of the 20th century when an aggressive process of restructuring viticulture occurred that was not accompanied by equivalent changes in water management. The restructuring led to a notable increase in the demand and effective use of water in the upper basin, but a commensurate loss of irrigated land in the lower areas of the basin with clear vulnerability impacts. This resulted in serious problems of water scarcity and worsening of quality, particularly in the lower sub-basin (Chambuleyron 2002), where water security became severely threatened.

The Sauce Grande River basin, Argentina, is another clear example of how the scale of analysis, the institutional framework and the climate conditions become inextricably linked to shaping how water resources are perceived and allocated among users (Zilio et al. 2019). The basin is located in an area of high temporal and spatial climate variability (Brendel et al. 2017b; Ferrelli et al. 2019), which results in periods of water abundance alternating with scarcity. Climate conditions also determine the attitude that stakeholders and decision-makers have toward water-security concerns: during dry periods, nobody demonstrates interest in improving water management, but during the wet periods, the pressure for water management is immediately apparent with competing claims over who holds the right to use water, with vulnerable populations less able to defend their claims. Such a conduct has been evidenced for wet and dry periods, but not for seasonal variability. Although it is completely counterintuitive, this change in stakeholder behavior could reflect that they passively accept the lack of water during long periods of drought, leaving aside redistributing issues until water availability is restored. Logically, extreme events such as drought or flooding affect both ecosystem services provision and economic use of water across the basin (Brendel et al. 2017a). For instance, the shallow Sauce Grande Lake, which is an important local and sport-fishing destination in the region, became desiccated during the dry period (i.e., summer 2013), but recovered to its highest water level three years later. This changing condition facilitated the collaboration between water authorities and stakeholders. After years of bureaucratic delay, the water authorities finally authorized the installation of a buoy in Paso de las Piedras Reservoir to measure and collect meteorological, biological and physicochemical data for scientific purposes. The rapid recovery of water levels allowed restoration not only of the touristic value of the lake but also of the interest of local authorities in improving infrastructure and associated services directly related to water provision. Although the situation in this basin appears counterintuitive, the results of several years of working with the stakeholders and decision-makers showed us this contrasting reality (Zilio et al. 2019).

In addition to climate variability, the Sauce Grande basin is managed by a complicated institutional framework that includes local regulations of the six counties that comprise the basin, a provincial institution in charge of supervising and monitoring all activities related to water use in the basin, and an “on-paper-only” basin committee that has never functioned since its establishment in 2000. This complicated situation creates a disarticulated scenario governed by a multiplicity of norms, often different and overlapping, without adequate space for dialogue on water management from a basin perspective. Furthermore, the most significant groups of river water users for domestic, industrial and other purposes, live outside the basin. Such conditions entangle even more the water management decision making process aimed at achieving basin water-security goals, creating tedious and confusing regulations and the intermittent interests of stakeholders. These stakeholders must also deal with an outside group that holds great negotiation power and more weight in the water resources management decision-making process (Zilio et al. 2019).

Worsening climate conditions of warming and drying have started to play a supportive role during the last few years, specifically by fostering the interaction among stakeholders, decision-makers and the scientific community and achieving significant signs of progress in terms of water management. In some cases, this higher interest in incorporating stakeholders into water management has already been reflected in water policy, such as the collaborative management included in the Sonoran Desert Conservation Plan mentioned above, or the successful participatory stakeholder engagement approaches developed in Laguna de Rocha, Uruguay (Rodríguez Gallego et al. 2013) and La Salada, Argentina (Zilio et al. 2017). In other cases, the formal incorporation of stakeholder participation into water policy still appears to be a long-term goal, mainly due to the complexity and rigidity of the governance structure and managers’ persistent reluctance to consider users’ opinion in the policy design process. Although the progress in such situations was insufficient to ensure substantial changes in water policy, noticeable stakeholder leadership has emerged in water management at local and regional levels and this could translate into policy impact in the future. In this context, clarifying and improving the institutional framework as well as keeping the social actors engaged in pursuing sustainable water management to address the climate situation is a necessary condition for moving from water insecurity to better water security at the basin level.

