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A comprehensive sustainability appraisal of water governance in Phoenix, AZ

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ABSTRACT

In Phoenix, Arizona and other metropolitan areas, water governance challenges include variable climate conditions, growing demands, and continued groundwater overdraft. Based on an actor-oriented examination of who does what with water and why, along with how people interact with hydro-ecological systems and man-made infrastructure, we present a sustainability appraisal of water governance for the Phoenix region. Broadly applicable to other areas, our systems approach to sustainable water governance overcomes prevailing limitations to research and management by: employing a comprehensive and integrative perspective on water systems; highlighting the activities, intentions, and rules that govern various actors, along with the values and goals driving decisions; and, establishing a holistic set of principles for social–ecological system integrity and interconnectivity, resource efficiency and maintenance, livelihood sufficiency and opportunity, civility and democratic governance, intra- and inter-generational equity, and finally, precaution and adaptive capacity. This study also contributes to reforming and innovating governance regimes by illuminating how these principles are being met, or not, in the study area. What is most needed in metropolitan Phoenix is enhanced attention to ecosystem functions and resource maintenance as well as social equity and public engagement in water governance. Overall, key recommendations entail: addressing interconnections across hydrologic units and subsystems (e.g., land and water), increasing decentralized initiatives for multiple purposes (e.g., ecological and societal benefits of green infrastructure), incorporating justice goals into decisions (e.g., fair allocations and involvement), and building capacity through collaborations and social learning with diverse interests (e.g., scientists, policymakers, and the broader public).

1. Introduction

Research on water resource governance has been limited in scope, synthesis, and integration both broadly and in our study region of Phoenix. Although numerous studies have been conducted in Arizona and the Phoenix area, for instance, they focus on particular segments of the water system (e.g., infrastructure; Pulwarty et al., 2005), components of governance (e.g., water conflicts; Bolin et al., 2008), or elements of sustainability (e.g., safe yield; Gober et al., 2010). Few studies address the entire water governance regime with a comprehensive, actor-oriented perspective (Wiek and Larson, 2012). Yet such studies provide an overall account of the sustainability of water governance regimes, thereby promoting innovation and reform (Quay, 2010). To address these gaps and aims, our holistic appraisal poses the following questions in metropolitan Phoenix:

1. How and why do various actors use, impact, and otherwise interact with hydro-ecological and technological systems in carrying out water governance activities?
2. How does the current water governance regime adhere to a comprehensive set of sustainability principles, or not?

We focus on Phoenix, Arizona because of the challenges faced by this region, which are similar to other arid and growing cities. In addition, much research has been conducted on specific water issues in the area, thereby allowing a synthesis of previous research in our comprehensive appraisal. Boundary work across the science and policy spheres is also underway in the area, and thus, our appraisal advances collaborative decision making and the regional dialogue on sustainability. Though we examine metropolitan Phoenix in

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particular, the approach is applicable to other regions around the world, especially urban and urbanizing ones. Finally, the framework we employ can facilitate comparative assessments across regions.

Building upon proposals to integrate actor-oriented perspectives with system dynamics (Binder et al., 2004), we apply a recently developed framework for evaluating sustainable water governance (Wiek and Larson, 2012). The holistic approach focuses on what people do with water and why. We especially consider the people affecting and effected by the water system, who in turn are responsible for its viability and integrity as *governance actors* (Ludwig, 2001; Ostrom, 2009). Beyond considering socio-political dynamics, our analytical and normative goals involve 1) examining interactions between actors and biophysical and technological systems, and 2) assessing water governance sustainability with an integrated set of principles.

The Wiek and Larson (2012) framework extends Ostrom's (see 2011 review) institutional framework and the broader social–ecological systems approach by focusing on various actors and action situations, including the social rules governing decisions and their interactions with biophysical resources. The approach adds to Ostrom (2011) and other actor-oriented frameworks (e.g., Pahl-Wostl et al., 2010) in that we detail the major interacting activities (or action situations) involved with water decisions specifically (i.e., supplying, distributing, using, and discharging water, along with activities that cut across those activities). The framework also follows Pahl-Wostl et al. (2010) by focusing on actions, rules (institutions), and social–ecological–technological interactions. Although the approach could be coupled with transitions frameworks (e.g., Brown et al., 2009) as well, we focus primarily on how water-specific actors and activities intersect with 'layered' biophysical and technological resources. Uniquely, our holistic approach outlines assorted water resource activities and decisions in relation to an integrated set of sustainability principles drawn from Integrated Water Resource Management (IWRM) and similar work (e.g., Mitchell, 2005, 2006).

Given our actor-oriented approach, we define *sustainable* water governance as *the decision processes of stakeholders who influence and are impacted by activities involving water supplies, deliveries, uses, and outflows in ways that ensure a sufficient and equitable level of social and economic welfare without compromising the viability and integrity of supporting hydro-ecosystems now and into the future* (Wiek and Larson, 2012). This definition draws on broader views of governance as a wide range of social, political, economic and administrative interactions (Pahl-Wostl et al., 2010), inclusive of actors in both the public and private sectors (Peters and Pierre, 1998; Stoker, 1998).

Due to space limitations, we cannot fully detail all the complexities and challenges associated with the numerous issues, actors, goals, and rules of urban water governance. Instead, the goal is a broad-based, qualitative synthesis and appraisal that informs actions and interventions to transform the Phoenix-area water system toward sustainability *as a whole*. Aligned with this purpose, we first establish the integrated, systems framework, and second, describe the general principles used to assess water resource sustainability (see Wiek and Larson, 2012 for more details on the general approach). Next, we synthesize the water governance activities and system dynamics in metropolitan Phoenix and then explain the extent to which the region is meeting (or not) the principles employed in this appraisal. We conclude with discussing recommendations and challenges to sustainable water governance.

2. Conceptual approach

The first part of our framework explains water systems by focusing on key governance activities, relevant actors and institutions (at the core of the social system), and how they interface with biophysical and technological systems. The second part outlines an integrated set of water principles.

2.1. Integrated analysis of regional water governance systems

The systems approach centers on what people are doing with water, in addition to how water is circulating through the social–ecological–technological system (Pahl-Wostl et al., 2010). Applied to a particular system or place, these "doings" broadly include supplying and extracting, treating and distributing, using and conserving, and reusing and discharging water, plus cross-cutting activities spanning them (e.g., planning). In applying the framework, the following considerations are delineated: 1) the scope or scale of the system (i.e., boundaries); 2) core water resource decision domains (i.e., activities), and 3) how the associated actors affect and are effected by social institutions as well as the hydro-ecological and technological systems (i.e., cause–effect structure; Wiek and Larson, 2012).

First, the *Boundaries of the Regional Water System* must be defined. Regional water systems can be delineated in different ways geographically, focusing on biophysical units (e.g. ecosystems or watersheds) or social ones (e.g. local and state to federal and international territories). Regardless of the scope, cross-scale interactions are critical considerations for any sustainability appraisal (Pahl-Wostl et al., 2010). In our appraisal, we focus on the greater Phoenix area since this is the primary scale at which water is hydrologically and legally connected (Jacobs and Holway, 2004). Throughout this paper, references to Phoenix encompass the entire metropolitan region including numerous municipalities, tribal lands, farmland and relatively rural areas, unless "The City of…" denotes a particular municipal government. Additional studies might delineate watersheds, political units, or other scales in their analyses, depending on the specific intent and other logistics.

Second, the *Activity Domains* outline the basic aspects of what people do with water. These activities reflect a broad understanding of major water resource decision arenas (e.g., supplies versus demands) and input from stakeholders (see Methods section, plus Wiek and Larson, 2012). With an input–output oriented view on how water flows through the system, we distinguish among interconnected but distinctive sectors of activities:

i. *Supplies:* how water is obtained, stored, allocated, diverted and managed technologically, institutionally, and otherwise from various sources.
ii. *Deliveries:* how water is distributed, treated, and delivered to end users through engineered and natural infrastructure as well as social institutions.
iii. *Demands:* how people consume and conserve water for various purposes among households, businesses, and governments, in addition to ecosystems.
iv. *Outflows*: how water and sewage is transported, treated, and dealt with after use, including immediate reuse (as effluent, or treated wastewater), groundwater recharge, or discharge back into the hydro-ecological system.
v. *Cross-cutting*: how policy and administration, research and assessment, and civic participation and advocacy span and influence the above activity domains. Although cross-cutting activities pertain to all four domains, this category is important for representing activities that span arenas and address system interconnections, as recommended for integrated water management (Mitchell, 2005, 2006).

