Chapter 2
Enhancing Water Governance for Climate Resilience: Arizona, USA—Sonora, Mexico Comparative Assessment of the Role of Reservoirs in Adaptive Management for Water Security

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Abstract Climate variability and change exert disproportionate impacts on the water sector because water is a crosscutting resource for food production, energy generation, economic development, poverty alleviation, and ecosystem processes. Flexible surface water and groundwater storage together with adaptive water governance are increasingly recognized and deployed to strengthen climate resilience, specifically by buffering drought and flood extremes, bridging interannual variability, and providing for multiple uses of water, including environmental flows. Adaptation can be further enhanced by the following: (1) accounting for hydro-climatic and water-demand uncertainties; (2) strengthening institutional learning in relation to reservoirs (reoperations as well as mechanisms to address growing civil-society critiques of "hard-path dependence"); (3) increasing flexibility of policies for infrastructure (including readaptation to past cycles of infrastructure development); and (4) building on science-policy dialogues that link infrastructure and governance. An array of complementary adaptation tools will buttress climate resilience. Some emerging techniques include underground storage, distributed basin-wide enhancement of water retention, efficient water use (with limits on the expansion of new demands on saved water), and wastewater reclamation and reuse (with their own emerging storage and recovery techniques). Each of these techniques is directly linked to reservoirs in practical and operational terms. Conjunctive surface-water and groundwater storage must be further developed through infrastructure, institutional, and policy approaches including groundwater banking, trading and credit schemes, water swaps (substitutions and exchanges), and a robust approach to targeted water storage for climate resilience.

Keywords Reservoirs · Infrastructure · Groundwater banking · Water security · Adaptation · Readaptation · Hard path · Soft path · Arizona · Sonora

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2.1 Introduction

Climate change exerts significant and increasing impacts on human societies and ecosystems globally. Rising atmospheric concentrations of greenhouse gases, particularly carbon dioxide, have resulted in warming temperatures and more variable precipitation accompanied by shifts in land cover, species distribution, and altered hydrological processes. For decades, the societal implications of climate variability and change have been recognized across a range of economic sectors, from agriculture to energy to urban development. The monitoring of environmental conditions and modelling tools have greatly aided the understanding of the spatial variability of climate impacts and their temporal trends (Overpeck et al. 2013). However, future uncertainty—particularly with regard to the distribution, timing, and intensity of precipitation (including its partitioning as rain or snow)—make freshwater availability an especially acute dimension of climate change. Additionally, climate variability resulting from El Niño Southern Oscillation (ENSO) and other decadal timescale variations in global circulation processes drives extreme events, including the unpredictable and often rapid sequencing of droughts and floods. As a result, the dynamics and uncertainty of terrestrial hydrological processes underlying the spatial and temporal distribution of water resources are central impacts of climate change.

Coupled with natural processes of global environmental change are human drivers, especially rapid demographic growth and accelerating economic development (Leichenko and O'Brien 2008). Together, natural and human drivers contribute to the integrated process of global change (Vitousek 1994). The exploitation of natural resources, mining, energy development, land conversion for agriculture and livestock production, soil-nutrient depletion, urban growth, industrialization, pollution (land, air, and water), and increasing carbon emissions from these and other human activities serve to intensify global change. Freshwater availability and quality are at the epicenter of global change, given the crosscutting importance of water for food (production using surface water and groundwater irrigation and food safety and handling), energy (electricity generation, biofuels, and environmental impacts of fossil and renewable energy sources), economic growth (essential provision of water and sanitation services for poverty alleviation, commercial and industrial development), and ecosystem processes (in-stream flows, wetlands, and biodiversity maintenance). Global change has resulted in systemic imbalances in water resource quantity and quality (Vörösmarty et al. 2013), particularly in arid and semi-arid regions (Scott et al. 2013). Expanding human demands for water in the context of erratic surface water availability are increasing the need for water storage to buffer extremes (Palmer et al. 2008), while at the same time shifting dependence to groundwater (Taylor et al. 2013).

The current understandings of climate and global change adaptation in the water sector are based on an underlying pressure-state-response (PSR) conceptual model. As extreme events, especially drought-induced water scarcity, exert pressure (P) and limit water-use activities (S), management responses (R) include efforts to increase supply and improve the effectiveness of current practices in the medium term. Water demand management is most often viewed as a strategy to alleviate short-term scarcity under the prevailing assumption that earlier conditions of supply will equilibrate. There is growing recognition, however, that interactive and bidirectional influences of mutual feedbacks in social-ecological systems can lead to unanticipated outcomes (Walker and Salt 2013; Moser and Pike 2015). Global change is producing a new normal; in other words, extreme conditions of the past are here to stay and indeed may well recur with increasing frequency. This raises the urgency of understanding global change adaptation in water management, including its spillover effects in other sectors.

Adaptation in the prevailing context of water scarcity produces a set of responses in individual sectors: for example, agricultural managers alter the timing and distribution of irrigation supplies, electrical power operators gear up for heightened electricity use, and urban water utilities seek to augment supply. Clearly, better integrated, cross-sectoral approaches to environmental and water governance (Tortajada 2010) are recognized, yet institutional disarticulation limits effective anticipatory planning and coordinated responses during and after times of crisis. Thus, short-term adaptation can be linear in that it posits a tangible set of manageable outcomes resulting from adaptive response measures. Such approaches are also based on static assumptions: that earlier conditions will recur with known frequency and that outcomes are predictable. These assumptions have too often led to chronic shortages in water availability and deteriorating quality for human and ecosystem purposes. This invariably entails iterative adaptation measures to respond to earlier cycles of management and, indeed, mismanagement—a process we refer to as readaptation, as expanded upon below.

The need for readaptation in the water sector responds to path dependency; that is, the prevailing courses of action and options that are available to managers are limited by the current stock of infrastructure, investments (both financial and institutional investments), and professional norms (Lach et al. 2004). Two principal, often contrasting, sets of options have been termed hard path and soft path strategies (Gleick 2003; Wolff and Gleick 2002, who acknowledge the use of hard/soft terminology from earlier thinking along similar lines in energy sector policy by Lovins (1976, 1979). Hard path options are primarily based on infrastructural or physical management (e.g., dams, reservoirs, aqueducts, and interbasin transfers), whereas soft path options are those based on social and organizational strategies (e.g., water pricing, public awareness, and changes in people's behavior; Brooks and Brandes 2011). New approaches based in engineering resilience (LRF 2015; Hollnagel et al. 2006) identify opportunities to enhance infrastructure robustness while ensuring safety and reliability of infrastructural assets, such as storage reservoirs and the services they provide—for example, water supply (Scott et al. 2012) and flood control. In most situations, particularly where water stress is pronounced and cumulative, hard and soft path measures coexist and may be judiciously combined. In other contexts, where infrastructural stock is low or the reduction of losses from disasters like flooding is an overriding imperative, hard path options have tended to receive emphasis.

The heightened variability of global change processes, the context-specific nature of impacts and responses, and above all, the uncertainty inherent in spatial and temporal trends in natural and human drivers raise the need for new understandings of water security. We define water security here following Scott et al. (2013) as "the sustainable availability of adequate quantities and qualities of water for resilient societies and ecosystems in the face of uncertain global change." We take water security to be more of a goal than a static condition or fixed end-state. This is particularly evident given the dynamic and evolving set of mutual interactions among water, energy, and food security. By pursuing flexible adaptive water governance, the resilience of societies and ecosystems to the water sector dimensions of global change can be significantly strengthened.