In other cases, dams and reservoirs have become the focal point for water-security planning within the larger watershed or basin. In watersheds located in water-scarce regions, rivers are intermittent, and reservoirs serve as the main water source, relied upon to ensure a supply during the dry season. For this reason, in some cases, it is preferable to consider the reservoir as the unit of management instead of the watershed. The Pajeú River Basin in Northeast Brazil is an example where reservoir management councils (CONSU) were created to facilitate the process of water management considering negotiated allocations that consist of deals made among multiple users aiming at rational use of water resources. The CONSUs have a framework similar to river basin councils with the representation of public institutions, civil society and water users. They have deliberative and consultative duties with a strategic role in the processes of water allocation and conflict mediation at the local level. The negotiated allocation defines the limits, rules and conditions of water uses provided by reservoir operations.

Of course, clear identification of stakeholders and their responsibilities should also be coupled with analysis of how water quality changes impact new basin SES dynamics and governance challenges (Fischhendler and Heikkila 2010; Pahl-Wostl et al. 2013; Pahl-Wostl 2017), and consequently stakeholder demand for adaptation and/or remediation measures. Considering all these factors when designing water-security policies does not ensure that a collaborative approach can in fact be successfully developed (Zilio et al. 2019), but it can undoubtedly improve the performance of water management strategies in a manner that addresses vulnerability. Furthermore, given the complexities outlined, the decision-making process must be guided by both natural and social scientific research, contributing to the bidirectional science-policy interaction. In this context, local knowledge is an increasingly important element in the design of water management strategies, especially at local levels. Deep engagement of local stakeholders is critical to implement any water management plan successfully (Steyaert and Jiggins 2007; Reed et al. 2009; Iniesta-Arandia et al. 2015). Logically, socio-economic conditions constitute a powerful driver of water security or insecurity – the more vulnerable the population, the greater the impact of climate variability on their livelihoods and quality of life. But socio-economic conditions interact with a range of physical, political, and environmental factors to determine how water insecurity impacts human communities and how policy makers face design and implementation challenges to achieve water security.

The scale and other characteristics of the cases are not uniform, and consequently, different methods for engagement were followed including the involvement of researchers in data generation and interactive modeling as well as the mobilization of water authorities based on the actions of stakeholders and decentralization of the decision process. When stakeholder participation is encouraged from the outset of the decision-making process, a knowledge co-production process is more likely to emerge and underpin more inclusive water resources management. Nevertheless, the evidence about the success of such interaction between co-production of knowledge and water management is spotty and not at all conclusive (Lemos, 2015; Djenontin and Meadow, 2018). In this sense, our collective experience provides us insights on how diverse the processes of stakeholder engagement can be and how this diversity can critically influence the results of water management strategies (Vilardy et al. 2011; Conde et al. 2015; Zilio et al. 2017, 2019). Stakeholder engagement is particularly important when the scale of analysis would permit influence in water management and thus impact to the SES. All the cases described above demonstrate how stakeholder participation can contribute to improving water security or minimizing anthropogenic impacts.

V. WATER SECURITY OVER TIME

Water security is, by definition, the result of a process in which the temporal dynamics of water (shortage and abundance) are matched by effective and equitable water resources management. Only by understanding the historical dimensions of water security is it possible to instill a more conscious decision-making process to manage water resources in such a way as to consider previous experiences and avoid the repetition of old mistakes. Our combined project experience indicates that history in some cases should be considered over time ranges including millennial (indeed, in some cases, the paleoecological record), centennial, and decadal (including future projections).