Finally, *the Systemic Cause–Effect Structure* details the actors and drivers of activities, along with their outcomes and interactions with various components of the water system (Kallis et al., 2006). Building on Ostrom (2011) and Pahl-Wostl et al. (2010), the assessment provides information on *actors and their guiding intentions and rules*. For each activity, we identify the individual and group actors (private and public) involved in water resource decision making to understand how they interact with (i.e., influence or are impacted by) other actors and institutions (social system), hydrological resources and ecosystems (ecological system), and human infrastructure (technological system) (i.e., as *system interfaces*; Pahl-Wostl, 2007; Pahl-Wostl et al., 2010). Each the social, ecological, and technological sub-systems constitutes a distinctive 'layer' in water systems. A fourth layer—*perturbations*—is also critical since actors must cope with stressors to the system (Fig. 1; Wiek and Larson, 2012).

a) *Social Actors.* Various individuals and organizations undertake activities and make decisions about how water is supplied, distributed, used and treated throughout water systems. Depending on societal goals and rules, government and non-government entities build, use, alter, manage and otherwise impact infrastructure while influencing earth system processes and ecosystem dynamics. Both networks of actors and societal institutions potentially facilitate and constrain activities (Pahl-Wostl, 2002; Pahl-Wostl et al., 2010). Guided by particular intentions or barriers (including perturbations; see below), both formal and informal institutions—respectively including *codified* rules, laws, policies, and mandates as well as *unwritten* social norms, expectations, and customs—must be considered in determining peoples' actions and interactions across system components (Mitchell, 2005; Ostrom, 2011).
b) *Ecological Resources.* Water activities rely on and impact the natural environment, including the basic elements of earth systems. The physical water resources on which life depends interact within and across these spheres based on: hydrological dynamics involving surface and underground water; terrestrial processes pertaining to soils and land use/cover; ecosystem dynamics encompassing vegetation and wildlife; and climatic processes including drought and environmental change, among other system interactions (Wiek and Larson, 2012).
c) *Technological Infrastructure.* Water activities involve creating and maintaining man-made infrastructure and facilities, including: extraction and retention facilities (e.g., dams) for

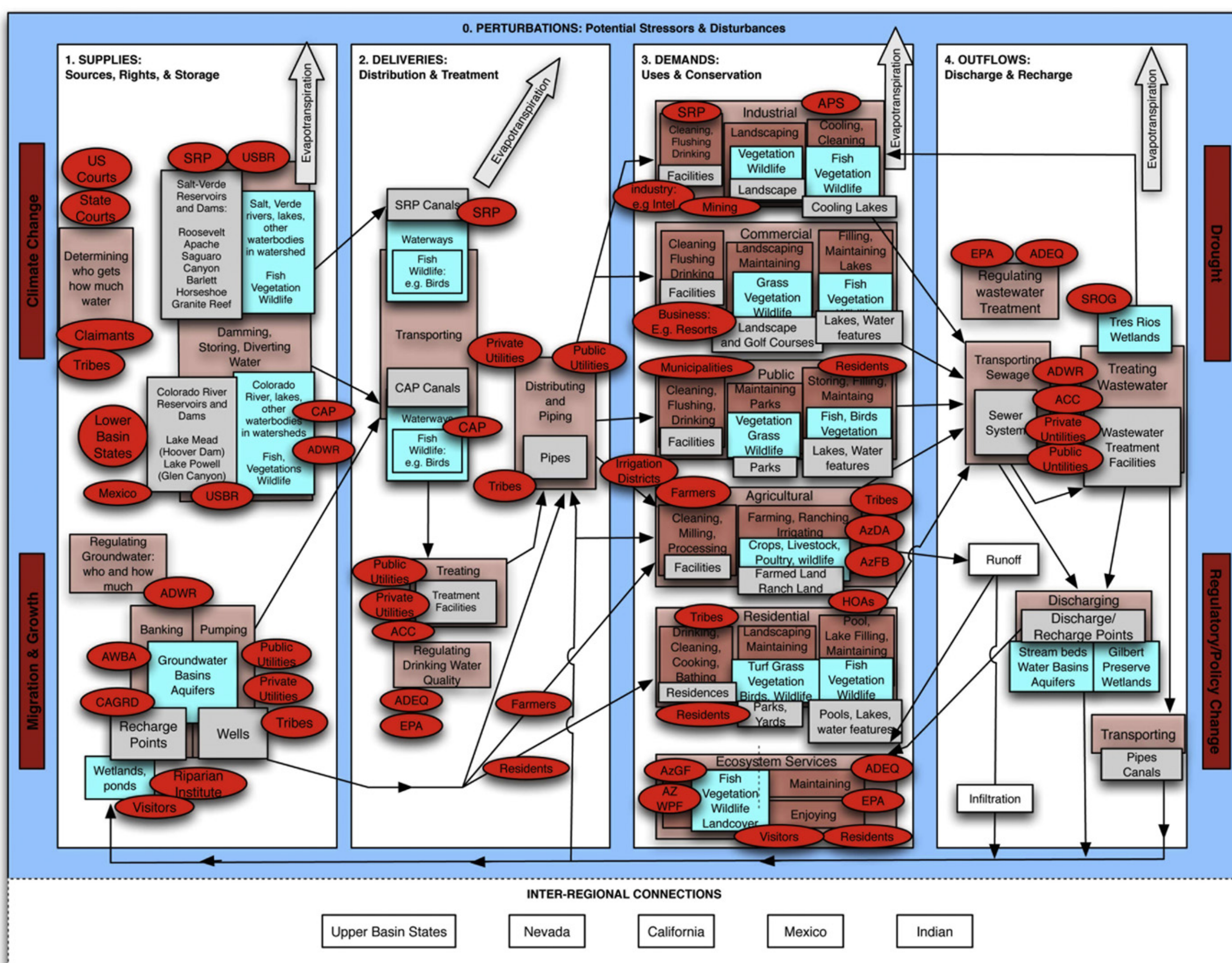

Fig. 1. Water governance information system for the Phoenix metropolitan region. Organized by activity domains, the diagram highlights key actors in *red circles* along with intersecting hydrological and ecological resources in *blue boxes* and human infrastructure in *gray boxes*. More specific key activities are denoted by gerunds in *tan boxes*, and *arrows* imply pathways and interconnections between various water resource activities and supporting natural or technological processes.

supplying water; canals, pipes, and pumps for distributing water; human infrastructure (e.g., pools, fountains, low-flow appliances) affecting water demands; and the treatment facilities involved with cleaning water and managing outflows (Wiek and Larson, 2012). Considering the transition from a "water supply city" to a "water sensitive city" (Brown et al., 2009), human-built infrastructure encompasses traditional 'gray' elements (e.g., dams and canals) as well as 'green' ones (e.g., created wetlands and retention ponds).

d) *Perturbations* influence actors and activities as potential stressors or disturbances to the system, or as barriers or constraints to particular decisions (Wiek and Larson, 2012). Critical perturbations involve climate and other environmental changes, along with shifts in growth and migration as well as modifications in regulations or policies governing regional decisions (Gober et al., 2011; Overpeck and Udall, 2008).

The information gathered on system dynamics can be represented in a layered manner, wherein the interfaces are the intersecting layers on which actors and activities depend (Fig. 1), and which in turn are effected or altered by them (Wiek and Larson, 2012).

2.2. Sustainability principles for water governance

The appraisal is based on a set of principles for water governance (Table 1), which were derived from literature on integrated water management (e.g., Mitchell, 2005, 2006; Brown et al., 2009; Pahl-Wostl et al., 2010) and sustainability broadly (e.g., especially Gibson, 2006; Ostrom, 2009). Seven principles—each with more precise specifications, or sub-principles—were compiled through iterative discussions among the research team, interviews with experts (see below), and applications to this and other cases (Wiek and Larson, 2012). While each principle is distinctive, they do overlap and affect each other due to intersecting system elements operating in the face of multiple criteria.