2.2 A Comparison of Arizona, USA and Sonora, Mexico

This study undertakes a comparative assessment of storage reservoir infrastructure for adaptive management and water security together with other emerging techniques to enhance climate resilience outcomes in Arizona, USA and Sonora, Mexico (see Fig. 2.1). The transboundary focus (Wilder et al. 2010; Browning-Aiken et al. 2004) is complemented by a discussion of broader relevance for the arid Americas (Varady et al. 2013), which addresses resilience to climate change and variability considering infrastructure, soft path measures, and governance.

2.2.1 The Arizona Case

Arizona's modern water history is inextricably linked to the development of water resources of the Colorado River and its tributaries. In 1911, Roosevelt Dam on the Salt River was completed with federal funding under the National Reclamation Act of 1902. After the 1922 Colorado River Compact that apportioned water to the seven states comprising the U.S. portion of the river basin, negotiations, political deals, and legal battles resulted in Arizona's current annual water allocation from the Colorado River of 3450 million cubic meters (MCM). However, the state was initially unable to utilize this allocation; agricultural lands and population centers of south-central Arizona were hundreds of miles away and at significantly higher elevations. The development of large dams on the Colorado River began with Hoover Dam, formally dedicated in 1935, which impounded Lake Mead with a maximum storage capacity of 35,700 MCM. This was later complemented by Glen Canyon Dam upstream, which created Lake Powell (Dean 1997) with a maximum storage capacity of 30,000 MCM. Lakes Powell and Mead are each capable of storing 2 years of average flow of the Colorado River, not considering climate change impacts.

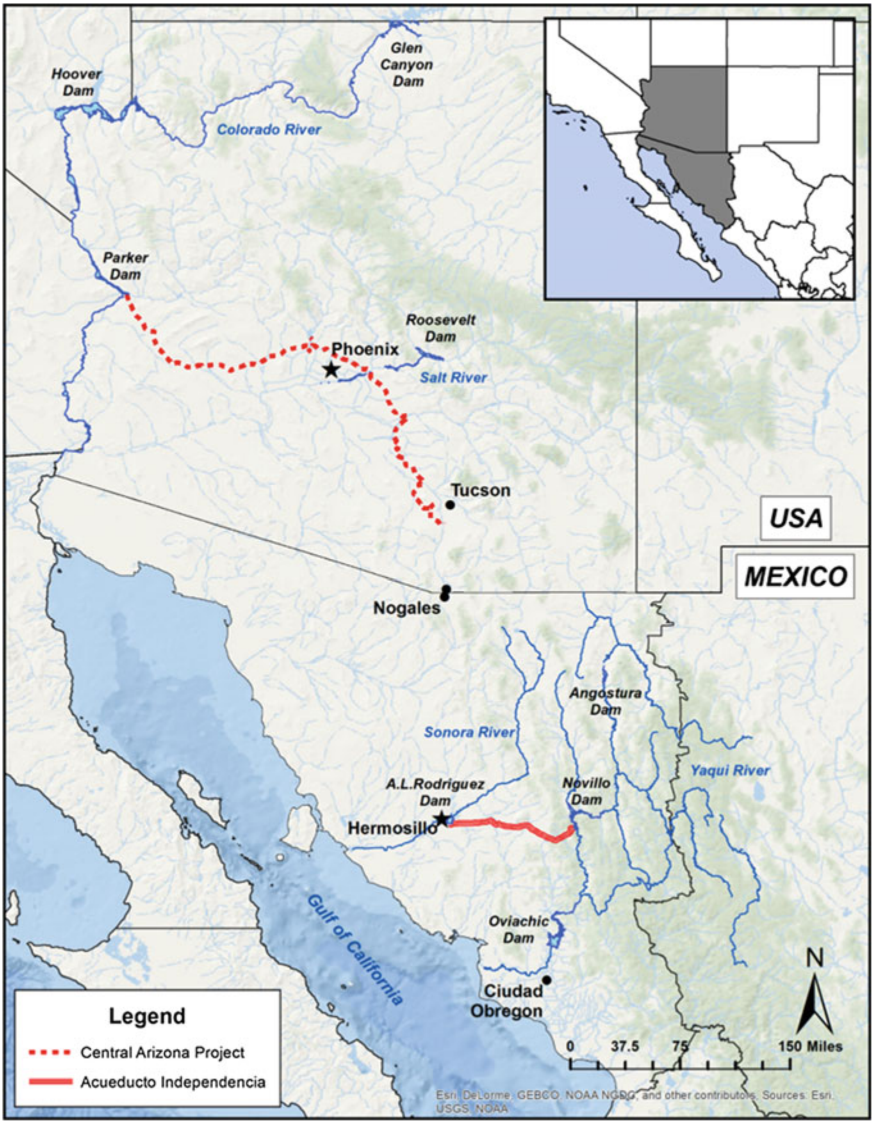

Fig. 2.1 Arizona, USA and Sonora, Mexico study locations

In 1947, the U.S. Bureau of Reclamation proposed to the Secretary of the Interior the construction of the Central Arizona Project (CAP). CAP is a 540-km aqueduct to convey water from Lake Havasu (capacity 798 MCM) behind Parker Dam on the Colorado River to urban and agricultural users in the central and southern parts of the state. CAP comprises pumped lift totaling almost 880 m over the length of the aqueduct, moving water up multiple individual pipeline systems with gravity flow in open-air, lined canals until the next lift (Eden et al. 2011). Construction of CAP began in 1973 and lasted 20 years, when water was delivered at Pima Mine Road just south of the city of Tucson. CAP is Arizona's largest supplier of water (1970 MCM annually) and its largest single consumer of electrical power (2.8 million megawatt-hours annually) (CAP 2010).

Development and financing of the CAP were imbued with hard- and soft-path considerations. The Carter administration in Washington was unwilling to approve federal funding for the CAP (or other large infrastructure projects of the time) unless Arizona took steps to better manage its water resources (Glennon 1995). These considerations led to Arizona's passage of the Groundwater Management Act in 1990 and establishment of active management areas around the state's main urban centers as well as irrigation non-expansion areas in water-scarce agricultural areas.

Climate change is having significant impact in the Colorado River Basin (Kates et al. 2012). During the late 1990s, through a combination of high inflows and alternative sources of water to at least partially meet off-river demand for irrigation and urban supply, the reservoirs were relatively full. However, persistently low inflows and high reservoir evaporation resulting from drought conditions in the 2000s through to the present coupled with growing demand and diversions of Colorado River water have reduced storage to near-record low levels.

As Arizona's population grew to 6.4 million people in 2010 (US Census Bureau 2010), in part due to assured water supply from CAP to the two main cities of Phoenix and Tucson, water management and associated infrastructure increasingly prioritized urban supply (Megdal 2012). Current strategies include interannual carryover of CAP water, particularly in the face of prolonged drought and interstate water-sharing of the Colorado River, and long-term storage, recovery, and banking of groundwater (Megdal et al. 2014). The readaptation challenges in the state are centered on flexibility in planning, demand management, and retooling the state water administration that was partially dismantled in 2008, ostensibly for budgetary reasons.

Roosevelt Dam on the Salt River, a Colorado River tributary within Arizona, presents an illustrative example of climate resilience opportunities and limitations. Constructed in 1911 to a height of 85 m, it was raised in 1996 at a cost of USD 430 million to its present level of 109 m with a maximum storage capacity of 2040 MCM. The dam, water supply, and hydroelectricity generation are managed by the Salt River Project (SRP), a community-based, not-for-profit public power utility in the greater Phoenix metropolitan area that is also the largest supplier of water to municipal, urban, and agricultural water users. SRP is an award-winning utility that reports highest customer satisfaction.