Paleo-studies use lake sediments to recreate past limnological, environmental and climatic conditions, and more importantly to understand how lake basins have responded to past natural and anthropogenic stressors. Paleolimnological studies have proven valuable for examining lake ontogeny (Wilson et al. 2012, Brenner and Escobar, 2009), climate and land use change (Escobar et al. 2012; Lacey et al. 2016, Velez et al. 2011), societal changes in response to climate and environmental change (Curtis et al. 1996), pollution of water bodies (Rosenmeier et al. 2004; Escobar et al 2013) as well as the efficiency of management practices for their recovery (Smol 2010, Bennion et al. 2011), and the evaluation of ecosystem services (Velez et al. 2018). Any decision involving water use, allocation and evaluation of ecosystem services should incorporate the long-term history of the particular location. This window into the past provides key information such as the identification of the main stressors or master variables of change in the ecosystem, the estimation of the relative changes in water budget and in water quality that resulted from past changes in climate (e.g. precipitation and temperature), and in the surrounding environment (e.g. agriculture, volcanism, deforestation, etc.) that makes any decision much more robust. Thus, paleodata are needed to contextualize management decisions related to water security and to make decisions more robust. In this section, we present some global examples that illustrate how paleo-studies can help contextualize water issues.

The first case we consider here is the paleohydrological reconstruction of the Athabasca River in Northern Alberta (Canada), which demonstrated that the water budget constructed to justify extraction of oil from the sands was far more optimistic than the actual water availability (Sauchyn et al. 2015). The paleo record indicated that the mining company had based their water estimations on meteorological data that covered only a short time period of above average humid conditions. Another paleolimnological study showed that the water acidification in northern European lakes was a recent phenomenon without historical precedents. Reconstructed water pH records indicated that lower pH levels were synchronous with industrialization (Norberg et al. 2008). This study was a key reference for the development of programs that aimed at water restoration building on baseline conditions identified through paleolimnological reconstructions.

A second case is the paleolimnological and paleoenvironmental reconstructions of the Ciénaga Grande de Santa Marta (CGSM). Here, paleo-studies indicate that the ecosystem's integrity had been maintained through the permanence of hydrologic connections with the open ocean and inland freshwater streams (Velez et al. 2014). This hydrological connection balanced water salinity and nutrient levels during past events of climatic and sea-level variations and thus the integrity and diversity of the community of primary producers was maintained through time (Vidal et al. 2018). As a result of 20th century water and transportation infrastructure and modifications of land use in the watershed and drainage for raising buffalo, rice, palm and banana plantations, the lagoon had become hydrologically isolated. For the CGSM's source rivers in the Sierra Nevada de Santa Marta, high intra and interannual rainfall seasonality (Restrepo et al. 2019) increase water insecurity. Their natural characteristics (small size, very steep topography, shallow soils) makes them highly sensitive to climatic drivers, i.e., low water storage and rapid hydrological response to both dry and wet conditions (Hoyos et al. 2019). Additionally, increased pressure on water resources from multiple sectors (large and small-scale agriculture, tourism, rural and urban population, Indigenous groups) as well as lack of coordination and institutional oversight has led to poorly planned allocation of water resources. As a result, inadequate infrastructure and institutional oversight make rural inhabitants more vulnerable to climate variability as their livelihoods depend largely on a few activities. Poorly managed wastewater from the inhabitants in the area and alterations in hydrology of the CGSM have created subsequent changes in water circulation, leading to anoxia and hypereutrophication that have put at risk the function of the ecosystem and the services it provides (Vilardy et al. 2011). This case shares some characteristics with the Colhué Huapí Lake mentioned above but provides greater insight because the paleo-data provide scientific evidence on the preponderance of anthropogenic impacts on the CGSM and its SES dynamics over the years.

A good example of the relevance of a more recent temporal dimension of water security can be found in Mendoza, Argentina. As part of a longer dry cycle, in the late 1960s, the annual flow of the Mendoza River dropped 35% from its historical average, falling from 1700 to 1100 million m^3. Consequently, groundwater was rapidly exploited for the expanding wine industry which demanded increasing irrigated grapes. Natural and human factors converged to produce a near-total collapse: a decade of intensified subsidies for grape planting (tax incentives, cheap electricity, easy credit) and rapidly rising grape and wine prices combined with the worst drought in a century. Over four years, from 1967 to 1971, the annual number of new wells drilled rose from 464 to over 2,000, and the total number of wells in operation doubled (Frederick, 1975). Groundwater compensated for the loss of river flow. In the following decade, the irrigated area of the province rose from 210,000 to just under 380,000 hectares. This rapid expansion made the whole system increasingly dependent on groundwater. At its peak, pumping would reach an average of 608 million m^3/year, more than half of the total river flow. Over this decade, the percentage of land irrigated with groundwater rose from 42 to 86%, while that irrigated solely by surface water dropped from 55 to 14% (Healey and Martín, 2017). Demand on the aquifer became unsustainable, as the first signs of failure, contamination, and salinization started to be noticeable in the mid 1970s.