1. The principle of *social–ecological system integrity* demands balancing anthropocentric needs and uses of water with those of ecosystems (Gibson, 2006; Mitchell, 2006) by: maintaining or restoring minimum stream flows for wildlife and riparian areas; preserving or enhancing the quality of water through pollution prevention and mitigation; ensuring aquifers are not taxed to points of instability (e.g. land subsidence); and, recognizing and coordinating resource uses and impacts within hydrologic units such as watersheds and groundwater basins (Mitchell, 2005).
2. The principle of *resource efficiency and maintenance* stresses getting the greatest benefit from using as little water as possible while minimizing excessive uses (efficiency) and avoiding irreversible actions or outcomes (maintenance) (Gibson, 2006). This involves: reducing water use through technological and behavior change; recycling water by reusing gray water or treated wastewater; eliminating water losses from leaky infrastructure or evaporation; and not extracting groundwater at rates that exceed recharge (Gleick, 2002; Jacobs and Holway, 2004).
3. The principle of *livelihood sufficiency and opportunity* ensures fair access to a sufficient quantity and quality of water for: basic livelihood needs for drinking, eating, and sanitation; recreation and enjoyment for broader personal and societal well-being; and, economic activities that depend on water (Gibson, 2006). Of course, in the face of tradeoffs, hard decision must be made across decision and outcomes (Mitchell, 2006).
4. The principle of *civil engagement and democratic governance* calls for participation and collaboration among all relevant and interested stakeholders. This entails: considering the interests, needs, and perspectives of local actors who affect or are effected by water resource decisions (Ostrom, 2009); engaging diverse stakeholders through various stages of decision making, from problem formulation and goal setting through to implementation, assessment, and adaptive changes; and establishing collaborative decision processes among entities who share resources or live in the same region (Larson and Lach, 2010). Ultimately, such participatory decision making leads to social learning and the co-production of knowledge, both of which are central to transforming society toward sustainability (White et al., 2008; Pahl-Wostl et al., 2010).
5. The principle of *inter-generational and intra-generational equity* safeguards equitable access to a sufficient quantity and quality of water for current and future residents (WCED, 1987; Gibson, 2006) by: guaranteeing all residents have access to safe water for basic needs; ensuring a fair distribution of benefits and costs among various stakeholders; facilitating fair involvement in decision making based on diverse representation (Larson and Lach, 2010); and, providing representation for future generations. The latter could be achieved through the use of delegates, as proposed and approved during the Rio+20 Conference in June 2012.
6. The principle of *interconnectivity from local to global scales* ensures the allocation and management of resources across hydrologic basins, which encompass the land area within which water flows and is interconnected as it moves downhill to an outlet such as the sea (Mitchell, 2005). This principle entails: minimizing negative impacts on actors and activities including those downstream; planning across political jurisdictions that are hydrologically interconnected within river and groundwater basins (Pahl-Wostl et al., 2010); and, considering and coordinating activities and impacts across local to broader scales of interaction (Ostrom, 2011).
7. The principle of *precaution and adaptability* calls for anticipating potential problems as well as mitigating and responding to them (Gibson, 2006) by: studying and understanding perturbations and possible impacts; lessening the stressors or effects of changes to the system; and, facilitating adaptations now and in the future through capacity building, policy making, behavior change, and other mechanisms for coping with systems changes and stressors (Pahl-Wostl, 2007).

3. Appraisal methods

Data and evidence for the analysis of water governance in Phoenix (Phase 1) and the sustainability appraisal (Phase 2) was gathered primarily from published literature and policy documents, along with expert interviews. We interviewed seven stakeholders with substantial knowledge of the water system in the Phoenix region to critique and validate our approach and assessment. The informants were purposively selected to represent diverse interests involved with boundary activities at the Decision Center for a Desert City (DCDC): two academics (one social and one ecological scientist); three 'policymakers' or managers (one each focused on the provision and quality of water and state policies), and two additional interests (one local environmental interest and one lawyer who deals with land development).

Interviews lasted approximately an hour, during which time student research assistants took notes about 1) the structure and perceived challenges for regional water governance, and 2) how the sustainability principles have or have not been met. Upon sharing the principles and our working systems diagram (Fig. 1) with informants, the anonymous professionals also suggested how to revise the appraisal to include the whole array of actors, activities, and interactions. This integrative, stakeholder process helped to validate the appraisal.

Altogether, we synthesized the literature and interview notes to understand the actors, rules, and system dynamics into a visual diagram (Fig. 1) accompanied by the following narrative (see also the Supplementary, summary table online). We now explain the major governance activities and actors across the water system interfaces of metropolitan Phoenix. Although we cannot provide intensive details on particular issues, we aim for an overall appraisal of how people and social organizations supply, treat, distribute, use, discharge and plan for water resources in the greater region.

4. Water governance in metropolitan Phoenix

A myriad of actors and institutions determine how water is used, managed, and treated as it flows through the social–ecological–technological system, ultimately resulting in various impacts and tradeoffs within and beyond the region. Below, we briefly detail ‘who does what with water’ to offer a holistic, actor-oriented view of water governance—organized by the five activity domains—for the sustainability appraisal that follows.

4.1. Water supplies

The Phoenix region has four primary sources of water: local rivers in the Salt-Verde watersheds, water from the Colorado River, groundwater, and effluent (Fig. 2). Each source is governed by different actors and institutions, as described below.

4.1.1. Salt-Verde River water

Rights to surface water are granted based on the ‘first in time, first in right’ principle, which means early settlers and settlements have senior rights over junior users who lose their allocations first during shortages. Despite Native Americans being ‘first in time,’ early rights were largely granted to agricultural settlers. Thus, local Native tribes have had to demand and negotiate their water rights. Under the 1908 Winters Doctrine, the law guarantees tribes enough water to meet the needs of reservations. Yet negotiations can take decades, and identifying water sources for allocations can be controversial (Smith and Colby, 2007). In the Phoenix region, the Gila River Community gained rights to 806.1 million cubic meters (m^3) (653,500 acre-feet, or af) of water through a 2004 settlement, while the Salt River Pima-Maricopa tribe gained 151 million m^3 (122,400 af) in 1988 and the Fort McDowell tribe gained 44.8 million m^3 (36,350 af) in 1990. Despite such rights to local rivers such as the Gila, most tribal settlements are honored with water from the Central Arizona Project (see more on the Colorado River below).

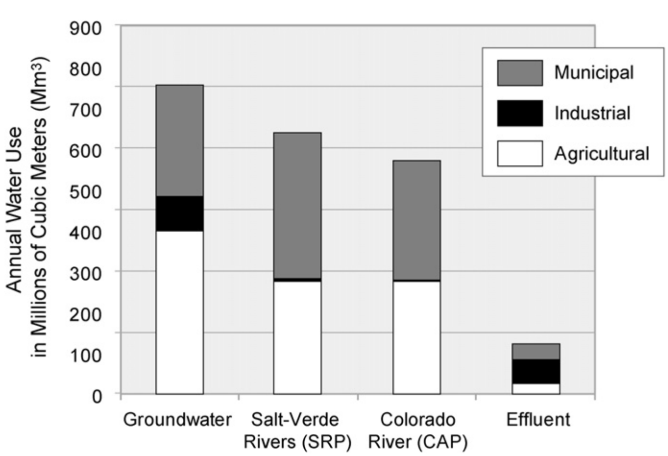

Fig. 2. Average annual water usage by source and sector for the Phoenix Active Management Area 2001–2005 (ADWR, 2010).

Adjudication and legal procedures continue to clarify water allocations while disputes continue to erupt over rights. Recently, for example, the Salt River Project (SRP)—which has senior rights to this water source over tribes and others—has contested groundwater pumping of the Big Chino aquifer in the Verde Valley, upstream of Phoenix, where groundwater is thought to feed the Salt-Verde Rivers downstream (Bolin et al., 2008).

To cope with another critical uncertainty, specifically high intra- and inter-annual variability in stream flows, the 1902 U.S. Water Reclamation Act funded the creation of the Roosevelt Dam and Reservoir to store up to 2.0 billion m^3 (1.7 million af) of water (SRP, 2011). Although dams are owned and overseen by the U.S. Bureau of Reclamation (USBR) nation-wide, the Salt River Project is a combined private–public initiative responsible for managing seven dams and reservoirs along the Salt-Verde Rivers, which have a total capacity of 2.9 billion m^3 (2.3 million af). SRP operates and maintains this storage infrastructure, along with 250 groundwater wells. They also administer the timing and delivery of nearly 1.2 billion m^3 (1 million af) of water to homes and businesses in their service area, which includes ten municipalities that receive water and five more that receive electricity (SRP, 2011).

As local rivers have been diverted for human uses, expansive areas of irrigated lawns and over 650 mad-made lakes and ponds have replaced narrow zones of riparian vegetation (Larson et al., 2005). Downstream of the regional dams, the Salt and Verde channels remain dry for much of the year. Changes to local hydrology have led to degraded ecosystems and endangered species, with ten species in Maricopa County designated as such by the U.S. Fish and Wildlife Service (USFWS, 2011) under the Endangered Species Act. Imperiled species include four types of fish and birds reliant on aquatic habitat. To comply with this and other federal laws such as the Migratory Bird Treaty Act, SRP undertakes activities such as an Avian Protection Program while permitting employees to take actions for preserving, rescuing, or moving birds, nests, and eggs.

4.1.2. Colorado River water

Beyond local watersheds, the Central Arizona Project (CAP) diverts and pumps water from the relatively distant Colorado River. Based on the Boulder Canyon Project Act of 1928, Arizona’s allotment is 3.6 billion m^3 (2.8 million af), an amount less than California’s 5.4 billion m^3 (4.4 maf) but much more than Nevada’s 0.4 billion m^3 (0.3 maf) (August and Gammage, 2007). For 25 years after this agreement, Arizona fought to secure its water, which unless diverted would flow downstream to California. Because of the ‘use it or lose it’ principle of prior appropriation law, the state sought to acquire its full allocation in advance of actual needs by creating the Arizona Water Banking Authority (AWBA, 2007). AWBA diverts water to underground savings facilities where water is stored for future use. AWBA also stores water for Nevada, in addition to providing water for tribal settlements. In 2010, AWBA recharged 261.1 million m^3 (211,712 af) including 23.4 million m^3 (19,000 af) for Nevada. From 1996 to 2010, the Authority transported and stored a total of 4.6 billion m^3 (3.8 million af), which would have otherwise gone ‘unutilized’ by the state (AWBA, 2010).

As a political compromise to secure funding for the CAP canal that now transports Colorado River water 541 km from the western border of the state to central Arizona, the state consented to junior rights, which means Arizona is the first to be cut-off in times of drought or shortages in the basin (USBR, 2010). Since the total 20.2 billion m^3 (16.4 million af) of water estimated during negotiations in the 1920s was based on data from the wettest century over the past 500–1200 years, the river is over-allocated and likely to experience shortages in the future (Hirt et al., 2008). On August 13, 2010, Lake Mead was at 331.3 m (m, or 1087 feet), the lowest level since 1956 and only 3.7 m (12 ft) above the 327.7 m (1075 ft) trigger point established by a 2007 shortage-sharing agreement among the states. Shortage allocations for Arizona would amount to 2.8–3.1 billion m^3 (2.5 million af), or more than a 10% cut. In early 2011, however, the Bureau of Reclamation sent 14.3 billion m^3 (11.6 maf) of water from upstream Lake Powell to Mead, raising the water levels to 9.1 m (30 ft) above the "danger zone" (McKinnon, 2011).

In anticipation of reduced flows and allotments, water managers' tradition of augmenting supplies (Gleick, 2002) currently prevails through Project ADD–Acquisition, Delivery, and Development–Water, an initiative by the Central Arizona Protect to secure more resources (CAP, 2007). The 'Drop 2' reservoir was initiated by inter-state negotiations over shortage-sharing in the Basin. With substantial funding from Nevada, the new reservoir is being built at the border with Mexico to increase storage downstream of Lake Mead in the U.S. This reservoir also ensures 'excess' water does not flow into Mexico—that is, beyond the 1.9 billion m^3 (1.5 million af) allocated to the nation according to a treaty signed in 1944. Another international agreement in 1973 established salinity standards since water quality is greatly diminished due to diversions and evaporative losses as the river flows downstream through the desert. Shortly thereafter in 1974, the U.S. authorized the Yuma Desalting Plant (YDP) with the intent of removing salt before delivery to Mexico (Judkins and Larson, 2010).

Before the YDP was built in 1992, agricultural drainage from Arizona was directed via a bypass canal to the Cienega de Santa Clara, thus creating a biologically diverse wetland ecosystem with thriving birds and wildlife (Judkins and Larson, 2010). Although operating the YDP was initially unnecessary because of a wet period, states including Arizona started looking to the desalting plant as an additional water supply when a long-term drought began around the turn of the century. In response to disputes over depriving this wetland ecosystem of water by operating the plant, U.S. stakeholders developed a collaborative working group to pursue agreeable resolutions to this conflict. CAP officials led the workgroup process, which only involved US interests while excluding Mexico from the discussions, but the group did develop recommended solutions to this conflict (see Judkins and Larson, 2010 for details).

4.1.3. Groundwater

Increasing reliance on the Colorado River in the late 1900s has allowed the state to wean itself off non-renewable 'fossil' aquifers to some degree, but groundwater still represents 39% of supplies for the region (Fig. 2). From historic to present, groundwater pumping has led to the drawdown of water tables as well as land subsidence and fissures (ADWR, 2010). Arizona adopted the 1980 Groundwater Management Act (GMA) to address overdraft problems in exchange for federal funding of the CAP canal, but this happened only after a political ultimatum under President Carter (see Connell, 1982; Hirt et al., 2008 for historic reviews).

The primary goal of the GMA in the greater Phoenix area is safe yield by 2025 (Connell, 1982), which mandates that groundwater only be withdrawn at rates that are replenished (Jacobs and Holway, 2004). The Arizona Department of Water Resources (ADWR) was established to oversee implementation of the GMA over a series of five planning stages. Thirty years later, however, overdraft remains a problem due to how the GMA has been implemented and loopholes that have developed since then (for details, see Hirt et al., 2008; Maguire, 2007). In 2005, groundwater withdrawals amounted to 1.0 billion m^3 (813,000 af), with 29.7 million m^3 (24,100 af) of natural recharge and 136.1 million m^3 (110,303 af) of artificial recharge leading to 837.0 million m^3 (678,597 af) of overdraft (ADWR, 2010). Meanwhile, funding for ADWR has been substantially cut by the state in the face of declining budgets and a lack of political will to support the agency (Larson et al., 2009a). From 2009 to 2011, resources declined from 236 to 98 employees and from \$21.6 to \$7.1 million (AMWUA, 2010).

Although the GMA and associated institutions are far too complex to detail here (for more information, see Colby and Jacobs, 2007; Jacobs and Holway, 2004), a few provisions are noteworthy. First, the GMA provides a structure for permitting and monitoring groundwater usage while requiring entities to report pumping, with the exception of small wells withdrawing less than 132.5 L per (35 gallons) per minute (Hirt et al., 2008). Second, despite heavy involvement of farming interests (along with urban and mining) in drafting the GMA (Connell, 1982), the policy stipulates 'no new irrigation' for agriculture, though each sector has demand management programs (see the demand section below). Finally, the GMA requires new subdivisions in the Phoenix area to demonstrate a 100-year Assured Water Supply (AWS), mostly using renewable sources but with recharge and recovery programs to allow pumping in return for replenishment (Jacobs and Holway, 2004).

Since the AWS rule posed a hindrance to development in areas without access to surface water, the state formed the Central Arizona Groundwater Replenishment District (CAGRD) in 1993 (August and Gammage, 2007). For a fee written into home mortgages, the CAGRD acquires water—typically from the Colorado River—to replenish extracted groundwater. Replenishment is not required at the place of use, even though recharge elsewhere might not compensate for the local hydrologic effects of withdrawals. Although these efforts neglect physical realities, the East Valley Water Forum (EVWF)—a consortium of water providers who share a groundwater basin—collectively models groundwater flows in order to understand how pumping in one location will alter water levels in other areas.

4.1.4. Effluent

Finally, water providers use treated wastewater, or effluent, to recharge groundwater, in addition to supplying non-potable water to irrigate golf courses, parks, and farms (Jacobs and Holway, 2004). Currently about 5% of regional supplies, effluent is also used as a coolant for power generation and industrial activities. The mixture of sources in effluent creates a fuzzy area of water law, giving rise to a dispute and ultimately a court case in the 1980s (Colby and Jacobs, 2007). The ruling declared that effluent is the property of the entity who treats the wastewater, but if or when discharged, ownership of the resource is lost and the water rights revert back to the alternative laws for surface or underground water. This may clarify the legalities of reusing treated wastewater, which is on the rise. Yet the 'yuck factor' and other barriers (discussed below) may limit its use generally (Russell and Lux, 2009).

Although the technology exists to clean wastewater to drinking water safety, pollutants plague some water sources and may render their use hazardous and/or their treatment expensive. The treatment and delivery of water is the focus of the next section.

4.2. Water deliveries

Water from various sources is distributed through a network of eight canals totaling 2092 km (1300 miles) (Gooch et al., 2007), with connections to aboveground ditches and underground pipes for direct irrigation purposes and for potable uses through treatment plants. Pumping and distributing water throughout the region requires 2.8 million MW h annually, which amounts to nearly 4% of Arizona's total energy use (UAWRRC, 2010).

Maintained by SRP and CAP, the concrete, open-air canals have traditionally been managed as functional conduits of water, with residents and businesses turning their backs to these man-made waterways. In recent years, attention has turned to beautifying and embracing the canals as amenities. The Canalscape project is one example wherein university professors and students worked with SRP and stakeholders to re-envision the canals as centerpieces of mixed-use development and leisure activities (Ellin, 2010). Municipalities such as Phoenix, Tempe, and Scottsdale have also developed paths, lights, and vegetation to improve canals locally as recreational corridors and, to a lesser extent, wildlife habitat.

Over 100 public (municipal) and private (for-profit) providers deliver water to customers (Bolin et al., 2010). Some non-potable water is delivered untreated for industrial uses and for residential and agricultural irrigation, but most water is treated at one of 97 drinking water plants (ADWR, 2009). Water treatment must comply with the US Safe Drinking Water Act, which sets the maximum contamination levels (MCL) for "primary" pollutants—microorganisms, organic and inorganic chemicals, radionuclides, disinfectants and related byproducts—that negatively affect public health. The U.S. EPA establishes the safe limits while also recommending guidelines for "secondary" contaminants, which result in aesthetic or cosmetic problems such as bad taste or tooth decay.

At the state level, the Arizona Department of Environmental Quality (ADEQ) oversees compliance with regulatory standards for 87 primary contaminants and 15 secondary pollutants (ADEQ, 2010b). When MCLs exceed federal limits, ADEQ develops remediation strategies (Smith and Graf, 2007). Locally, water providers must provide the public with information on contaminant levels in drinking water, which is typically done with periodic water quality reports mailed in customers' bills.

Salinity, especially in surface water, can affect the taste of water and it is also hard on treatment systems. Nutrients and endocrine-disruptors also are ongoing pollution concerns that are not currently mitigated through treatment technologies. The region also struggles with arsenic, which naturally occurs in soils (Welch et al., 2000). Recent increases in federal arsenic standards have created treatment difficulties for some water providers and regulators in central Arizona (UACE, 2005). Higher standards mean higher treatment costs.

Industrial activities have polluted water in Phoenix so much so that multiple groundwater plumes have been designated Superfund sites. In the 1980s, for instance, Trichloroethylene (TCE)—a chlorinated solvent used for cleaning metal parts and circuit boards that has toxic, ozone-depleting, and carcinogenic characteristics—and other volatile organic compounds (VOCs) were released into the groundwater at several industrial facilities in Phoenix. With multiple parties potentially responsible for several pollutants, the contaminated groundwater and bedrock extend well beyond the release sites despite various legal agreements, scientific assessments, and treatment efforts (ADEQ, 2010a). While some water has been contained or treated, some contaminants still pose health risks to well users or nearby neighborhoods, such as exposure to VOCs (released through vapor degassing) as polluted water is brought to the surface and transported for non-potable uses via open-air canals. In 2009, the U.S. Environmental Protection Agency (USEPA) and Arizona Department of Environmental Quality (ADEQ) released a community involvement plan to structure the process for eliciting concerns and input over this Motorola Superfund site (EPA, 2009). Working with industrial polluters (e.g., Freescale, Honeywell) and citizen advocates, the EPA leads the ongoing remediation projects (USEPA, 2009). In other Superfund cases, some entities must sue and continue to push the responsible parties for compensation under the Superfund Act.

4.3. Water demands

Agriculture has historically used the majority of water region-wide, primarily through the production of water-intensive cotton, cattle, and citrus, which have long dominated the Arizona economy. Down from 57% in 1985, agricultural uses now represent 33% of regional water demands, with Native American reservations using 10%, and large industrial users 7% (Fig. 3). At 50%, municipal uses by households, businesses, and the public sector (e.g., for parks and schools) now lead water demands. Residential and outdoor uses are paramount; within the City of Phoenix, for example, households consume two-thirds of water, mostly for watering landscapes.

Lawns, pools, and large lots contribute most to consumption levels in Phoenix neighborhoods, along with household size (Wentz and Gober, 2007). Largely as a result of the region's lush 'oasis' landscapes, which have been promoted with historical slogans such as 'do away with the desert,' water use rates are high compared to climatically similar areas, with a rate of 871 L (230 gallons) *per capita daily* (LPCD, or Gallons PCD) in Phoenix relative to 651 LPCD (172 GPCD) in Tucson (Larson et al., 2009a).

Water-intensive commercial users include carwashes, water parks, plant nurseries, and golf courses, although the latter increasingly use effluent to irrigate turfgrass. The largest industrial consumers in the Phoenix area produce electricity (e.g., Arizona Public Service or APS) and electronic chips (e.g., Intel), among other goods. Industrial users often use effluent, as with cooling at SRP's Kyrene Electric Generator Station. At APS's Palo Verde Nuclear Generator, for instance, over 90.8 million m^3 (24 billion gallons, or 73,613 af) of wastewater were used in 2009 to produce energy which is largely exported to California (SWEEP, 2009).

Regarding demand management overall, the GMA specified conservation targets and programs for three sectors (Jacobs and Holway, 2004). First, ADWR sets allotments for farmers (with more than about 4 ha, or 10 acres) based on the historic crops grown and assumptions about irrigation efficiency (Paul, 2010). Second, industrial limits apply for those using more than 12,335 m^3 (10 af) of water, depending on the best available technologies for conservation. Third, municipal standards require 'reasonable reductions' in water use over time for providers delivering more than 308,370 m^3 (250 af).

Despite these policies, recent evidence indicates gross failures in achieving significant reductions in water demands (Larson et al.,

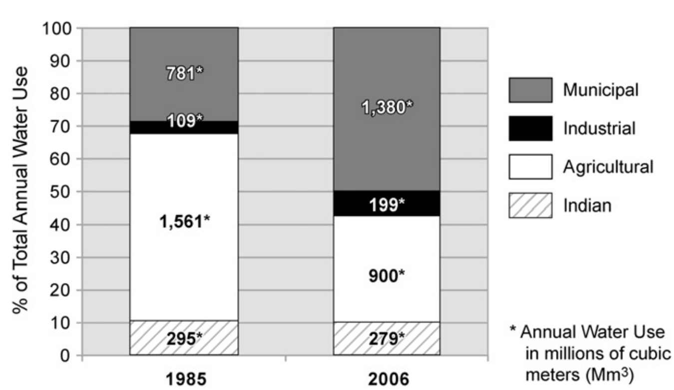

Fig. 3. Water demands per year by sector 1985 and 2006 (ADWR, 2010).

2009a). For example, the state backed away from enforcing municipal water-use standards (as measured by Gallons Per Capita Daily) in the face of local resistance. As water providers contested regulatory standards, which some failed to meet, ADWR eventually created an alternative program that rewards conservation efforts (e.g., outreach, incentives) while no longer mandating actual reductions in water-use rates.

Finally, environmental demands constitute resources used to maintain vegetation and ecosystems as well as water 'lost' to evaporation. So far, the Phoenix region has not allocated water to in-stream flows (McKinnon, 2009). Some localized, small-scale projects dedicate water to maintain habitat, as with the Rio Salado project in central Phoenix, where shallow groundwater is being pumped by the City to maintain wetlands and native riparian vegetation in the river channel, which also receives stormwater flows. Funded largely by the U.S. Army Corps of Engineers (USACE), the project enhances redevelopment opportunities in an old industrial area that has historically turned its back to the river channel. The project also facilitates recreation and wildlife habitat, with an Audubon Center on site to support activities.

In the arid desert, evaporative losses from pools, lakes, and canals are high. Tempe Town Lake, which was created by damming the Rio Salado channel with water from the Colorado River and other sources, loses 1.7 million m^3 (1338 af) annually to evaporation (City of Tempe, 2011). Transpiration, or the release of water by plants, represents another environmental loss. Yet when water is used on lawns and other vegetation, local cooling can occur along with energy savings for air conditioning. In other words, a tradeoff exists between heat mitigation and water conservation in landscaping (Gober et al., 2010).

4.4. Outflows

Once used outdoors, water flows back into the hydrologic system via evaporation, runoff into local water bodies, and infiltration into soils and aquifers. Some water is also carried through underground pipes to one of the 92 wastewater treatment plants, which are typically separate from drinking water plants and whose discharges are regulated by the U.S. Clean Water Act (ADWR, 2010). In the City of Phoenix, about 30–40% of all water deliveries flow through the sewer system after usage. At wastewater plants, water is then treated through physical, chemical, and biological processes before being discharged. In general, treated wastewater faces three potential fates—discharge into surface water or river channels, recharge into groundwater basins, or direct use for non-potable purposes, thereby completing the cycle of water back into the system to maintain supplies or meet demands (Fig. 1).

While wastewater treatment often relies on engineered (gray) technology, biological (green) approaches include the use of vegetated wetlands to filter water and remove pollutants. The Tres Rios project at the 91st Street Treatment Plant, which is run by a Sub-Regional Operative Group (SROG), is one example where after basic mechanical treatment, wastewater is filtered through wetlands to ensure the water discharged into the stream channel meets federal standards overseen by the U.S. EPA and ADEQ (similar to drinking water regulations, though stemming from the Clean Water Act) (City of Phoenix, 2011b). This project treats wastewater at lower costs than plant upgrades would have been. The wetlands also provide habitat as well as recreational and educational benefits for bird-watchers, students, researchers, and others. With similar features and the goal of reusing 100% of the town's effluent, the City of Gilbert's Riparian Preserve is about 45 ha (110 acres) with seven recharge wetlands that allow treated wastewater to percolate into aquifers while also serving wildlife and recreational purposes (USFWS, 2011).

4.5. Perturbations and cross-cutting activities

In the Phoenix area and elsewhere, critical perturbations include: climate variability and change, regulatory or policy changes, population growth and urban development. Drought conditions, for example, lower surface water supplies while also increasing demands (Balling and Goodrich, 2007). Human-induced climate changes are also expected to result in greater aridity and lower surface water flows in the southwest. In the Colorado Basin, climate change models for the 2010–2100 period suggest a temperature increase of 1.2–4.4 °C leading to runoff reductions of up to 11%, with all scenarios showing a decline in water flows to the lower basin (Christensen and Lettenmeier, 2006). For the local Salt-Verde Rivers, the modeled effects of various climate change scenarios into 2050 illustrate a range of uncertain outcomes, with the likelihood of lower runoff in the SRP watershed (Ellis et al., 2008).

Climate conditions affect water physically, in addition to potentially triggering shortages imposed by the shortage-sharing agreement for the Colorado River. Additional institutional stressors include regulatory changes such as the federal increase in arsenic standards. Shifting market conditions can also impose stress on the regional water system, as with the current economic recession and mortgage crisis, which have hit the Phoenix area hard given the central role of land development in the regional economy (Larson et al., 2009a,b). Declining funds due to political and economic factors may therefore thwart initiatives—especially government ones—to help anticipate, mitigate, or adapt to changes.

While large municipalities such as the City of Phoenix (2011a) have conducted water resource assessments and have several plans in place, including a Climate Action Plan, smaller towns often lack the resources for anticipatory activities (Larson et al., 2012). The City of Phoenix has also developed a drought-contingency plan with trigger points for adaptive actions, but participation has been limited to the city council, water suppliers, and special interests (Quay, 2010). Overall, drought planning has increased over the last decade as the region has faced a long-term drought.

In-migration and growth increase water demands, though the exact effects of urbanization depend on the type and form of development. From 1970 to 2010, the region grew from one million to about four million people (Hirt et al., 2008). Urban development has led to rising temperatures due to the Urban Heat Island (UHI) effect, which has increased water demands (Guhathakurta and Gober, 2007). Nighttime summer temperatures have risen 4–10 °F in central Phoenix, where a 1° increase in daily lows amounts to an average monthly increase of 1098 L (290 gallons) consumed per single-family unit. While research has helped inform understanding of these dynamics—especially as Arizona State University's Decision Center for a Desert City (ASU DCDC; see http://dcdc.asu.edu/), collaborative initiatives such as the Phoenix's UHI task force (which involves municipal officials and other stakeholders) also help to mitigate and cope with the urban heat island.

Funded by the National Science Foundation, DCDC has served as a "boundary organization" since 2004 to facilitate science-policy research and collaborative events to support water resource decision making under climatic uncertainty (White et al., 2008). Working with local stakeholders, ASU researchers conduct interdisciplinary research on climatic variability and uncertainties; urban dynamics, and tradeoffs; and adaptation and governance decisions (as largely synthesized above). DCDC has also created "WaterSim," an interactive simulation model that examines how alternative climate conditions, rates of population growth, and policy choices interact to impact future water supply and demand conditions (Gober et al., 2011). Together, past and ongoing DCDC activities have strengthened understanding of the regional water system among researchers and decision-makers, especially water providers and resource managers/planners who work for local to federal government agencies or other entities (Crona and Parker, 2012). Although these collaborations have led to cross-sector and cross-jurisdictional interactions, some stakeholders have not yet been very involved.

5. Sustainability appraisal of water governance in Phoenix

Based on the examination of water governance activities above, we now apply the sustainability principles presented earlier (see also the Supplementary table online) to summarize the successes and challenges of the Phoenix water system.

5.1. Social–ecological system integrity

Diversion of water from streams and riparian areas—largely for human uses—has diminished the ecological integrity of aquatic ecosystems in the Phoenix area, where streams and riparian 'ribbons of green' have been transformed into reservoirs, lakes, and expansive blankets of turfgrass and other irrigated landscapes. Damming and diverting water have left streams dry and species endangered. Select local projects, especially to treat wastewater or recharge groundwater, have created new wetlands and habitat areas to support birds and other wildlife while also providing recreation and other opportunities. Although restoration projects could further enhance ecological integrity, such efforts have been limited and institutional arrangements (e.g., over-allocated rivers, effluent laws, anthropocentric customs) currently constrain such activities. Moreover, created and restored habitat areas may not function the same as natural ones.

Though aquifers are being recharged to some degree, overdraft still taxes groundwater. From 1980 to 2000, overdraft was cut in half; but between 1995 and 2025, ADWR expects overdraft to increase by 30% at the "current use" trends from 444.1 to 581.1 million m^3 (or 360,019 to 471,085 af) (Hirt et al., 2008). As aquifer drawdown continues, problems such as pollution and land subsidence will heighten.

While some contaminated water poses little risk, other polluted resources (e.g., Superfund sites) harm people and the environment (Foley et al., 2012). Although emerging approaches to biological (e.g., wetland filtration) or technological (e.g., nanotechnology filtration) treatment hold promise for improving water quality, future challenges include making treatment cost-effective (especially for meeting raised arsenic standards). Another barrier to improving water quality results from the lag time in identifying contaminants and then developing treatments.

Rising attention to the interactions and tradeoffs across environmental sub-systems, along with associated collaborations, is promising for maintaining social–ecological integrity. Positive steps include regional management under the GMA for the Phoenix 'Active Management Area' (AMA), which corresponds to groundwater basin boundaries of the greater region (Jacobs and Holway, 2004). Whether these increases in awareness will lead to change has yet to be seen, but other aspects of interconnectivity are discussed further in Section 5.6.

5.2. Resource efficiency and maintenance

As noted above, the integrity of aquifers is threatened by continued overdraft. Achieving the legislative mandate for safe yield by 2025 is now highly unlikely due declining state support and loopholes in implementing the GMA (Hirt et al., 2008). A recent USGS (Tillman et al., 2011) study found that most of the 1300 wells tested across Arizona indicate aquifer levels are dropping. Maintaining water tables and flows will be increasingly difficult over time as supplies dwindle and demands rise. Region-wide, the geographic mismatch between groundwater withdrawals and recharge sites especially threatens local resources where pumping is occurring but recharge is not.

Though water demands have been reduced somewhat, regulatory targets for municipal conservation in the Phoenix area have been abandoned by the state and water-use rates remain relatively high (Larson et al., 2009a). Political resistance and lifestyle changes present barriers to enhanced efficiency. In addition, cheap water prices and the 'lose it or use it' principle of prior appropriation law reinforce flagrant water uses while thwarting conservation and the preservation of in-stream flows. Ultimately, these practices and rules harm both resource maintenance and ecosystem integrity.

Conservation gains have been greatest in newly developed areas with low water-use landscapes (e.g., without grass) as well as efficient fixtures and appliances. But lush landscapes, pools, and other factors still place high demands on water (Wentz and Gober, 2007). The efficiency of new infrastructure is critical for reducing water use, but so is retrofitting older areas (e.g., upgrades to leaky and aging canals, pipes, and other storage and conveyance infrastructure). High evaporation rates in open-water systems (e.g., pools, canals) further represent intervention points for minimizing atmospheric losses in such a warm, dry region.

Progress in the efficiency of water use has been made with the increased use of effluent for recharge and some direct uses (e.g., landscaping, industrial processing). Recharge projects like the Gilbert Preserve serve the dual purpose of reserving water for future use and preserving ecosystem functions. However, the use of treated wastewater is constrained by perceptions that lead customers to reject its use (Russell and Lux, 2009), in addition to regulations, salinity problems, and the centralized nature and downstream location of treatment infrastructure. These factors also explain why the use of gray water (e.g., dirty dishwater or laundry water) and other decentralized modes of capturing and utilizing water are not widespread across the region.

5.3. Livelihood sufficiency and opportunity

The basic needs of Phoenix-areas residents are being met overall through the widespread provision of treated drinking water and adequate sanitation systems. Still, some residents are exposed to detrimental pollutants, especially due to untreated water and contaminated aquifers (see associated inequities below).

Regarding societal enjoyment, some localized projects provide water resources for birding, learning, and other forms of recreation around canals, ponds, lakes, wetlands, and some riparian areas. The creation of man-made lakes and the redevelopment of canals as amenities and transit corridor also provide recreational opportunities (e.g., walking, biking, boating, fishing), rather than simply functioning to store or distribute water. Yet these projects are relatively new and few, resulting in uneven access to such amenities.

As for economic livelihoods, agriculture has been somewhat marginalized with a 'no new irrigation' clause, thereby privileging municipal and industrial uses. Some communities have even drawn high water-use industries, specifically microchip processors (e.g., Intel in Chandler) that consume resources and also contribute to toxic emissions (Bolin et al., 2000). Such water-reliant industries may mean jobs and economic growth in the near term, but greater economic losses may result from water shortages into the future (e.g., compared to fallowing irrigated farmland during shortages).

5.4. Civil engagement and democratic governance

Power in water governance is largely centralized among a few agencies such as SRP and CAP, along with other water providers and managers. The minimal involvement of select interests (e.g., water providers) in decision processes (e.g., development of regional plans) marginalizes some interests while potentially leading to detrimental outcomes (e.g., erosion of conservation policies). With respect to continuous involvement, the Groundwater Act does structure planning periods that require adaptive consideration of implementation successes and failures over time. Yet participation among the broader public is limited (e.g., to short 'comment periods'). While environmental and other interests have also been largely absent from regional deliberations over the GMA and its implementation, Mexico has been excluded from some Colorado Basin deliberations.

Led by the EPA and DEQ, the decontamination efforts at the Motorola Superfund site demonstrates a explicit lack of democratic governance. For over two decades, the community—which includes some of the poorest neighborhoods in Phoenix—has confronted flaws in stakeholder representation and involvement, access to comprehendible information, resources for legal and expert advice, effective remediation strategies, and negotiations of adequate compensation (Foley et al., 2012). Although the EPA established a community engagement process in 2009, increased government involvement has only served to further deepen the community's frustration and mistrust.

Although participatory decision making is weak overall, collaboration appears to be rising (see Interconnectivity Section). DCDC, in particular, has fostered science-policy deliberations since 2005, although not among a wide range of interests. Thus, deliberative governance is improving somewhat, but certain interests tend to be excluded, especially those outside of formal decision arenas in the U.S. government. Who participates in decision making has equity implications, as described next.

5.5. Inter- and intra-generational equity

While residents broadly have access to sufficient water, some areas lack secure, long-term access to resources given both contaminated aquifers and dependence on single sources (e.g., non-renewable groundwater). Newer areas along the metropolitan fringe are especially at risk, since older and more centrally located areas have greater access to diversified sources (Bolin et al., 2010). Rural areas and private landowners dependent on untreated groundwater are also particularly vulnerable to pollution (Madrid, 2010). Further, low-income neighborhoods are most exposed to contaminants and least equipped to demand effective remediation (e.g., in Superfund decisions; Foley et al., 2012).

In negotiating the 1980 GMA, municipal, mining, and agricultural interests were well represented, but environmental and others perspectives were not (Connell, 1982). While urban and industrial interests have ultimately been favored over agricultural users by state policies and economic imperatives, Native American rights have been historically neglected. Adjudication processes have started to remedy this issue through legal negotiations with tribes (e.g., Gila River), through power asymmetries may perpetuate inequalities into the future for the tribes as well as Mexico or other marginalized actors. Mexico is perhaps the biggest loser in the Colorado Basin, since they receive limited, low-quality water as the downstream user. Regarding equity of representation, Mexican interests have also been excluded from some collaborative processes as U.S. interests have worked among themselves.

Finally, future generations receive no formal representation in governance, and explicit consideration of future residents is limited. The 100-year timeframe for "Assured Water Supply" provisions only applies a few generations out, for example, and loopholes allow development where water could become scarce or eventually depleted (Hirt et al., 2008). As a whole, inequitable uses, impacts, and involvement occur across upstream and downstream entities of river basins, different areas within the region, and current and future generations.

5.6. Interconnectivity across scales and sectors

Although some coordinated decision making within hydrologic units is happening through negotiated treaties (e.g., with Mexico for Colorado River) and regional workgroups (e.g., East Valley Water Forum), consideration of upstream–downstream interconnections is lacking for the Colorado Basin (e.g., since downstream users such as Mexico have been excluded from workgroups) and the Salt-Verde Watershed (e.g., where hydrologic connections between surface and groundwater have been ignored until recently). With ongoing conflicts raising attention to hydrologic interconnections among political jurisdictions (e.g., Big Chino aquifer in Verde Valley), water professionals increasingly call for conjunctive management and basin-wide institutions for effective governance (Colby and Jacobs, 2007). However, the legal separation of water rights laws constrains integrated governance in Phoenix and elsewhere, as does the fragmentation of local water providers and multiple bureaucratic agencies across towns and government levels (e.g., separate missions and planning for water, land, and energy resources at varying scales).

Improved communications and capacity-building across municipalities as well as state and federal governments could help local communities as they adapt to changes and cope with stressors on water systems, especially in the face of perturbations, constraints, and tradeoffs. Of particular importance are: the water–energy nexus (e.g., given the energy costs of pumping, treating, transporting water; Scott and Pasqualetti, 2010) and the water-land use/cover intersection (e.g., given the implications of land use/cover and irrigation on water use/conservation versus heat mitigation; Gober et al., 2012). Even more complex sectoral interconnectivity—for example, relationships among land, water, energy and climate—should be considered among researchers and policymakers in planning for sustainability.

Attention to interactions and collaborations across scales and sub-systems has increased in recent years, specifically activities led by ASU's DCDC. Yet integrated planning is still limited (e.g., across the land–water sectors; Larson et al., 2012) and some disconnected activities threaten certain risks (e.g., groundwater replenishment removed from the point of withdrawals). The regional group studying groundwater flows (EVWF) could help coordinate pumping to minimize risks, but ultimately the decision to pump depends upon territorial jurisdictions and political will.

5.7. Precaution, mitigation and adaptability

Academics, consultants, government agencies, and others have conducted numerous studies in the Phoenix area to anticipate the effects of climate conditions on supplies and demands (e.g., Ellis et al., 2008; Balling and Gober, 2007). DCDC-affiliated activities have: expanded knowledge of climatic and land use/cover changes on water supplies and demands (e.g., Balling and Goodrich, 2007; Ellis et al., 2008); identified interactions and tradeoffs between water, energy, and land planning (e.g., Gober et al., 2012; Guhathakurta and Gober, 2007), and examined how individuals and groups make decisions about water (e.g., Larson et al., 2009b; White et al., 2008). Meanwhile, few studies and events addressed ecological impacts and ecosystem functions, and little intervention research has been conducted to critically assess public involvement in decision making. These gaps may exacerbate ecosystem degradation and injustices in water governance. Yet, overall, DCDC activities have advanced anticipatory understanding and social learning across scientists and policymakers (e.g., through modeling and cross-sectoral events such as land–water planning workshops).

Insufficient resources and inabilities to conduct assessments, develop plans, or participate in activities limits adaptive capacity, especially in smaller towns with fewer staff and less money (Larson et al., 2012). Inadequate data and limited knowledge—for instance, about small wells exempt from reporting—also inhibit monitoring and adaptations to change. Meanwhile, political resistance and popular assumptions among policymakers (e.g., 'there will be water'; Holway et al., 2006) thwart transformative research as well as certain mitigation and adaptation strategies (e.g., demand management). A pro-growth culture and cheap water rates prevent related management and adaptation strategies as well, while making it difficult to pursue research on sensitive topics (e.g., incorporating higher prices in DCDC's model). Overall, the customs of water managers—which emphasize centralized, technocratic strategies and supply augmentation (Lach et al., 2005; Larson et al., 2009b)—block or diminish adaptation mechanisms (e.g., harvesting rainwater or restricting demands). Open dialogue and trust building can aid discussions about such controversial matters, especially since political–economic forces present significant barriers to mitigating and adapting to water scarcity.

Given the relatively inefficient water-use rates and the lack of water dedicated to aquatic ecosystem functions in the Phoenix area, there is room to explore stronger conservation initiatives in the region. In fact, many residents seem more supportive of conservation efforts (e.g., water pricing and bans) than policymakers have suggested, indicating that public support may exist for more stringent efforts (Larson et al., 2009b). Into the future, lifestyle changes—including reduced water consumption—will be necessary for continued growth regardless of climate conditions (Gober and Kirkwood, 2010). Managing demands through people's choices will be particularly essential since water use is more sensitive to land use/cover conditions than climate (Gober et al., 2012), in part due to human management of technology (Balling and Gober, 2007).

While 'doing more with less' or 'doing the same with less' are central to efficiently using finite water supplies and adapting to urban-environmental change, too much efficiency may lead to "demand hardening" wherein squeezing more water out of current uses reduces flexibility and adaptive capacity (at least in the short term; Larson et al., 2012). Thus, we recommend managing demands for efficiency while avoiding complete hardening for long-term sustainability. In Phoenix, this could mean halting some farmland development while making the remaining agricultural activities more efficient—that is, to reduce demands in the near term while reserving irrigation water as a flexible adaptation strategy (i.e., through water transfers) during times of need (e.g., temporary or extreme shortages).

6. Discussion and recommendations

The Phoenix region faces various water resource challenges including high consumption rates, degraded ecosystems and habitats, inequities in outcomes and involvement, and fragmented decision making. From irrigating agriculture to increasingly urban lifestyles, anthropocentric and economic uses of water for residents and businesses have trumped biocentric uses for preserving aquatic ecosystems and wildlife. Meanwhile, a warmer, drier climate and degraded water quality threaten finite water supplies, which will require increased demand management into the future (Gleick, 2002; Gober and Kirkwood, 2010). Collectively, these issues present a range of choices and tradeoffs involving multiple actors: supply versus demand management, centralized (top-down) versus decentralized (bottom-up) governance, and 'gray' versus 'green' technologies (Mitchell, 2006; Pahl-Wostl et al., 2010). In pursuit of sustainable water governance, there are no one-size-fits-all options. We therefore suggest a number of alternatives among diverse actors in order to achieve multiple objectives and address tradeoffs in an integrated, coordinated fashion.

One critical need is to enhance the integrity of degraded ecosystems. The Phoenix region currently has some isolated projects to restore or protect ecological functions (e.g., habitat and biodiversity) while primarily serving other purposes (e.g., water treatment and recharge). The development of such green infrastructure (e.g., wetlands and ponds) can enhance the ecological value of water for wildlife, help to clean water and replenish water supplies, and provide societal benefits such as recreation and enjoyment. Although local municipalities may pursue such projects, citizens and non-profit organizations (e.g., local 'friends of' groups or those such as Audubon Society) increasingly play key roles in governance (Stoker, 1998; Peters and Pierre, 1998). Non-governmental groups can garner support and help to manage green infrastructure, especially in instances where resources are limited or partnerships are formed across public and private actors.

Dedicating water and managing resources for ecological purposes could also create a 'buffer' against shortages, such that water might be shifted from ecosystems (e.g., dedicated stream flows) to essential uses to protect livelihoods during times of scarcity. As agricultural land is developed in favor of 'higher' economic uses, losses or hardships during water shortages will likely increase since the flexibility to transfer water from low- to high-value uses will diminish (Larson et al., 2012). Reconsidering the future of agriculture in the study region and elsewhere could therefore transform the region toward sustainability as an adaptation mechanism (at least temporarily or in the short-term), while potentially providing still other benefits (e.g., local food production that could minimize greenhouse gas emissions and preserve open spaces between urban and undeveloped lands). Finally, one other option for managing water uses and tradeoffs—while avoiding demand hardening—may be to carefully irrigate landscapes to achieve greater efficiency as well as heat mitigation and other purposes, including the adaptive capacity to move water from outdoors to indoors during times of shortages. However, flagrant or wasteful uses of water should be eliminated for resource maintenance and social–ecological integrity as well as equity of use and access.

With high outdoor water uses, drought-tolerant landscaping, shared pools, and other ways to reduce such demands are imperative in the Phoenix region. While some progress has been made in this area, especially in new developments, attention to older area with lush landscapes and outdated, leaky infrastructure (e.g., pipes, fixtures) is imperative to conserve water in residential and other areas. Investments to minimize water losses from canals are another option, particularly as facilities age and become less efficient. Decentralized initiatives such as gray-water reuse or rainwater harvesting can further improve efficiency while helping to avoid costly supply-augmentation strategies. Although awareness and adoption of such strategies is rising (especially in other places such as nearby Tucson), barriers must be overcome including the dominant centralized infrastructure and lawsuits concerning the right to capture water under surface water law.

Institutional constraints present barriers to changes in management—that is, toward "soft path" approaches (Gleick, 2002) involving decentralized strategies such as conservation and green infrastructure. These barriers encompass the informal norms and customs embedded in water managers and government planners, who are formally governed by jurisdiction-based missions and activities that are too narrow and fragmented to address the complexities of regional water systems (Larson et al., 2012). The centralized, technocratic, and supply-oriented culture of water managers will be hard to change given long-engrained traditions embedded in professional mindsets and organizations (Lach et al., 2005). Although organizational change tends to be slow, collaborative initiatives and deliberative dialogue can facilitate change through social learning (Pahl-Wostl et al., 2010). Transformations are particularly needed in terms of integrated planning across water sources, societal sectors, and biophysical units of relevance for maintaining social–ecological integrity and resource systems. Attention to the interconnections across places and sectors (e.g., land–water and water–energy) will enhance resource maintenance while addressing tradeoffs (e.g., water conservation versus heat mitigation and energy use) and minimizing inequitable outcomes (e.g., vulnerabilities to heat or pollution) (Mitchell, 2005; Larson et al., 2012).

Despite cultural and political constraints surrounding the largely centralized nature of water management, increased participation is needed for sustainable water governance in metropolitan Phoenix and elsewhere, including the involvement of marginalized groups (e.g., low-income neighborhoods, Native Americans, and representatives from Mexico). Deliberative processes can facilitate fair participation and outcomes in decision making while potentially bolstering political support and actions (Larson and Lach, 2010). However, given weak political will and leadership to implement and enforce rigorous decisions and policies, participation is likely to remain limited, especially in the absence of public resistance or actions that challenge the status quo. Non-governmental and non-profit entities (including universities) may therefore play leadership roles in pursuit of sustainability and social learning across diverse actors (Pahl-Wostl et al., 2010).

Although useful, our appraisal is limited by a number of factors including the available data and studies for various components of water system dynamics. Future research can build on this appraisal to address these limitations. In doing so, studies might focus on developing in-depth appraisals where information is lacking (e.g., ecosystems and participatory governance). Scholars, policymakers, and still other stakeholders might also develop indicators (or metrics) to quantify and monitor how well various (sub)principles are being met (e.g., per-capita demand as a metric for water use efficiency or established minimum flows for habitat integrity). Deliberative discussions about how to proceed in the future could also bolster such appraisals and the participatory nature of research, which we will continue to pursue collaboratively by developing and exploring scenarios at DCDC.

7. Conclusions

Our appraisal of water governance in Phoenix offers insights and recommendations for transforming this arid metropolitan system toward sustainability. Although the region is doing well in some respects, several problems and stressors threaten communities and ecosystems. Key steps toward sustainability encompass: conservation advances for enhanced efficiency as well as groundwater recharge and effluent reuse programs to maintain resources and ecological integrity; multi-purpose green infrastructure projects that provide wildlife habitat and enrich livelihoods while also potentially recharging aquifers or filtering pollutants; enhanced participatory governance and decision making on current challenges and future possibilities; and, increasing attention to groundwater–surface water interactions, water–energy tradeoffs, and integrated land–water planning.

These lessons apply widely to diverse areas since water systems must be governed holistically considering multiple objectives and tradeoffs, degraded water quality and ecosystems, and rising demands and resource costs, among other challenges. Not only can other areas learn from this study, but the Phoenix area can also learn from other places (e.g., Colorado's in-stream flow policies, California and Singapore's water-reuse efforts, or Australia's water conservation and drought planning experiences). In the face of dwindling supplies and environmental change, building adaptive capacity through collaborative research and participatory decision making is critical for sustainable water governance that is effective, efficient, and equitable in Phoenix and elsewhere. Applied within and across regions, moreover, our framework can assist with holistic, interdisciplinary assessments to advance sustainability.

An actor-oriented, systems approach to water sustainability must consider who is doing what with water, coupled with the goals, rules and implications of those activities and their interactions with natural and engineered infrastructure. Not only is this comprehensive approach useful for synthesizing research and conducting comparative appraisal; it also provides a framework for innovating water systems through the co-production of knowledge and adaptive learning, both of which are essential for anticipating and coping with perturbations and environmental change. Future assessments employing deliberative processes will benefit from such an approach by synthesizing and improving understanding of water systems from multiple perspectives and with an eye toward the future.

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Appendix A. Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2012.11.016.

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