The river basin is subject to significant interannual variability (Wentz and Gober 2007). High rainfall in the watershed resulted in record inflows in February 1980, although flood operations of the reservoir proved capable of averting major damage downstream in the cities of Mesa and Phoenix. Complementing the reservoir's flood control functions is the Flood Control District of Maricopa County, which provides up-to-date hydroclimatic information, flood-hazard maps, and details on flood insurance. SRP is partnering with researchers at the University of Arizona to better incorporate downscaled climate model information into reservoir operations.

Downstream of Roosevelt Dam, conversion of agricultural water rights to urban supply (Gooch et al. 2007) in urban areas with low population densities supplied by the Salt River Project mean that on a per-area basis water allocations are considerably high. Thus, Roosevelt Dam, SRP, and complementary functions provided by the flood control district in the lower Salt River basin have ensured water security through active and engaged institutional learning. The effects of expanding demand in the context of climate change and variable flows on the Salt River, however, require planning and control of urban growth that extend beyond SRP's mandate and are under the purview of zoning regulations and assured water supply rules.

2.2.2 The Sonora Case

Sonora's water administration is qualitatively different from that in Arizona, because formal institutions are centralized at the federal level in Mexico. The main organization managing water resources is the National Water Commission (CONAGUA), which is under the Ministry of Environment and Natural Resources (SEMARNAT). The modern water history in Mexico is centered on the creation of CONAGUA in 1989 and the enactment of the Law of National Waters in 1992 (Aboites 2009). In 1998, CONAGUA divided the Mexican territory into 13 hydrologic-administrative regions to facilitate water management and also designated river basin organizations including the Northwest Basin Organization (OCNO) in Sonora and tributary rivers in Chihuahua State (Diario Oficial de la Federación 1998). Although these actions were intended to decentralize water management, in reality the process was only partial because CONAGUA still retains control over water allocation, concession titles, regulations, and policy-making (Scott and Banister 2008).

Sonora also has its own state-level Water Commission (CEA Sonora) in charge of implementing local policies, data generation, and infrastructure development within the institutional boundaries set by the federal law. Approximately 90 % of all the water allocated in Sonora is for the agricultural sector, with 5 % for urban public supply (CEA Sonora 2008). Sonora relies heavily on groundwater, as does the entire country; it is the largest groundwater user in Latin America (Scott and Banister 2008). The state's 2.7 million population (INEGI 2010) is served by five river basin systems: Sonoyta, Concepción, Sonora-San Miguel, Yaqui-Mátape, and Mayo (CEA Sonora 2008). The Yaqui-Mátape basin—the largest in terms of area, availability of water resources, and irrigated area—is transboundary (with the United States) and interstate (with Chihuahua). In the lower basin lies the second largest city in the state and the second largest agricultural district in Mexico, which is the major wheat producer in the country. The Sonora-San Miguel basin includes the capital city of Hermosillo, the majority of the state's population, and the largest copper mine in Mexico.

In the heyday of infrastructure development, the Ministry of Hydraulic Resources (SRH), a predecessor of CONAGUA, built most of the 31 dams existing in Sonora. Three of the largest ones are located in the Yaqui basin, with volume stored of more than 6500 MCM. Of these, El Novillo Dam (also referred to as Plutarco Elias Calles), was built in 1964 in the mid-basin and is managed by the Federal Electricity Commission (CFE) for hydroelectricity generation. El Oviáchic (Álvaro Obregón) Dam, the largest in the basin, is a multipurpose reservoir like El Novillo; it controls water flows, generates electricity, serves eco-tourism enterprises (such as sport fishing), and, most importantly, is the primary source of water for Irrigation District 041, Río Yaqui, and for Ciudad Obregón, with its public water supply system connected to the district's network. Two other dams—Abelardo L. Rodriguez and El Molinito—were constructed in the Sonora River basin to regulate water flows and supply Hermosillo. Together, these two store almost 350 MCM (CONAGUA 2015).

Because of its geographic location, Sonora is subject to significant interannual climate variability with a strong influence of El Niño Southern Oscillation (Robles-Morua et al. 2015). It has a bimodal precipitation regime dominated by the North American Monsoon, with frequent occurrence of Pacific cyclones making landfall. In the last two decades, Sonora has had very low precipitation accompanied by record high temperatures. The Abelardo L. Rodriguez reservoir has been in a state of near-total depletion since the end of the 1990s. The Hermosillo water utility and state authorities have been looking for different solutions to meet urban water demand, in many cases relying on poor-quality, unreliable groundwater sources such as peri-urban wells, or purchasing agricultural water rights from ejidos surrounding the city, which generates social and political opposition (Pineda-Pablos et al. 2012). The recent history in Hermosillo and the Sonora River Basin (SRB) reflects the vicissitudes of achieving water security in a context of prolonged drought, intersectoral and intrasectoral competition, and less than transparent decision-making processes.

The strategies all have the same underlying logic—appropriating and transferring water from nearby sources to Hermosillo city through ad hoc combinations of soft and hard path measures, sometimes involving socioeconomic and institutional measures (such as purchasing agricultural water rights) and at other times construction of pipelines, new wells, or other infrastructure. In 2004, the recently municipalized urban water utility, Agua de Hermosillo, bought water rights from Ejido Las Malvinas, north of Hermosillo city, within the San Miguel watershed (SMW). This action generated strong opposition from CONAGUA and local residents of the area at the time. During fieldwork conducted in mid-2015, small-scale farmers and ranchers in the ejidos of the lower SMW believed that Hermosillo's water extractions were one of the reasons for the depletion of the San Miguel Aquifer, although Hermosillo's rights account for less than 15 % of the aquifer's annual recharge of 52 MCM (Pineda-Pablos et al. 2009), while large-scale agriculture has become an important player in the region. In 2006, the municipal utility bought rights for 17.4 MCM of groundwater from the Costa de Hermosillo Valley at Los Bagotes by negotiating the purchase with organized ejido and private farmers. In 2008, the State Government built a 28.3-km pipeline connecting El Molinito to a water treatment plant close to the Abelardo L. Rodríguez Dam. Although this was conceived as an augmentation strategy for providing Hermosillo with water during drought, in real terms the transfer was redundant because both dams were already part of the city's supply (Scott and Pineda-Pablos 2011). Soft path strategies during the 2000s included rationing and rotational water supply, leak detection, and educational programs in schools, communities, and the business sector under the general banner of water culture. These programs were based on discursive contents, not differentiated for each social group, more than on capacity building. Their effectiveness has not systematically been assessed (Lutz-Ley 2013). Hermosillo managed to cover urban demand during the drought in 2014; however, long-term supply challenges remain.