The model of expansion based on indiscriminate drilling reached a crisis, accompanied by the bursting of the wine-price bubble, followed by the decline of the century-old mode of winemaking. The abandonment of wells that had been dug and vineyards that had been planted in the explosive growth after 1967 were clear evidence of social and environmental degradation. Between 1978 and 1990, more than 100,000 hectares of vineyards were abandoned in Mendoza. In only 13 years, the region lost 39% of its acreage of vines. An early sign of the depth of the crisis was the swift drop in the number of new wells between 1973 and 1976, at rates exactly mirroring the rise. In addition, many existing wells were abandoned due to disrepair, the dropping water table, or the rising price of fuel for pumps with the onset of the oil crisis (Healey and Martín, 2017). Contrary to the Athabasca and Santa Marta cases presented above, the example of Mendoza does not account for centuries of history but demonstrates that critical scrutiny of recent events can shed light on the drivers of the current water insecurity in the area.

Finally, also in South America, a case in Brazil exemplifies forward-looking temporal studies, which are useful to plan for water security. These planning activities also face important challenges, including inadequate hydroclimate records in some regions as well as incomplete knowledge of future climatic and land use changes at the management scale. The Brazilian National Policy of Water Resources establishes water resources master plans as one of its instruments. The plans assess water demand and water availability, define priority actions, assess water pollution control and water allocation for dealing with conflicts, among other topics. Plans are delineated at national, state or watershed scales. So far, those plans do not adequately consider scenarios associated with global change drivers, such as land use and climate change. In a certain way, this is understandable because the timespan considered in the plans (years to a few decades) does not overlap that for the global change scenarios (a few decades or longer). The Capibaribe River Basin in Pernambuco state has a water resources plan in which the planning time horizon is 15 years into the future with just minor comments in relation to climate change impacts. Considering the importance of the plan for water management, members of our team evaluated the performance of indicators proposed in the master plan of the Capibaribe River basin, referring to the period 2010 to 2013, and pointed out the major factors for vulnerability and resilience. The classification of the water quality was polluted in 7 of 9 stations located along the basin. The pollutants are predominantly from industrial sources in the upper and middle stretches of the Capibaribe and domestic sources in the lower stretch. Reductions in the cultivated area were also identified in most of the 42 municipalities in the basin. This may be a result of the water shortage in Brazil's northeast semiarid region in this period. The population has increased in most municipalities, which translates into increasing demand for environmental sanitation services. The GDP per capita and the Firjan index (quality of employment and income, education and health) exhibited growth in the majority of the 42 municipalities in the basin. Despite the improvement of economic indicators, environmental indicators did not have positive performance. This discrepancy shows the need to analyze social and ecological indicators in an integrated way.

The Capibaribe River Basin master plan was also assessed in terms of the progress of the investment actions foreseen in the plan. Four obstacles were identified in the process of investment plan monitoring: (1) staff turnover of the state public agencies, (2) lack of a system to carry out the monitoring through document and data storage, (3) access to information. and, finally, (4) dialogue and articulation between institutions in charge of investment implementation (Moura et al. 2018). The interruption of actions is probably the main effect arising from fragile institutional capacities. Once again, scale and institutional issues mentioned above play a crucial role, interacting with the temporal processes that, in this case, implied the complete omission of the fact that climate variability can alter the planned scenarios and then override the results of water management.

Because reducing vulnerability is a priority on the path to water security, long-term natural cycles of the ecosystems as well as short and medium-term human processes should be considered to better understand the dynamics of each SES, its livelihood security, resilience and sustainability. Undoubtedly, knowing the system in the past can be useful to understand changes in the amount of water through time, the long-term hydrology, sources and sinks, and also to better understand human uses and dependence on water in order for water management plans to be resilient to the combined natural and human conditions in the future. In particular, understanding how key variables for ecosystem services provision and water security behave in the past constitute a necessary basis for effective and sustainable management of water resources.

VI. SYNTHESIS AND DISCUSSION

Based on the examples presented above and others from the SAFER and AQUASEC projects, our experience suggests that water security in operational terms is never absolute, nor can it be defined as a single condition for all uses or actors. Achieving security for crop irrigation is very likely to affect water security for drinking water, other human uses, or for ecosystem functioning in itself. And even within the same use, water security is not a homogeneous condition either. For example, the Mendoza and Tunuyán river basin cases illustrate that agricultural production seemed to be guaranteed, even though the authorities were reporting water emergency conditions. For many years, the hectares actually irrigated were lower than those registered in official documents. However, at the same time, in those same periods we witnessed the substitution of water rights and expansion of lands cultivated under irrigation, not only in the Tunuyán but also in the Mendoza basin. Groundwater irrigation mainly used for these processes opened up another principal tradeoff between water and energy, which was not considered when thinking solely about water-security solutions and measures. Water authorities point out that the emergency is the new normal and announced a series of measures. Some are relatively simple to apply, aimed at introducing demand criteria into a management traditionally guided by supply, as well as strategies for the integrated use of groundwater and surface water. Others are more controversial, involving mechanisms for the reallocation of water and even the expropriation of rights. The ability to implement these measures is obviously highly dependent on the veto power of some stakeholders. So far, the clearest progress is seen in those actions that, like the former, only require administrative and management planning procedures. There are no clear indications of profound changes in distribution. Thus, despite the definition of a new normal, it is still managed as an emergency and exceptional situation.

The Mendoza case is useful to summarize three principles for the pursuit of water security. These are systematically evidenced in all our study cases and lead to our concluding remarks.

First, developing new equilibria that are ecologically and socially acceptable is only possible at the expense of some impact on ecosystem functioning. In turn, recognizing the unavoidability of such impact supports the idea that water management is impossible to split up from water security and ecosystem resilience concepts. In this point, achieving a sustainable water management condition implies a continuous tradeoff between both uses and users, and some complementarity relationships between water for productive uses (more evident in AQUASEC sites) and conservation or recreation goals (prevalent on SAFER sites). The tradeoffs, even if unavoidable, are usually exacerbated by insufficient planning. In fact, the cases in which water management strategies are poorly conceived or erroneously implemented more often exhibit failures in the distribution and allocation of water resources. Furthermore, recent hydrologic changes and future steady states should be considered to reduce the conflict of interests embedded in the tradeoffs. For example, in a case not discussed previously, the trout fishery in La Paloma complex (Chile), demonstrates how both productive and recreational uses may overshadow biodiversity conservation objectives, implying a complementarity among uses or, from another perspective, a different tradeoff between human and natural uses. In spite of being considered one of the most damaging and aggressive invasive exotic species in the Southern hemisphere, trout has a great social value in the recreational fishing industry, and thus trout is highly promoted instead of being limited or banned to protect biodiversity.

Second, supporting local and traditional livelihoods and vulnerable populations is essential to achieve water security and ecosystem resilience. In other words, water security has to account for vulnerability and ecosystem protection, and how communities perceive and achieve this (or not) is critical for determining the results of water policy. No water user, however seemingly invulnerable, is fully immune from water insecurity that may result from major natural hazards or bad policies and poor governance. Climate change is currently a major driver of water insecurity and in the case of Santa Cruz, Arizona, for instance, is surpassing the expected conditions and determining the perpetuation of the current situation over time, in spite of all the efforts made to revert such condition. Planning for extreme events has also been the guiding light of the water management master plans in Pernambuco, but they do not properly incorporate the lessons learned to improve water management. The traditional livelihoods and measures adopted by the population to live with drought can be understood as adaptation actions for climate change impacts and should be considered in the plans.