The 2006–2012 state administration developed the program known as Sonora SI (Sonora Sistema Integral), an ambitious plan of water infrastructure that included new and refurbished past projects, with investments ranging from improving irrigation channels to building dams for urban supply in different parts of the state (Robles-Morua et al. 2015; Prichard and Scott 2013). The centerpiece of these projects is the Acueducto Independencia, an interbasin transfer scheme originally projected to convey 75 MCM of water per year from El Novillo Dam in the Yaqui basin via a 150-km aqueduct to Hermosillo in the lower Sonora basin. Rights to the water to be transferred via the aqueduct were purchased from agricultural users in communities upstream of El Novillo. The construction of the aqueduct was accompanied by allegations of corruption, lack of transparency, and highly conflictive relationships between the water stakeholders of the Yaqui Valley (including urban, agricultural, and indigenous users) on the one hand, and the population of Hermosillo city and the state government on the other (Scott and Pineda-Pablos 2011; Lutz-Ley et al. 2011). The aqueduct is currently an important source of water for Hermosillo, especially after pollution in the Sonora basin in 2014 resulted from a major spill of the copper mine tailing ponds upstream in Cananea. Heavy metal contamination reached the Molinito Dam and is suspected to have also affected some of Hermosillo's wells in that area (El Imparcial 2015).

Several important issues emerge from the development and implementation of these strategies. First, it is clear that hard path and soft path strategies are intermingled and it is difficult to draw clear lines between their respective outcomes. The building of infrastructure for water transfers has led to institutional reorientation in the form of innovative responses, new rules, incipient water markets, and social learning. Evidence of this is the past two decades characterized not only by severe drought, but also by intense institutional learning and governance changes in Sonora.

Realistic options for the reallocation of water rights as required by water transfers are themselves dependent on the stock of infrastructure in place. In other words, the capacity and flexibility to actually move water require built infrastructure. In Sonora, this capacity is less well developed and, therefore, the policy mechanisms for reallocation, such as market and pricing, are less well articulated than in Arizona. It is clear that different levels of development and the evolution of governmental institutions affect the perceptions of decision-makers. Diverse actors across multiple levels of government and civil society have shifted roles and power positions in terms of water decision-making, characterized in general by the retreat of federal authorities to give room to more empowered local intervention, although CONAGUA fully conserves its regulatory capacity. Although not formalized in new legislation, this is a major governance change in comparison to management by CONAGUA and prior federal agencies relying on highly bureaucratic, centralized, and top-down approaches.

Second, the shifting power positions are also accompanied by innovations in infrastructure funding. Insufficient monetary resources have been one of the main reasons for the delay or cancellation of several water projects in Sonora (Pineda-Pablos et al. 2012; Scott and Pineda-Pablos 2011). The financial burden has progressively moved from the governmental bodies—particularly at the federal level—to more distributed financing schemes involving private and users' participation to a greater degree. For example, the Sonora SI plan included a major proportion of capital from build-operate-transfer (BOT) contracts, federal and state funds, irrigation districts, and Hermosillo city (Scott and Pineda-Pablos 2011). On the other hand, financing from local sources has not necessarily been matched by a commensurate degree of local self-determination in water or climate governance, because water legislation still remains in the hands of federal authorities. For example, an important component for starting the Sonora SI plan advocacy was directly related to the declaration of drought emergency in the state. This declaration must be approved by the Mexican Ministry of Interior (SEGOB) and is the key for accessing funds from the federal Fund for Natural Disasters (FONDEN). Drought declaration also played a major role in the social construction of water scarcity in Sonora (Lutz-Ley et al. 2011), which would ultimately serve to legitimate the decisions made by the Sonora SI plan.

On the other hand, the strong El Niño that started in 2014 after several years of drought evidenced the combined effects of both hydroclimatic stress and governance solutions to water scarcity. These outcomes are associated with: (1) the priority of managing drought instead of a broader planning framework that considers the full range of extreme events in the region (i.e., flooding and cyclones; Farfán et al. 2013); and (2) the imbalance of water allocation decision-making over spatial and power differences among water sectors. Urban and large-scale irrigation actors have been the most powerful negotiators when it comes to infrastructure (Scott and Pineda-Pablos 2011). This has promoted a large gap in the physical infrastructure available to deal with drought and flooding in rural settings in contrast to cities. While drought conditions have affected all reservoirs in the state, leading them to historic low levels of storage, the extraordinary rainfall in late 2014 and early 2015 entailed water releases from El Molinito and partial filling of the chronically depleted Abelardo L. Rodríguez Dam. In the SMW towns, located less than 100 km north of Hermosillo, the river washed away many hectares of cropland, according to the report of farmers interviewed in the summer of 2015. The rural communities depending on agricultural livelihoods are vulnerable to climate extremes because they lack the infrastructure to withstand drought for crops, livestock, and human domestic consumption. They are served by aging water pipelines, inadequate or inexistent storage facilities, and lack of wastewater treatment for effective wastewater reuse. Prevention of flooding risks is also a major concern in a basin where reservoirs and flow control are concentrated only in its lower section. In the words of some rural inhabitants, they are at their capacity limits when it comes to drought, not prepared at all when flooding or other extreme climate events hit the region. Cities such as Hermosillo do not have effective strategies to deal with flooding, other than reactive measures to protect or support the population after these events. However, certainly in terms of flood control, the dams existing close to cities have prevented major disasters so far. Tropical cyclones making landfall in Sonora (and other Pacific coast states in Mexico) pose very widespread flood risk from intense precipitation occurring over the entire coastal plain (Farfán et al. 2013). Cyclone events are difficult if not impossible to manage with infrastructure alone.

Today, Sonora faces important water challenges related to dual climatic and human impacts. Persistent gaps in wastewater treatment, partial enforcement of rules and legislation, and the effects of policies that have prioritized hard path measures all raise important (re)adaptation challenges in the state. In this sense, the potential of reservoirs to increase resilience to climate change is critically assessed in the context of new institutional arrangements for water transfers in urban–rural settings. These arrangements need to be referenced to particular contexts, especially based on the strong opposition that many water works have raised in Sonora in the recent past. The implications are not the elimination of reservoirs from the water security portfolio but the careful analysis of cost-benefit ratios of investments in ecosocial terms—that is, analyses that factor in social and ecological impacts. Climate change is projected to increase the frequency of extreme events in the region, requiring urban and rural populations to deal with continued and more severe droughts as well as with more extreme flooding. Robles-Morua et al. (2015) assessed the impacts of the SONORA SI proposed Sinoquipe and Las Chivas reservoirs (27 and 41 MCM, respectively) under the context of future climate change in the SRB and found that, in contrast to projections for the Southwest United States, more precipitation and water inflow can be expected for the next 30 years in Sonora, together with a shift in rainfall seasonality. However, the proposed reservoirs would add little to the existing dams in terms of flood control. The role of reservoirs thus must be viewed in full river basin terms, with soft path strategies that enhance partial resilience offered by infrastructure-based solutions.

2.2.3 Arizona–Sonora Comparative Assessment of the Role of Reservoirs in Enhancing Water Security

The concept of water security provides an analytical framework for the effectiveness of reservoirs as a tool for adaptive management. Water security entails the dual character of water resources as productive—when water makes possible the existence of irrigated agriculture—and destructive—when an extreme event produces fatal flooding (Scott et al. 2013). To be water secure means to have the amount and quality of water required for the specific uses that are intended. In addition, the criterion of resilience of societies and ecosystems means that water distribution and management should generate flexible and equilibrated dynamics that do not decrease the capacity of one social group or ecosystem to adapt when this same capacity is improved somewhere else in the system.

Reservoirs must be viewed in broader social-ecological resilience terms. The academic literature tends to stress the adverse social and environmental impacts of dams and related infrastructure when they are viewed as part of a management approach that prioritizes water storage as an isolated or unique supply-oriented objective. In this view, reservoir management is based on simple economic cost-benefit analysis, fragmentary visions of the social-natural landscape, and static climatic and environmental conditions. The policy outcomes under this type of management have been historically characterized by environmental degradation, increased social inequality between winners and losers, inflexible management in the long run, and, in numerous cases, social protests related to water and land appropriation for the construction of storage reservoir (World Commission on Dams 2000).

By contrast, multipurpose surface reservoirs as well as additional water storage and supply augmentation techniques, including groundwater recharge-recovery and banking, water reuse, and rainwater and storm water harvesting, can enhance resilience. In order to do so, however, adaptive management must be based in social and ecological processes, incorporate institutional learning, and assess benefits and costs not solely in monetary terms but in the ability to increase flexibility and minimize risks. Typically, the timeframes for such analysis should be centuries, even though infrastructure may have a useful life of decades. Crucial to enhancing the role of reservoirs in adaptive management are appropriate siting, design, construction, operation, and decommissioning.

In terms of the comparison of the role of reservoirs in achieving water security in Arizona and Sonora, dams to store water have helped in physically managing the two main impacts of climate variability in the region: water shortage resulting from drought and heightened demand, on the one hand, and flooding and the loss of life, property, and certain ecosystem functions and services on the other. However, dependence on single hard path strategies has translated into the neglect, even rejection, of alternative options. For instance, the lack of a comprehensive portfolio of supply and demand management policies in the case of Sonora led to chronic water insecurity for Hermosillo city after the main supply reservoir was depleted in the late 1990s. Similar conditions were endured for the larger Yaqui river reservoirs that reached record low storage levels after the drought of 1995–2003, causing the loss of many cultivated hectares in the Yaqui Valley Irrigation District. In 2003, the district planned 40 % more land area for irrigation than was feasible given the drought conditions. The economic output of the district dropped to less than 40 percent of the average real output during the preceding decade (McCullough and

Matson 2011). Although the district has a diverse array of technological and scientific sources of information (McCullough and Matson 2011), path dependency on dams prevented further development of watershed-based complementary strategies to face the increased variability of water supply.

In Arizona, the reservoirs built on the Colorado River (much larger than both the Sonora and Yaqui River reservoirs), together with the CAP aqueduct, have buffered water scarcity. However, long-term drought and heightened water demand have challenged the capacity of this complex system to provide water and energy in the quantity, timing, and quality it was designed for. Arizona has developed combined hard and soft path strategies to support the river storage system, particularly in urban areas (i.e., the active management areas [AMAs]). However, climate change and variability coupled with rapid demographic and economic growth continue to exert pressure on the Colorado River system. In contrast to Sonora, in Arizona, a better organized civil society and academia have pushed the consideration of ecological flows in water planning, which may contribute to enhanced adaptive management in the long term. Nevertheless, in both cases, hard and soft path policies still need further modification (readaptation) particularly to better integrate multiple sectors, especially as integrative approaches like the food-energy-water nexus gain momentum. Also in both states, a predominance of the urban and large-scale agricultural sectors in defining water policy directions (and historically, also determining the construction of dams) has been detrimental to environmental security, in general, and to water security of rural communities in particular (Lutz-Ley 2014).

To strengthen water security and adaptive outcomes in the future, reservoir planning needs to do the following:

(1) Better account for hydroclimatic and water demand uncertainties over longer timeframes;
(2) Strengthen institutional learning in relation to reservoirs (reoperations as well as mechanisms to address growing civil society critiques of hard path dependence);
(3) Increase the flexibility of policies for infrastructure that better address governance through further inclusion of all stakeholders involved, not only those directly benefitted or financially involved; and
(4) Build decision-making on science–policy linkages to underscore reservoir infrastructure coupled to governance mechanisms, which would need improved information systems and regionalized climate models (if possible, to the level of basins).

Based on the overview provided above, the principal characteristics of water security management in Arizona and Sonora are synthesized in Table 2.1.

Following this, an empirical study of stakeholder perceptions of water security and the role of infrastructure comparing the two states is presented.

Table 2.1 Comparative overview of factors contributing to water security

Global-change resilience factors contributing to water security	Sonora	Arizona
Hydroclimatic variability:	Medium-high:	High:
– Drought occurrence	– High drought risk	– Extreme drought risk
– Flooding, severity	– Frequent, severe floods	– Moderate flooding
Water storage, conveyance, infrastructure:	Hard path:	Post-hard path:
– Reservoirs	– Under development	– Overbuilt, no new plans
– Interbasin transfers	– Early stages	– Post-CAP soft measures
– Groundwater storage, recovery, banking	– Not currently practiced	– Well developed
– Water reuse	– Informal, undeveloped	– Well developed
Adaptive water management:	Nascent stages:	Moderately advanced:
– Water allocation frameworks	– Flexible administered	– Rigid, rights-based
– Risk assessment/insurance	– Emerging	– Developed
– Public awareness	– Moderate	– Moderate, politicized
– Demand management/pricing	– Nascent	– Active in urban areas
– Integrated water-energy-food security	– Nascent	– Nascent
– Institutional learning	– Active	– Moderate
Institutional arrangements:	Centralized:	Polycentric:
– Water rights	– Regulated, unenforced	– Legal rights, enforced
– Agency mandates, financing	– Clear, inadequate $	– Overlapping, declining $
– Stakeholder coordination	– Opaque	– Transparent
– Civil society participation	– Low/non-existent	– Medium/structured
– Science-policy dialogues	– Nascent dialogues	– Active, results unclear
Water security:	Moderate-low:	Moderate-high:
– Societal	– Moderate	– High
– Ecological	– Low	– Low

2.3 Empirical Study Methods

2.3.1 Goals and Questions

The purpose of the empirical study of stakeholder perceptions is to undertake a comparative assessment of the factors affecting water security in Arizona and Sonora considering: (1) hydroclimatic and water demand uncertainties; (2) the capacity for institutional learning in relation to reservoirs in the broader context of hard path and soft path strategies; (3) the level of flexibility of policies for infrastructure that also address water governance; and (4) the existence of science–policy linkages to underscore reservoir infrastructure coupled with governance mechanisms to improve resilience. Through application of surveys to selected water sector stakeholders in both Sonora and Arizona, we aim to answer the following questions:

- What are the most important factors influencing water security in Arizona and Sonora?
- How do stakeholders in both states perceive the effectiveness of hard path strategies to improve water security in comparison to soft path strategies?
- Which are the discrepancies between the investment in the water sector perceived by stakeholders in both states and the preferences for future funding strategies considering water security?
- How can hard path and soft path strategies be compared in terms of their outcomes in both states?
- Which are the institutional strategies that stakeholders in Sonora and Arizona consider to be important for improving governance and water security?

2.3.2 Participants

Recruitment of 105 potential respondents (50 in Arizona and 55 in Sonora) was done through e-mail invitations that provided a brief explanation of the study, the assurance of confidentiality and protection of data, and the link to the online survey. The potential respondents were purposively selected from governmental, academic, and civil society groups representing water and environmental issues or management. A total of 50 completed surveys (48 %) were received online—34 from Arizona (68 % response rate) and 16 from Sonora (29 % response rate). An additional eight surveys were applied in person by the researchers through a snowball technique. These participants include governmental officers from the water utility in Hermosillo, the state's water agency (CEA Sonora), and the federal water agency (CONAGUA). Of the total of 24 participants in Sonora, 50 % were from the academic sector, 33 % from the government, and 17 % from civil society and private sector organizations. An advantage of the in-person surveys was the elicitation of detailed comments and perspectives on water security from the participants. Overall, the combined response rate was 55 %.

2.3.3 Instruments

A questionnaire survey was developed, related to ongoing water security research by the University of Arizona's Udall Center for Studies in Public Policy, which has existing approvals for human subjects research via the Institutional Review Board. The survey was administered online through Survey Monkey in both English and Spanish and consisted of descriptive data (organizational affiliation and state of respondent) and seven questions using a combination of Likert-type ranking text boxes and checklist formats. In Survey Monkey, the random sequencing of potential responses for each question was used in order to minimize the bias that might result from preset sequencing. While 50 of the surveys were completed online, eight were applied in person in Spanish. These were printed versions of the same survey that was available online.

2.3.4 Analysis Procedures

Preliminary analysis was done using the data processing tools provided online by Survey Monkey; secondary analysis was conducted in Microsoft Excel. Survey Monkey generates descriptive statistics of responses, the average score of ranking and Likert-type questions, and total summaries for checklist questions. Those preliminary results were further processed to obtain final results and graphical representations of participants' responses. We accompany these with a discussion of factors likely to explain the observed results for individual questions and components of the survey.

2.4 Results

2.4.1 Factors Affecting Water Security (Fig. 2.2)

In both Sonora and Arizona, inadequate management of water was ranked most frequently as the most important factor affecting water security. Arizonans gave

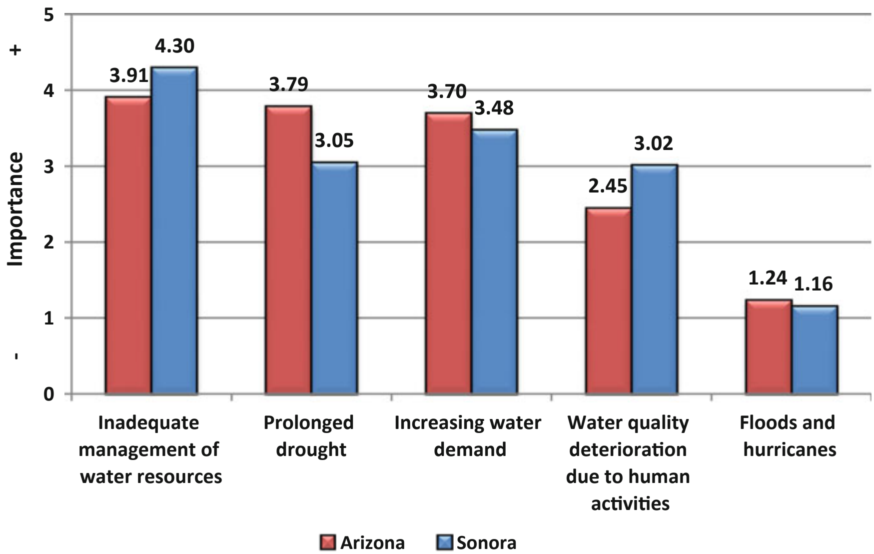

Fig. 2.2 Factors affecting water security

higher importance than Sonorans to prolonged drought as the next most important factor affecting water security, while Sonorans considered increasing water demand and water quality deterioration due to human activities as the next most important factors after inadequate management of water.

These findings are partly related to the term prolonged drought being considered in Arizona as shorthand for "climate change," which carries political implications particularly with conservative lawmakers and decision-makers. In Sonora, by contrast, ongoing water-quality impacts of mining (with the recent 2014 tailings-dam spill) and urban sanitation and wastewater challenges are considered to exert important influences on the responses. Water quality in Sonora was a recurrent topic during the surveys conducted in person with governmental officials, who mentioned that quality rather than the quantity was one of the major motivations for construction of the Acueducto Independencia. Because the Abelardo L. Rodríguez reservoir dried in the late 1990s, Hermosillo city has been relying on deep wells in the city's periphery. In the view of the local utility officials, overpumping promoted high concentrations of certain dangerous elements (particularly arsenic) in several wells of the supply system during the last years. The levels in some cases were very close to the limits established by the Mexican Official Norm (NOM) regulating the quality of water for human consumption. However, one official said these finding had not been revealed to the general public in order to prevent further conflicts and demands.

2.4.2 *Effectiveness of Strategies for Enhancing Water Security* (Fig. 2.3)

Participants in Arizona ranked price mechanisms as the most effective way to enhance water security. Participants in Sonora ranked policies for efficiency higher than Arizonans in terms of achieving improved water security. In general terms, Sonoran participants considered soft path strategies to be more effective for enhancing water security than did participants in Arizona.

2.4.3 *Perceived and Desired Investment in Water Management Strategies* (Fig. 2.4)

Participants were asked their perceptions on the percentage of total investment in different types of strategies in Arizona and Sonora over the last 10 years, as well as the percentage they would like to see invested in each of these in the coming decade.

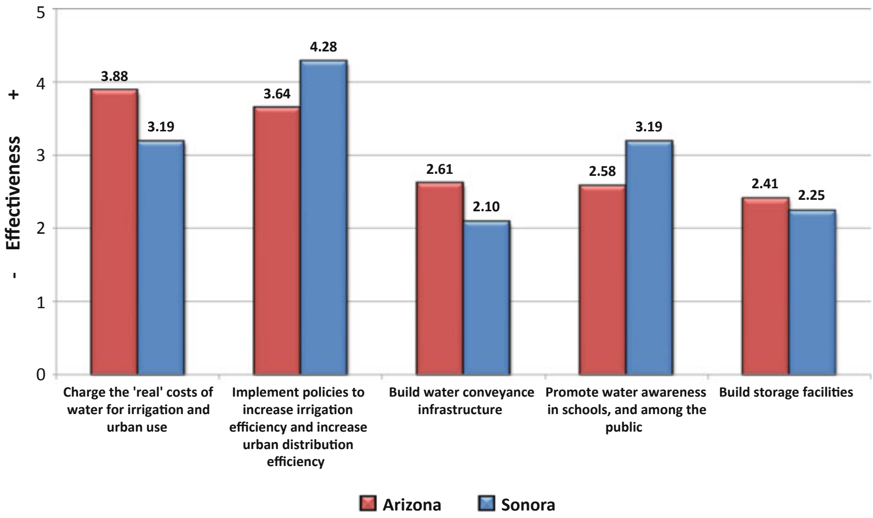

Fig. 2.3 Effectiveness of strategies for enhancing water security

Participants in Sonora think that an average of 45 % of financial resources during the last 10 years have been invested in building new aqueducts and inter-basin transfer projects, followed by 17 % in increased groundwater pumping (considering costs of electricity and equipment). This arises from the recently commissioned, often controversial, Acueducto Independencia that was built to transfer up to 75 MCM from the mid-Río Yaqui basin to Hermosillo city, in the lower Río Sonora basin. Groundwater pumping and aquifer drawdown are pervasive practices in both states. Clearly, each of these strategies incurs costs to different sectors in society; i.e. aqueducts and transfer projects are publicly funded while pumping is largely private. In the coming decade, Sonoran respondents would like to see at least 22 % of investments in the water sector going to wastewater treatment, 19 % to improved drainage for stormwater recharge, and 14 % to awareness and conservation programs.

Participants in Arizona think that approximately half of the investments during the last 10 years in their state have gone to three main strategies: water awareness and conservation programs (18 %), increased wastewater treatment (16 %), and increased groundwater pumping (16 %). Arizona respondents would like to maintain the current principal strategies into the coming decade, but decrease groundwater pumping and improve water markets and policies connecting water and energy (20 % of the investment on average).

What is notable in both states, at present and especially in the future, is the relatively low priority accorded to increased water storage in dams (or new dams), aqueducts, or interbasin transfer projects.

2.4.4 *Strategies to Enhance Governance for Water Security* (Fig. 2.5)

In terms of the strategies for improving governance of water security, respondents in both Arizona and Sonora consider evaluation and dissemination of water management outcomes as the most effective way for enhancing governance of water security.

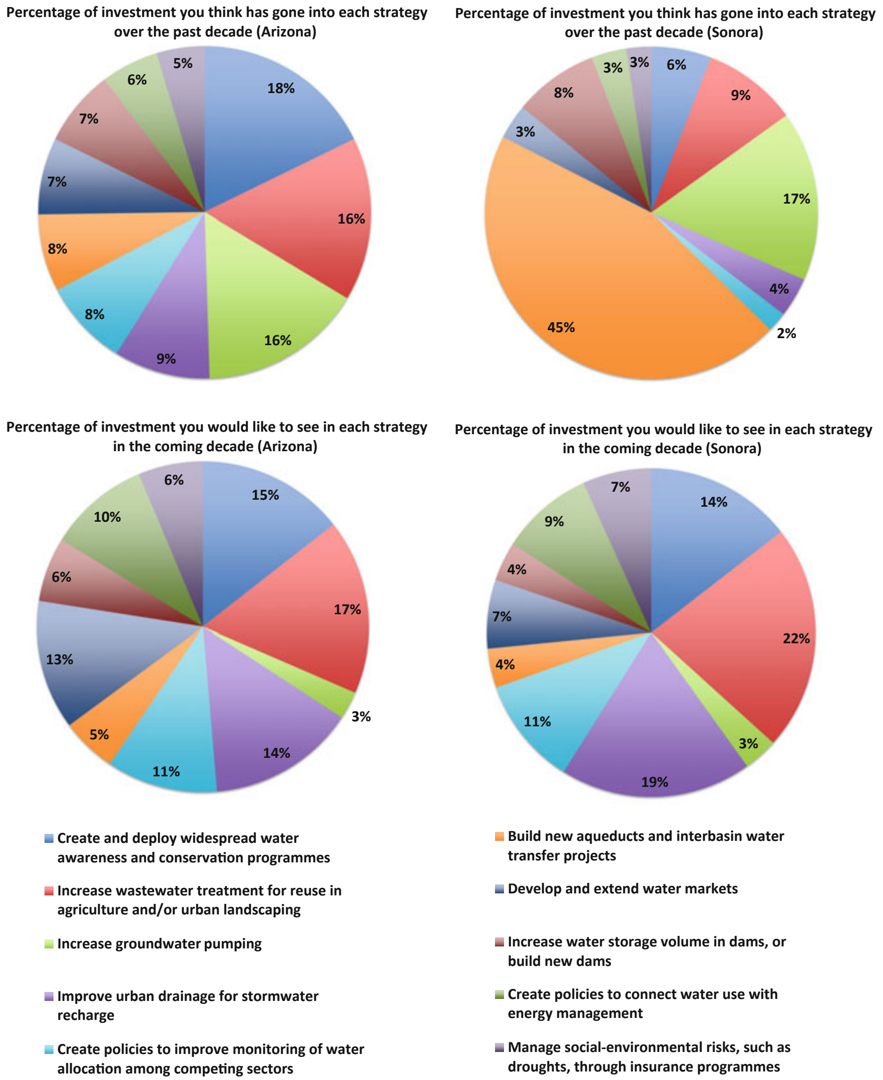

Fig. 2.4 Perceived and desired investment in water management strategies (Arizona, *left*; Sonora, *right*)

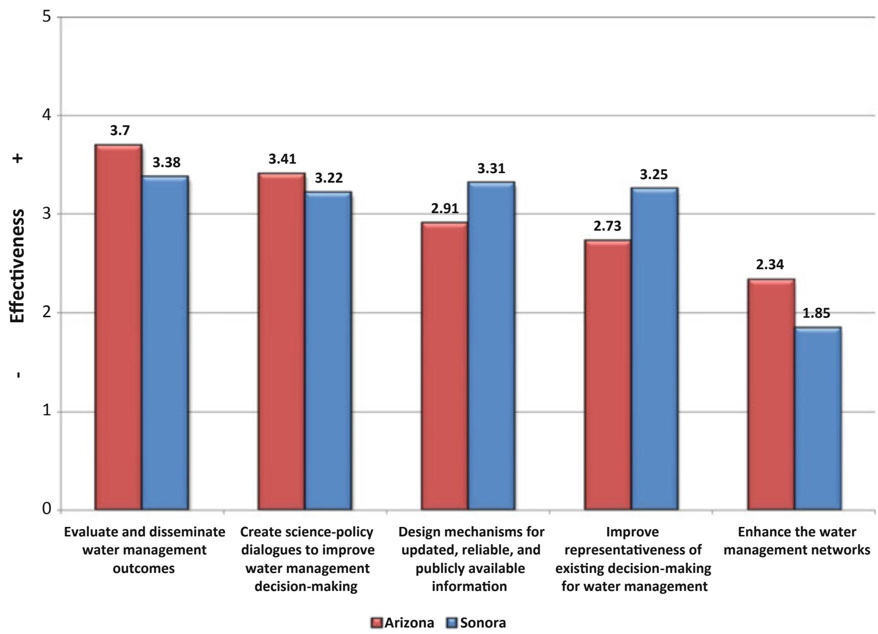

Fig. 2.5 Strategies to enhance governance for water security

In addition, both Arizona and Sonora participants place high value on updated, reliable, and publicly available information on variables affecting water resources. By contrast, enhancing water management organizational networks was ranked in both states as the least effective strategy to improve governance. The context of Sonora as part of a country with recurrent issues of transparency and corruption are reflected in the higher scores given by Sonoran participants to the necessity to have reliable sources of information, as well as improved representativeness in decision-making bodies and procedures. For example, during the in-person surveys with public officials in Sonora, all the respondents agreed that the aqueduct solved a notorious supply problem for Hermosillo city, but they also agreed that the political and social treatment of the issue could have been much better and more inclusive than was done by the state government.

2.4.5 Outcomes Attributable to Hard Path and Soft Path Strategies (Fig. 2.6)

This section of the study requires some clarification. The intent was to reverse the line of questioning from the first part of the survey in which survey respondents were asked which strategies contributed to water security. Here, respondents were

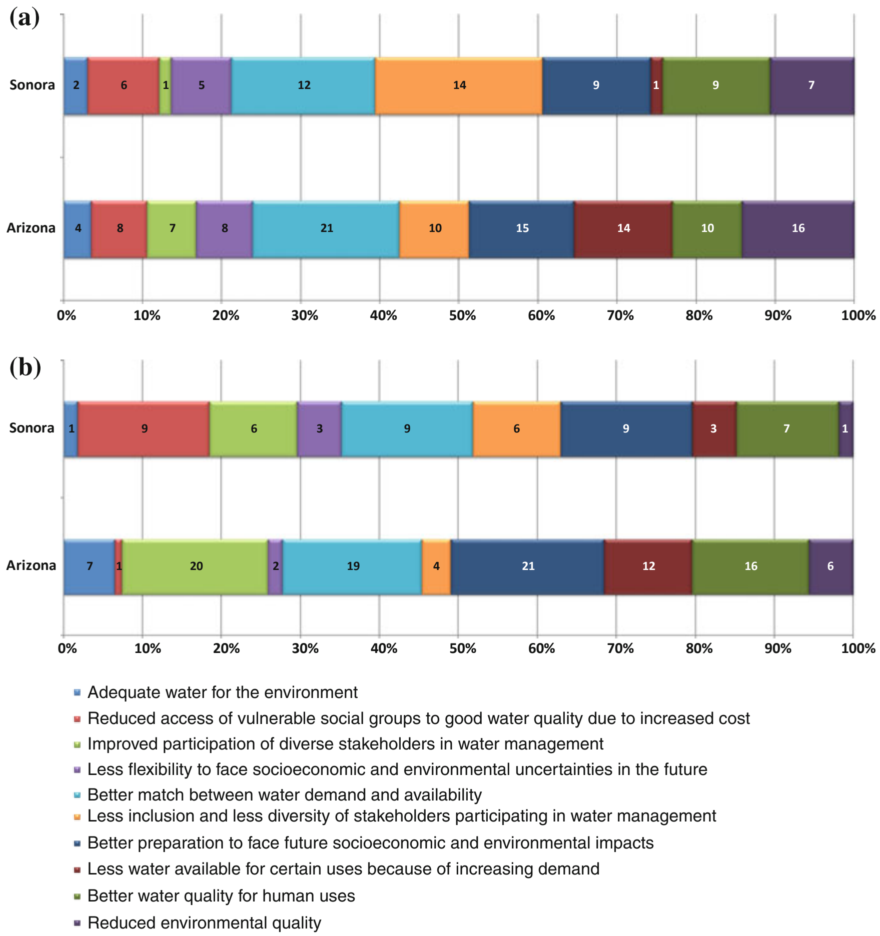

Fig. 2.6 Outcomes attributable to **a** hard path and **b** soft path strategies

asked to check the principal outcomes of hard path (infrastructure-led) strategies compared to the same set of outcomes they considered to result from soft path (policy-led) strategies.

In Sonora, the two most frequently indicated outcomes of water infrastructure are less inclusion and diversity of stakeholders participating in water management (selected 14 times) and a better match between water demand and availability (12). In turn, the outcomes of water policies (soft path strategies) more frequently mentioned were the reduced access of vulnerable groups to good water quality due to increased cost (selected 9 times), better match between water demand and availability (9), and better preparation to face future socioeconomic and environmental impacts (9). There is understandable concern that pricing water as a means to reduce demand will result in disadvantaged populations losing access. In fact, one official from the water utility in Hermosillo mentioned high cost as one of the main constraints for pursuing alternative sources of water, such as a desalination plant on the Gulf of California coast. Nevertheless, the principal representative from the federal agency CONAGUA indicated that a desalination plant was still economically feasible if big agricultural producers helped to offset the costs for the city.

In Arizona, too, a better match between water demand and availability (21 responses selected) is the most frequently mentioned outcome of water infrastructure, and better preparation to face future socioeconomic and environmental impacts (21) is the most mentioned outcome of water policies. Another frequently mentioned outcome of water policies is improved participation of diverse stakeholders in water management (20). This reflects social learning and participatory approaches to water management.

2.5 Discussion

In general terms, the results are indicative of the major impacts assigned to human management as compared to natural or climate-related factors that influence water security. In particular, reservoirs are viewed as one of multiple adaptation strategies. It is interesting to note that floods and hurricanes did not receive a high score, especially in Sonora, which has borne severe impacts from these events in the near past and is expected to face further extreme events in the future. This coincides with the broader managerial approach in Sonora that emphasizes adaptation to drought, instead of a framework that includes the full range of potential hydroclimatic events in the region under climate change scenarios. Underestimation of the full range of events could also have been associated with the higher priority accorded to soft path measures in Sonora compared with Arizona. While scarcity of water can be addressed through a combination of supply and demand management policies (and Sonoran respondents actually think that a big proportion of water investments during the last decade were directed to hard path strategies, and that educational programs are necessary), riverine flooding may require more than behavioral or institutional (soft path) solutions—that is, improved operation and management of existing reservoirs and associated floodworks. As commented, however, cyclone landfall and coastal-zone flooding are less amenable to infrastructural solutions.

The recent experience of Sonora in building the Acueducto Independencia, and the implementation of Sonora SI in general, are reflected in the responses of participants, who gave lower scores to infrastructural solutions than in Arizona in terms of enhancing water security. "Traditional" or "monumental" infrastructural solutions in Sonora have also been associated with lower public participation, often contributing to important social conflicts, making large infrastructure undesirable in public opinion. However, on the other hand, "greener" and more flexible water infrastructure is deemed necessary (for example, drainage for storm water recharge and wastewater treatment plants). This also reflects the gap—both real and perceived—in localized water infrastructure to solve specific problems: for example, the lack of wastewater treatment that still exists in large Sonoran cities such as Hermosillo as well as in rural communities. Additionally, hard and soft measures are needed to promote sustainable groundwater yield and recharge to minimize the effects of the overpumping that has depleted the Costa de Hermosillo aquifer and threatens other aquifers surrounding the capital city as well as the agricultural valleys of northwest Sonora.

2.6 Conclusions

Infrastructure development has played a critical role in water supply, often fueling growth in demand, in both Arizona and Sonora. Water security in both states is significantly influenced by hydroclimatic drivers, chiefly drought, while growing populations and expanding economic activity (much of it water intensive) drive water demand and therefore the risk of water insecurity. While it can be argued that Arizona embarked on the hard path of dams and reservoir construction earlier than Sonora and therefore has entered a post-hard path stage sooner, the relations that each state has with its federal government (and the role of federal financing, and therefore incentives) are crucially important determinants of the options available to stakeholders. Federal–state institutional design in both Mexico and the United States also influence the locus of adaptive response—that is, which organizations and stakeholders are engaged in assessing water (in) security and subsequently in proposing and modifying adaptation plans for implementation. Arizona's polycentric institutional arrangements are in contrast with Sonora's reliance on centralized federal decision-making.

In addition to surface water storage in reservoirs, infrastructure-based adaptive responses include flexible systems of groundwater storage and recovery as well as wastewater treatment and reuse. In the urban sphere in Arizona particularly, rainwater harvesting from rooftops, parking lots, and streets forms an increasingly important set of water augmentation approaches. All of these interventions must be accompanied by flexible governance arrangements to facilitate priority setting, maintenance and upkeep, and iterative processes of adaptation.

The findings of the empirical survey, set in historical context, point towards an emerging integrated view of water security resulting from infrastructure (especially that which is already built and in place) combined with more flexible and adaptive water management and policy. It appears evident, particularly with tight budgets and growing concern over social equity, that greater emphasis will be placed on soft path measures in the future than on hard path measures.

Particularly in river basins where water resources are overallocated, reliance on increasing reservoir storage as the principal adaptive governance tool in the context of climate change must increasingly be complemented by policy measures that respond to hydroclimatic and water demand uncertainties. Additional adaptation tools include basin-wide planning of water storage (especially to avoid low-elevation, high-evaporation storage), efficiency in irrigation and urban water distribution with regulations and enforcement on expansion of new demands for saved water, wastewater reclamation and reuse including effluent storage and recovery techniques, and conjunctive surface and underground storage programs that innovate with groundwater banking and flexible water allocation (e.g., substitutions and exchanges). Social learning will be enhanced through information deployment and uptake, tailored modelling studies that include user-generated data, and collaborative adaptation planning. Finally, management and policy for infrastructure that accounts for multiparty cost-shared financing and civil society participation in decentralized decision-making will enhance water governance for climate resilience.

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