Third, the role of stakeholders on the path to water security is indispensable and it also invariably enhances outcomes. The interaction among users, policymakers and local decision makers can substantially improve the performance of water management strategies as well as optimizing the efficiency of water-security policy. In turn, the perception about the relevance of managing water resources in a sustainable way plays a critical role in stakeholder engagement. Obviously, water stressed basins will always be in conflict, independently of social actors' involvement and commitment, and power relationships strongly influence the failures of water resource planning.

Based on our results from across the Americas, it is apparent that human water security does jeopardize environmental water security and that, simultaneously, human use of water surpasses sustainability limits in most of the cases, particularly in developing countries. In fact, water-based ecosystem services in the Argentinean, Uruguayan and Colombian cases exhibit a high degree of degradation as a result of many decades of unplanned and unorganized water resources use, a lower adaptive capacity linked to its higher level of vulnerability, and a total absence of clear guidelines for preserving water ecosystem services with a long-term perspective.

In this sense, it is critical to establish priorities to integrate water ecosystem services for both human and environmental purposes. Identifying mutual interests requires engagement among local stakeholders, academics, and decision makers from different levels as well as education and consciousness-raising. However, these are simultaneously the major challenges in how priorities are set and implemented. Our experience in the particular cases of Laguna de Rocha, Uruguay (Rodríguez Gallego et al. 2013; Nagy et al. 2014) and La Salada, Argentina (Smyth et al. 2016; Zilio et al. 2017) indicates that when mutual interests and education are considered, planned, executed and maintained over time, the priorities for integrated ecosystem services can be defined and implemented with a certain degree of success.

Of course, there will always be tradeoffs, or conflict in values, but the situation will worsen if there is insufficient or ineffective planning for water management. Findings from our combined sites suggest that the level of water security is mediated by water abundance, commitment to mutual human and ecosystem values, and regional development conditions. The Santa Cruz case in Arizona shows that in spite of water scarcity, an economically powerful region can enhance water security by responsive governance of water infrastructure and institutions to identify and implement appropriate policies that protect ecosystems and regulate demand.

Furthermore, if we understand water security as a combination of abundant and high-quality water for resilient ecosystems and societies with good governance and equitable economic development, we might expect to find that our case in water-rich Canada was indeed water-secure. However, water resources are typically referred to in aggregate for the nation and these resources are widely distributed but the population is not: the majority of Canadians live in a fairly narrow band along the southern border while most of the water flows are located north. The infrastructure needed to ensure equitable water availability, especially for the more vulnerable who are sparsely distributed across a vast landscape in both the north and the south, is unaffordable in the short and medium term.

VII. CONCLUSION

Our comparative analyses of water-based social-ecological systems (SESs) over gradients of water security (access, equity, ecological quality), over time and over spatial scales have implications for global-change science in the Americas. The discussion above has elucidated several principles with overarching significance beyond the individual cases in which they were identified. We have shown that water security is the outcome of an inextricable mix of – often an outright tradeoff between – human and ecological processes. In a strict sense, ecosystem insecurity and social vulnerability undermine water security. The pursuit of water security, then, requires informed, evidence-based decision-making.

This paper has expanded on four tenets for decision-making that we consider to be relevant across the Americas and beyond. First, *decision-makers need to focus on protecting ecosystems* because water security (along with food and energy security) depend on them. The most effective means to protect e-flows is to enshrine those flows in legislation. However, with or without formal laws, inclusive and participatory governance is essential to identify and implement mechanisms for ecosystem services with combined human and environmental benefits. This must be backed by an understanding that the economy, human health and the maintenance of water infrastructure systems all depend on a healthy environment. Second, *water-use and allocation decisions should be made considering future vulnerabilities and climate projections*. Current conditions that are considered water secure can easily and rapidly change to being insecure. Third, *holistic and integrated approaches (at the basin or other appropriate level) should be followed* to ensure SES resilience. Efforts must be sustained to reduce ecological impacts (resulting from declining flows and degraded water quality) and social vulnerability (driven chiefly by inequitable access to water and influence over its governance). Fourth, and finally, *it is essential to support local/traditional livelihoods, and vulnerable populations to achieve water security and ecosystem resilience for all*. The successful pursuit of water security is predicated on reducing social vulnerability and mitigating ecosystem insecurity, thereby enhancing broader social and ecological security.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: