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A metropolitan scale water management analysis of the food-energy-water nexus

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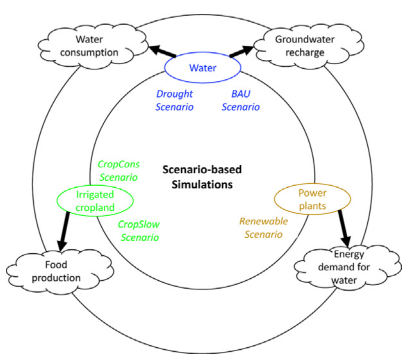
HIGHLIGHTS

- Interactions of the food-energy-water nexus are quantified in Phoenix Metro.
- Preserving food production and megadrought will compromise groundwater safe-yield.
- Preserving food production and megadrought will increase energy needs for water.
- Solar photovoltaic technologies will support groundwater sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

Quantifying the interactions of the food-energy-water (FEW) nexus is crucial to support new policies for the conjunctive management of the three resources. Currently, our understanding of FEW systems in metropolitan regions is limited. Here, we quantify and model FEW interactions in the metropolitan area of Phoenix, Arizona, using the Water Evaluation and Planning (WEAP) platform. In this region, the FEW nexus has changed over the last thirty years due to a dramatic population growth and a sharp decline of cultivated land. We first thoroughly test the ability of WEAP to simulate water allocation to the municipal, agricultural, industrial, power plant, and Indian sectors against historical (1985–2009) data. We then apply WEAP under possible future (2010–2069) scenarios of water and energy demand and supply, as well as food production. We find that, if the current decreasing trend of agricultural water demand continues in the future, groundwater use will diminish by ~23% and this would likely result in aquifer safe-yield and reduce the energy demand for water. If agricultural activities decrease at a lower rate or a multidecadal drought occurs, additional (from 7% to 33%) water from energy-intensive sources will be needed. This will compromise the ability to reach safe-yield and increase energy demand for water up to 15%. In contrast, increasing the fraction of energy produced by solar power plants will likely guarantee safe-yield and reduce energy demand of 2%. This last solution, based on an expanded renewable portfolio and current trends of municipal and agricultural water demand, is also projected to have the most sustainable impacts on the three resources. Our analytical approach to model FEW interconnectivities quantitatively supports stakeholder engagement and could be transferable to other metropolitan regions.

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1. Introduction

The food-energy-water (FEW) nexus (also referred to as WEF (e.g., Leck et al., 2015) or WFE (e.g., Meza et al., 2015) in the literature) has emerged since the early 2010's as a new approach to collectively manage three crucial resources, whose accessibility is increasingly threatened by climate change, population growth, urbanization, and environmental concerns (Hoff, 2011; Keairns et al., 2016; Scott et al., 2015; Vanham et al., 2019). The need for a nexus approach has been motivated by the fact that food, energy, and water resources are highly interdependent. For example, water is needed to irrigate land for food production and cool power plants for energy generation. Energy is required for agricultural practices and to transport and treat water. Agricultural activities can generate energy through biofuels, but also affect water quality. As a result of these interconnectivities, a holistic view should be adopted to develop synergistic policies and make decisions in each managing sector that produce benefits for the other sectors and guarantee the security of all resources (Leck et al., 2015; Ringler et al., 2013). Currently, food, energy, and water are instead generally or often managed in isolation because of the inherent complexities of each system, and the difficulties in identifying, quantifying and modeling the physical and social interrelationships among the three sectors across different spatial and temporal scales (White et al., 2017).

Recently, several conceptual frameworks have been proposed to identify the linkages within FEW systems (e.g., Bhaduri et al., 2015; Chang et al., 2016; Gain et al., 2015; Mayor et al., 2015; Meza et al., 2015). However, only a limited number of studies have developed or adopted analytical approaches to quantify FEW interactions. As reported in a recent review by Albrecht et al. (2018), FEW systems have been mainly assessed through approaches commonly applied in environmental management, including life cycle assessment (e.g. Salmoral and Yan, 2018) and foot printing (e.g. Lee et al., 2018; Ramaswami et al., 2017; Zhang et al., 2019); economics, via input-output analysis (e.g. Xiao et al., 2019); and social science, using social surveys (e.g. White et al., 2017). Other studies have utilized indicators (e.g. El Gafy, 2017; Schlör et al., 2018), system dynamics models (e.g. Berardy and Chester, 2017; El Gafy et al., 2017; Hu et al., 2019; Tan and Yap, 2019; Wa'el A et al., 2018), and optimization models for long and short-term operations (e.g. González-Bravo et al., 2018; Li et al., 2019a,b). A lower number of cases have applied hydrologic, energy, and food models, eventually integrated (e.g. Zeng et al., 2019). We refer the reader to Albrecht et al. (2018; their Table 1) for an extensive list of additional references for each type of analytical methodology. Albrecht et al. (2018) also concluded that, to effectively assess FEW systems, there is a need to develop methods that: (i) combine quantitative and qualitative approaches (Miralles-Wilhelm, 2016); (ii) account for the specific conditions of the study site while, at the same time, being flexible to accommodate different spatiotemporal dynamics and geographic regions; (iii) rely on transdisciplinary collaborations and engage stakeholders; and (iv) can be easily operationalized to support policy- and decision-making.

The majority of the FEW nexus assessments have been conducted at multinational (e.g. Abulibdeh et al., 2019; Guillaume et al., 2015; Ozturk, 2017; Taniguchi et al., 2018), national (e.g. Bazilian et al., 2011; Daher and Mohtar, 2015; El Gafy, 2017; El Gafy et al., 2017; Gain et al., 2015; Lee et al., 2018; Schlör et al., 2018; Tan and Yap, 2019; Vora et al., 2017; Wang et al., 2018; Xiao et al., 2019), or basin (e.g. Li et al., 2019a; Mayor et al., 2015; Meza et al., 2015; Salmoral and Yan, 2018; Zeng et al., 2019; Zhang et al., 2019) scales. Few studies have been instead carried out at the scales of cities or metropolitan regions (e.g., González-Bravo et al., 2018; Hu et al., 2019; Ramaswami et al., 2017; Romero-Lankao et al., 2018; Wa'el A et al., 2018; Walker et al., 2014). In one of these studies, White et al. (2017) examined, through qualitative analysis, the governance structure and linkages in agricultural, water, and energy sectors in the metropolitan area of Phoenix, Arizona. This region of the US desert Southwest represents a compelling case study to investigate FEW interactions for a number of reasons. First, it relies on energy-intensive water supply sources that heavily depend on climate variability and that will be likely affected by shortages under the on-going drought conditions (e.g., ADWR, 2018a). Second, agriculture has historically been a key driver of the local economy because of the favorable climate that allows year-round growing for several types of crops (Bausch et al., 2015; Berardy and Chester, 2017). However, farmed land in the metropolitan area has declined by ~50% over the last three decades to allow construction of new houses and accommodate about 3 million new residents (Gober et al., 2016). As a result of this process, the municipal water and energy demands now exceed those of the agricultural sector (ADWR, 2010a). Finally, due to environmental and economic reasons, there has been increasing pressure

Table 1
Summary of the datasets used in this study, grouped into main categories.

Main Category	Source	Reference
Water supply	USGS records	USGS (2019)
	SRP daily water report	SRP (2019)
	CAP monthly delivery report	CAP (2019b)
	CAP report	CAP (2015)
	WaterSim 5 simulations	Gober et al. (2016); Sampson et al. (2016)
	Arizona Water Atlas, Volume 8, Active Management Area Planning Area	ADWR (2010b)
	ADWR	ADWR (2010a)
Groundwater	SRV regional model	ADWR (2019b)
	ADWR well registry web	ADWR (2019a)
Water demand	ADWR	ADWR (2010a)
Population	Office of Economic Opportunity, State of Arizona	Office of Economic Opportunity State of Arizona (2018)
	ADWR	ADWR (2010a)
Cropland area and type	MAG	MAG (2019)
	USDA NASS	USDA NASS (2019a)
	ADWR	ADWR (2010a)
Evaporation	WRCC	WRCC (2019)
Power plants	EIA	EIA (2019a,b)
Waste water treatment plant	EPA	EPA (2019)

Note: acronyms are defined as follows. CAP: Central Arizona Project; EIA: United States Energy Information Administration; MAG: Maricopa Association of Governments; NASS: National Agricultural Statistics Service; SRP: Salt River Project; SRV: Salt River Valley; USGS: United States Geological Survey; USDA: United States Department of Agriculture; WRCC: Western Regional Climate Center; EPA: United States Environmental Protection Agency.

to modify the energy generation portfolio by reducing the use of fossil fuels and increasing renewable sources, with focus on solar (AZCC, 2019; Hurlbut et al., 2012).

In this study, we use a water management model to quantify future FEW scenarios in the Phoenix Metropolitan region and, ultimately, support the engagement effort with local and regional stakeholders initiated by White et al. (2017). For this aim, we apply the Water Evaluation and Planning (WEAP) platform (Yates et al., 2005) to the Phoenix Active Management Area (AMA), a political/hydrological region created by the passage of the 1980 Groundwater Management Code (Higdon & Thompson, 1980) with the goal of controlling the overdraft of groundwater resources. The Phoenix AMA includes most of the Phoenix Metropolitan region and the surrounding agricultural fields. Fig. 1 shows a diagram that summarizes our effort. WEAP is used to simulate the allocation of water from different sources to the demand sectors, which include power plants and agriculture that quantify food and energy resources, respectively. We first devote a significant effort to build confidence in our modeling tool. This is a crucial step for its potential operationalization and use in scenario planning activities with stakeholders (White et al., 2010). To achieve this, we calibrate and validate WEAP simulations against historical estimates of water demand and supply published by the Arizona Department of Water Resources (ADWR). We set up WEAP at an annual scale, using the same demand categories and spatial granularity of the ADWR data. In doing so, we integrate datasets from water utilities and federal and local agencies characterizing water flow, storage, and consumption, as well as water infrastructure characteristics and management rules. In addition, we use previous simulations of WaterSim, a model of water demand and supply for the municipal providers of the Phoenix Metropolitan region (Gober et al., 2016, 2011; Sampson et al., 2016, 2011).

Once tested, we use WEAP to carry out a scenario analysis of possible future changes of the FEW nexus in the region. This anticipatory approach based on multiple scenarios has proved useful to guide both short- and long-term decisions (Chakraborty et al., 2011; Quay, 2010; Walker et al., 2013). We create a set of plausible scenarios of water and energy demand and supply, as well as agricultural production (ellipsoidal elements in Fig. 1). We account for the uncertainty of water supply through statistical simulations of river flow fluxes and reservoir levels under current climate and megadrought conditions, as in Gober et al. (2016). We compare the scenarios placing particular emphasis on the impacts on nonrenewable groundwater resources, whose recovery has been the target of state regulations for more than thirty years (Hirt et al., 2008). In addition, we postprocess WEAP outputs to explore the changes of key variables characterizing the FEW nexus (elements outside the black box in Fig. 1) under the different scenarios.

Our work provides several novel contributions. First, we quantify FEW interactions at the metropolitan scale that, as mentioned above, has received less attention, likely because of limited data availability at this spatial granularity. Second, we adopt a modeling approach that reproduces in continuous fashion the allocation of water resources from supply sources to demand sectors while accounting for both water management rules and infrastructure constraints; the adopted platform is a flexible tool that can be applied at multiple scales with different levels of spatial granularity and is then able to model a large range of FEW systems. Third, we integrate several data sets from different sources to thoroughly test our modeling tool and gain confidence in its ability to simulate future scenarios. To our knowledge, this is the first time that a well-calibrated water management model is utilized to investigate FEW interactions in a metropolitan region. Finally, results of our effort complement and expand previous regional studies that investigated different aspects of FEW and water-energy nexuses with alternative modeling approaches (Bartos and Chester, 2014; Berardy and Chester, 2017; Mounir et al., 2019; Yates et al., 2013b). Our work is part of a broader effort, initiated by White et al. (2017), that has the long-term goal of developing interdisciplinary scientific understanding of FEW dynamics by engaging relevant stakeholders through an integrated modeling, visualization, and decision support infrastructure for FEW systems, in line with the desirable characteristics of FEW analytical approaches outlined by Albrecht et al. (2018).

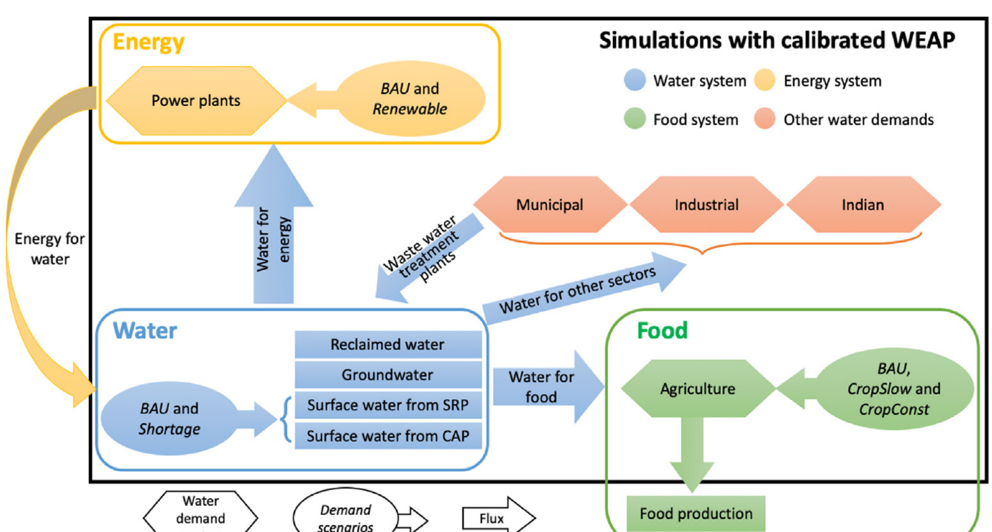

Fig. 1. Schematic of the modeling approach adopted to simulate the interactions among food, energy, and water sectors in the Phoenix AMA. WEAP simulates water fluxes from the different sources to all demand sectors. Future scenarios of water and energy demand and supply, as well as agricultural production (ellipsoidal elements) are applied to explore future impacts on the FEW nexus. WEAP outputs are post-processed to compute energy for water and food production (elements located outside the black box). SRP is the Salt River Project and CAP is the Central Arizona Project (see Section 2.2). The future scenarios are BAU (business as usual), CropSlow, CropConst, Renewable, and Shortage (see Section 3.4).

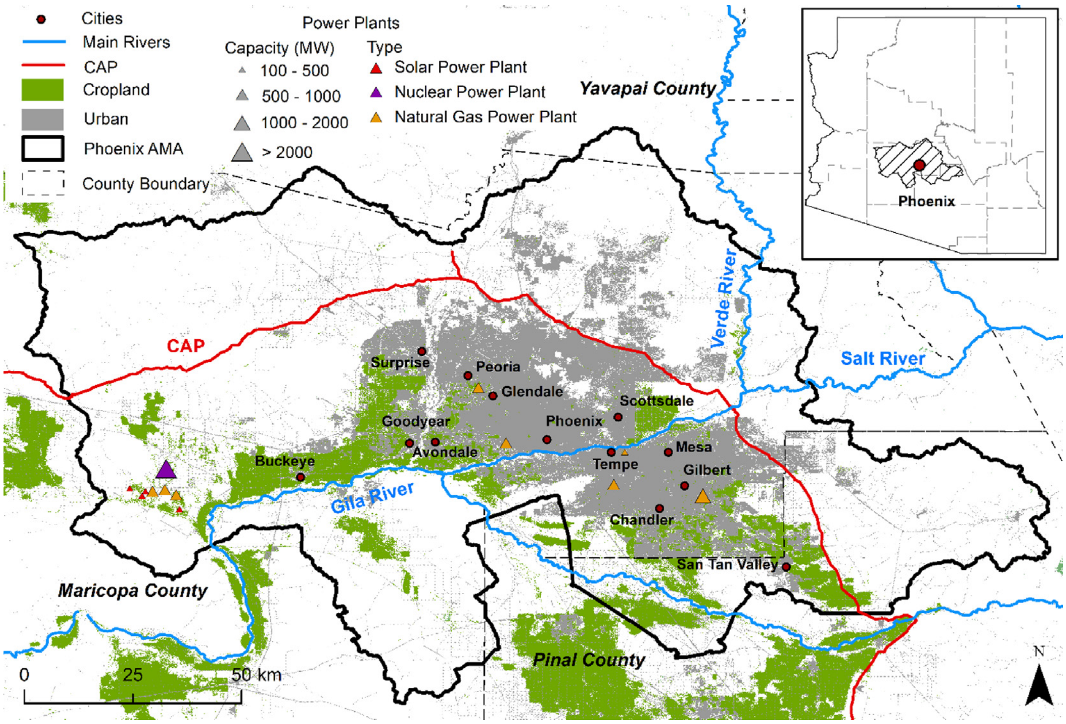

Fig. 2. The Phoenix AMA in central Arizona, along with the thirteen largest cities that make up the Phoenix Metropolitan region; urban and cropland areas (derived from a land cover map released by USDA NASS (2019b) in 2017); power plants, plotted as a function of type and capacity; the three major rivers (Salt, Verde, and Gila Rivers); and the Central Arizona Project (CAP) aqueduct.

2. Study area

2.1. Overview of the Phoenix AMA

The Phoenix AMA is an administrative region of 14,623 km^2 in central Arizona created in 1980 by the State of Arizona to achieve safe-yield of groundwater by 2025, which is defined as the balance between annual withdrawal and recharge to the aquifer. For this aim, ADWR has released four management plans describing the requirements to achieve the long-term water management goals. Fig. 2 shows the boundaries of the Phoenix AMA that is mainly part of Maricopa County along with the main cities that make up the Phoenix Metropolitan region, the urban and cropland areas, the power plants generating electricity, the main rivers (Salt, Verde and Gila Rivers), and the Central Arizona Project (CAP) aqueduct. In this desert region, climate is dry and arid, with average maximum (minimum) temperatures ranging from 19 °C (7 °C) in December to 41 °C (28 °C) in July and a mean annual rainfall of 204 mm (Mascaro, 2017).

The Phoenix AMA (hereafter used to refer also to the Phoenix Metropolitan region) has experienced, over the last several decades, one of the fastest population growth rates in the country. The population in the region has ballooned from about 1.86 million people in 1985 to over 4.75 million people in 2018 (ADWR, 2010a; Office of Economic Opportunity State of Arizona, 2018). Due to limited water resources and their management through complex legal rights, the population growth has been possible through the conversion of agricultural into urban land (Bausch et al., 2015; Fan et al., 2017) and housing development and construction have become crucial for the economy. The cropland area decreased from ~1400 km^2 in 1985 to ~700 km^2 in 2009 (ADWR, 2010a; Fan et al., 2014), but, since 2007, the trend appears to have stabilized. As of 2009, the main crops in the Phoenix AMA are barley (~9% of total cropland), cotton (~15%), alfalfa (~60%), and wheat (~16%) (USDA NASS, 2019a). The growth of the urban regions has also led to the expansion of energy infrastructure. In the Phoenix AMA, electricity is currently generated by ten large-scale (>300 MW) plants, including the Palo Verde nuclear station that, with a capacity of 3.9 GW, is the largest in US (EIA, 2019a). The other plants are mainly fueled by natural gas with a cumulative capacity of 7.4 GW, while only a small fraction of energy is generated by renewable sources, including solar (0.6 GW), hydropower (0.095 GW), and biomass (0.006 GW) (EIA, 2019a).

2.2. Water supply in the Phoenix AMA

To introduce and quantify the water supply and demand in the Phoenix AMA, we refer to the fourth management plan of ADWR (ADWR, 2010a; hereafter, ADWR10). In this report, the demand of water for the different uses in the Phoenix AMA has been quantified each year from 1985 to 2009 along with the supply sources. If not stated otherwise, the data reported in Sections 2.2 and 2.3 are those published in ADWR10. We point out that, throughout the paper, water demand refers to the water volume needed by a given demand sector, and water use or consumption refers to the water actually utilized by the demand sector or provided by a given source. The Phoenix AMA relies on one non-renewable and three renewable sources of water supply. The first source is groundwater, which is pumped from seven sub-basins by different entities and water providers. There are approximately 26,000 wells registered in the Phoenix AMA, with a median depth of 122 m (ADWR, 2019a). Surface water from the Salt and Verde Rivers basins (Fig. S1; drainage area of ~33,800 km^2) represents the largest source of water supply to the region. This water is managed by the Salt River Project (SRP), which has a water service area of ~1000 km^2 and operates seven dams (Fig. S1), 248 groundwater wells and 2092 km of canals and laterals (Phillips et al., 2009). Water from the Salt and Verde Rivers basins is allocated by SRP to ten cities of the metropolitan region through complex water rights based on daily flows on the rivers and water storage in the system reservoirs (see Sampson et al. (2011, 2016) and Text S1 of the Supporting Information for details). A third source of water supply comes from the Colorado River through the Central Arizona Project (CAP), a ~541-km canal diverting water from Lake Havasu on the California-Arizona boarder to central and south-eastern Arizona. The annual water volume assigned to CAP depends on the water level at Lake Mead in the Colorado River: CAP has an entitlement of ~1881 hm^3/year (after losses; 1 hm^3 = 1 million m^3) if the level is above 1075 ft (327.7 m), while different shortages are prescribed if the level drops below this elevation (see USBR (2007) for details). The effective water volume transported by CAP depends on the actual demand of its customers. If a shortage is declared, CAP will cut deliveries based on priorities and rules that are described in detail by Maguire (2007) and summarized in Text S2. Finally, the fourth source of water in the Phoenix AMA is reclaimed water generated with different levels of treatment.

The total water volume collectively supplied by the four sources remained fairly constant from 1985 to 2009 (~2800 hm^3), but the annual water deliveries of each source changed significantly (Fig. 3). The percentage of the total demand satisfied by groundwater declined from 47% of the total water use in 1985 to 27% in 2009. The contribution of SRP water allocations also decreased from 51% to 39%. The decline of the volumes supplied by these two water sources has been possible by (i) the availability of CAP water, whose percentage has increased steadily since 1986 reaching nearly 20% in 2009 (26% if in-lieu groundwater–or CAP water used instead of groundwater–is also accounted for), and (ii) increased use of reclaimed water, which rose from 2% in 1985 to 9% in 2009.

2.3. Water demand in the Phoenix AMA

Irrigation in agriculture has been the largest water consumer in the Phoenix AMA until the late 1990s. The intense urbanization experienced by the region over the last three decades led to a reduction of cropland area that, in turn, caused a decrease of water consumption for irrigation from 1561 hm^3 in 1985 to 908 hm^3 in 2009, corresponding to 57% and 33% of the total water demand, respectively (Fig. 3). This water demand has mainly been satisfied by groundwater and SRP water up to the mid 1990s and, subsequently, also by CAP. On the other hand, the population growth caused an increase in municipal water demand from 782 hm^3 in 1985 to 1318 hm^3 in 2009. Despite this total increase, water conservation policies have induced a decrease in water use per capita over time, which dropped from 1.2 m^3/day/capita in 1985 to 0.9 m^3/day/capita in 2009. Prior to 2000, the municipal demand was mainly satisfied by SRP water and groundwater and, after 2000, by SRP and CAP water. An additional consequence of the intense population growth has been the increase of water demand

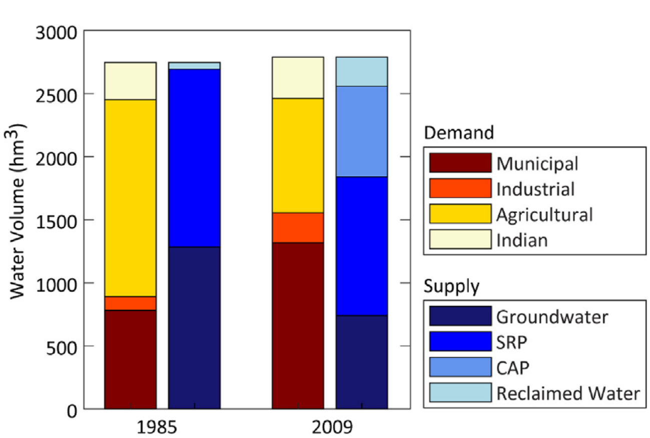

Fig. 3. Historical estimates of annual water allocations from four supply sources to the four principal water demand sectors in the Phoenix AMA in 1985 and 2009 (ADWR10).

for energy generation, which is mainly required for the cooling systems of the power plants. The total water demand for electricity generation increased from 19 hm^3 in 1985 to 104 hm^3 in 2009. The main water sources for energy generation are reclaimed water and groundwater, with a small amount of CAP water. It is worth to notice that the Palo Verde nuclear generation station uses approximately 76 hm^3 of effluent annually (CAP, 2019a). The increasing urbanization has also caused a rise of water demand for industrial use that went from 90 hm^3 in 1985 to 133 hm^3 in 2009. The industrial sector relies mainly on groundwater and reclaimed water. Finally, another category of water demand in the Phoenix AMA is due to the three Indian communities of Salt River-Pima Maricopa, Fort McDowell Yavapai Nation, and Gila River. The Indian demand comprises all uses in the communities, including municipal, agricultural and industrial. During 1985–2009, the Indian demand remained relatively constant to ~292 hm^3 annually, with agricultural use contributing for 97% of the total.

2.4. Challenges related to water management and their relations with food and energy systems

A number of critical challenges affect water resources management in the Phoenix AMA, with relationships and consequences on the food and energy systems that have not been fully analyzed and quantified. First of all, surface water supplies in this desert region are limited and there is high uncertainty about their future availability. The flows of the Colorado, Salt and Verde Rivers are characterized by high interannual variability (Christensen et al., 2004; Demaria et al., 2017) and are currently (and have long been) under severe drought conditions. Even if with a high level of uncertainty, future climate projections indicate that the Colorado (e.g., Christensen & Lettenmaier, 2006; Gautam & Mascaro, 2018; Vano et al., 2014) and Salt and Verde Rivers (Ellis et al., 2008) will likely experience runoff reductions by 2050. Probable reductions in surface water availability would be expected to negatively impact the sustainable use of groundwater resources that has been the target of current state policies and, at the same time, to affect the overall energy demand required to pump and convey groundwater and CAP water. Uncertainty in the future water demand represents an additional challenge to water management in the Phoenix AMA. For instance, while population growth will likely continue, questions remain whether urban expansion into agricultural lands will persist, or whether agriculture will remain viable driven by favorable market conditions (Bausch et al., 2015). Considering energy, state incentives have been promoting the transition from fossil fuels to renewable sources (mainly solar) with different water footprints (Scott and Pasqualetti, 2010). Overall, the uncertainties affecting the future water supply and demand are causing severe concerns to local and regional water managers (Gober et al., 2016), who have so far adopted the "silo-thinking" approach while making decisions, i.e. they have not taken into account the feedbacks with energy and food systems (White et al., 2017).

3. Materials and methods

3.1. Brief description of WEAP

The WEAP system platform was designed to model and manage water resources and allocation (Yates et al., 2005). WEAP incorporates programming elements that control water flux transfers among supply and demand nodes that can include the operating rules of infrastructure elements, such as canals, reservoirs, diversions, etc. Optimization routines assign the distribution of water at each time step to demand nodes based on user preferences, conservation of mass, and other system constraints. The model can be forced with time series of river flow, as done here, and/or water diversions from reservoirs. Alternatively, WEAP can compute these variables by simulating the physical hydrology of watersheds from precipitation and temperature inputs, and the reservoir management rules. Outputs of WEAP include several variables characterizing the time-varying water allocation in the system, such as percent of demand covered by each source, reservoir and groundwater storage, and inflow and outflow of water in the transmission links, among others. WEAP has been utilized for several research and operational applications at different scales, including studies of the FEW nexus in the Mauritius (Howells et al., 2013), Lake Tana in Ethiopia (Karlberg et al., 2015), and western Himalayan region in India (Momblanch et al., 2019); the water-energy nexus in Southwest US (Yates et al., 2013a, 2013b; Yates and Miller, 2013), northern California (Dale et al., 2015), and the Mauritius (Welsch et al., 2014); evaluation of the impacts of climate change on irrigated agriculture in a district in Spain (Esteve et al., 2015), the Cache Creek watershed (Mehta et al., 2013), Yolo County in California (Winter et al., 2017), and Sacramento Valley in California (Purkey et al., 2007); and analysis of water management practices under shortage conditions in basins in South Africa (Lévite et al., 2003), western Algeria (Hamlat et al., 2013) and China (Li et al., 2015).

3.2. Overview of datasets

We used a large variety of data sources to parameterize and calibrate the WEAP model and apply it under future projections of water supply and demand (Table 1). These data were collected from reports and data sources from water service providers, as well as local federal and state agencies. They include data for streamflow, reservoir volumes, river and lake evaporation, population estimates, cropland area, and power plant characteristics. The next sections and Text S1-S2 of the Supporting Information describe how the data have been used.

3.3. Model setup, calibration and validation

The WEAP platform requires the definition of a network where supply sources are connected to demand nodes via transmission links. Fig. 4 presents the WEAP interface with the network configuration for the Phoenix AMA. The supply sources include: (i) CAP and SRP, whose nodes are located along the CAP canal and the Salt River, respectively; (ii) two sources of groundwater, including one connected to all demand nodes (GW) and one, which represents the wells managed by SRP, linked to the SRP surface water system (GW_SRP); and (iii) a source of reclaimed water that is provided by two waste water treatment plants (WWTP_1 and WWTP_2) linked in series to simulate the different levels of treatment. A transfer link was created to simulate the exchange of water from CAP to SRP. We set up six demand nodes including municipal, agricultural, Indian, industrial, power plant and riparian. The transmission links from the supply sources to the demand nodes include connections of: (i) CAP and SRP to all demand nodes except power plant and riparian; (ii) GW to all nodes; and (iii) WWTP_2 (reclaimed water) to all demand nodes except Indian and riparian. We linked the municipal node to WWTP_1 and this, in turn, to WWTP_2. Finally, we created links connecting all demand nodes (except riparian), WWTP_1 and WWTP_2 with the Salt River to simulate the return flow, which is required by WEAP to preserve the mass balance.

We simulated the physical constraints of the system and the water management rules by (i) assigning preferences to the supply sources, (ii) limiting the capacities of the transmission links, and (iii) fixing the maximum percent of demand that can be satisfied by a given source. We assigned preference 1 to SRP and reclaimed water (i.e., these sources are selected first to meet the demand) and limited the capacity of SRP links based on the maximum capacities of the associated water treatment plants. We attributed preference 2 to groundwater fixing a maximum percentage of demand that can be satisfied by this source (see Text S2 and Table S6 for details). This simple approach was adopted to (i) simulate the complex groundwater management policies put in place by ADWR (Sampson et al., 2016), and (ii) the allocation of water to regions that have only access to groundwater and cannot rely on SRP and CAP water. Finally, we assigned preference 3 to CAP and limited the maximum capacity and priority of the associated links based on CAP water entitlements to different sectors (see Text S2 and Table S4 for details).

We used historical data for the period 1985–1997 for model calibration (see Table 2). For the supply sources: (i) the SRP head flow was obtained from two stream gauges upstream of the Granite Reef diversion dam from which water is delivered to the metropolitan region (Fig. S1); (ii) the groundwater volume pumped

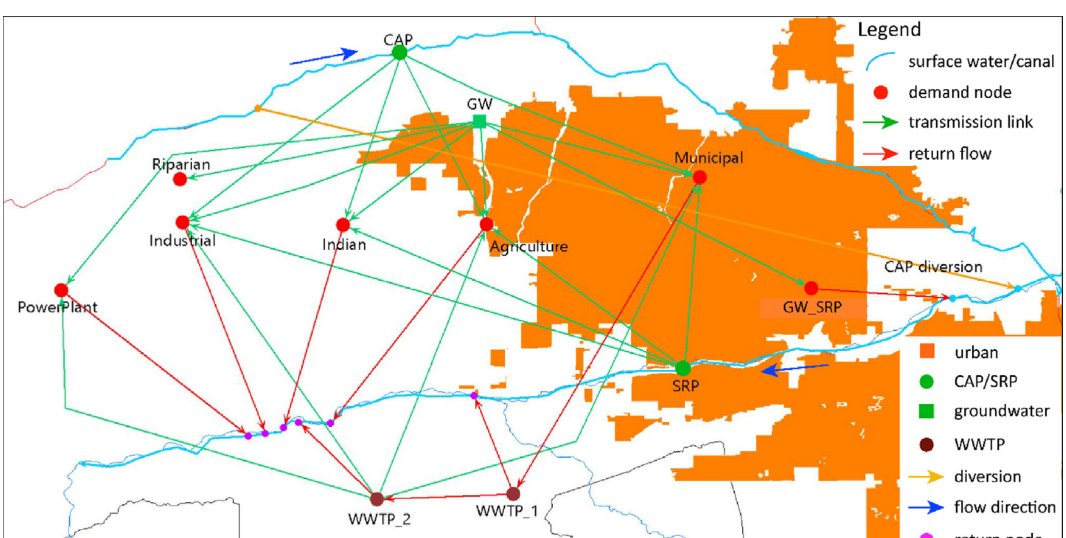

Fig. 4. Configuration of the network in WEAP simulating the water allocation from the supply sources to the main demand nodes in the Phoenix AMA. Details on names and acronyms are described in the main text. Note that, although GW_SRP is represented with a demand node, it practically acts as a source node that accounts for the groundwater pumped by SRP.

Table 2
Main datasets used to force and parameterize the WEAP model during the calibration and validation phases.

WEAP Element		Calibration (1985–1997) and Validation (1998–2009)	Validation for Future Use (1985–2009)
Supply	SRP head flow	USGS (2019)	SRP routine based on inflow to reservoirs and storage on May 1st (Text S1)
	SRP groundwater	Phillips et al. (2009)	
	CAP diversion to SRP	CAP (2019b); SRP (2019)	Same as calibration
	CAP head flow	CAP (2015)	Same as calibration
	Groundwater parameters	ADWR (2019b)	Same as calibration
Demand	Municipal Agricultural Industrial Power plant Indian Riparian	ADWR (2010a)	Estimated with the same relations used in the BAU future scenario
Transmission links	Maximum capacity	CAP entitlements from (ADWR, 2019c, 2018b)	Same as calibration
		Capacity of water treatment plants (personal communication from Gretchen Baumgardner from the City of Tempe)	Same as calibration
	Losses	ADWR (2010a,b); CAP (2019c)	Same as calibration

Table 3
Summary of future scenarios designed to simulate water allocation in the Phoenix AMA with WEAP in the period 2010–2069.

Scenarios Names	Description	Supply	Demand
BAU	Historical variability and trends of water supply and demand	Same management strategies and climate variability of 1985–2009	All water demands projected based on future population, except for Indian that is assumed constant
CropSlow	Cropland area declining at a slower rate compared to BAU	As in BAU	Decreasing cropland area as shown in Fig. 5b. All other water demands as in BAU
CropConst	Constant cropland area	As in BAU	Constant cropland area as observed in 2009. All other water demands as in BAU
Renewable	Increasing electricity generation by solar power plants	As in BAU	Water for electricity generation estimated based on population increase and water use rate of the power plants operating each year. All other water demands as in BAU
Shortage	Shortage of water supply due to a megadrought	Megadrought conditions based on Gober et al. (2016)	As in BAU

by SRP was based on a storage-groundwater relationship reported in Phillips et al. (2009) and further explained in Text S1; (iii) the CAP diversions to SRP were derived from CAP and SRP reports; (iv) the head flow in the CAP aqueduct was obtained from CAP reports; and (v) the physical parameters of the aquifer were derived from the SRV Regional Model (ADWR, 2019b). The water demand of each sector was provided by ADWR10. To calibrate the model, we adjusted the percentage of treated water flowing from WWTP_1 to WWTP_2 in order to match the volume of water supplied by the different sources to the demand nodes in the Phoenix AMA. A detailed description of the model setup and calibration is given in Text S2.

We tested the model performance in two ways. First, we applied the calibrated model in the period 1998–2009 using the same data sources adopted for the calibration. Second, we tested the performance of WEAP for its application in future scenarios. As described in the next section, we developed relations to estimate future water demand as a function of ancillary data (e.g., population, trends in water use, trends in agriculture and energy) and a routine to compute the SRP water supply. To further assess model performance, we applied these relations and routine to re-estimate the water demand and supply in the period 1985–2009 and, then, we used these values as input for WEAP to simulate the water allocation in the Phoenix AMA. For both validation efforts, we computed error metrics between simulated and observed annual water deliveries to each sector.

3.4. Future scenarios

Once calibrated and validated, we applied the WEAP model under five different scenarios of water demand and supply (Table 3) for the period 2010–2069. For these scenarios, we estimated the water demand for each sector using empirical equations as a function of population and time (Text S2; Table S8). We designed a "business as usual" (BAU) scenario assuming that the water demand in the future will follow trends observed over the last 25 years, found to be strongly correlated with population growth. Our population estimates project that the Phoenix AMA will approach 10 million people by 2069 (Fig. 5a). We obtained the municipal water demand as the product of population and per capita water use, which we assumed to decline with time from 0.9 to 0.4 m^3/day/capita (Sampson et al., 2016). We projected the industrial and power plant demands to increase at a rate of ~2.1 and ~2.4 hm^3/year, respectively, while we assumed the Indian demand to remain constant. For the agricultural sector, we hypothesized that the cropland area will continue to linearly decrease over time, as the inverse of population, to a minimum value suggested by future land use projection of Maricopa Association of Governments (MAG, 2019) (Fig. 5b). We then obtained the agricultural water demand as a function of the cropland area (Table S8).

For the BAU scenario, we estimated the water supplies from the four sources using historical climate variability and water management rules. For CAP water, we assumed no shortages out to 2069. To generate the water deliveries from the SRP system, we developed a routine that simulates the annual allocation of surface water and groundwater as a function of the annual inflow to the reservoirs and the storage at the end of the runoff season on May 1st (see Phillips et al., 2009; Sampson et al., 2016; Appendix B). The development, calibration and validation of the SRP routine is described in detail in Text S1. To characterize the uncertainty of climate variability, we stochastically generated an ensemble of 1000 time series of 60 years of annual inflow to the reservoir system by randomly sampling the observed inflow from 1945 to 2015, as in Gober et al. (2016). We tested the validity of this approach by verifying the absence of a statistically significant autocorrelation in the observed time series. For each generated time series of inflow, we applied the routine to simulate the allocation of SRP water and used these volumes as inputs for WEAP.

We created four additional scenarios to explore the impacts of changes in food production, electricity generation, and surface

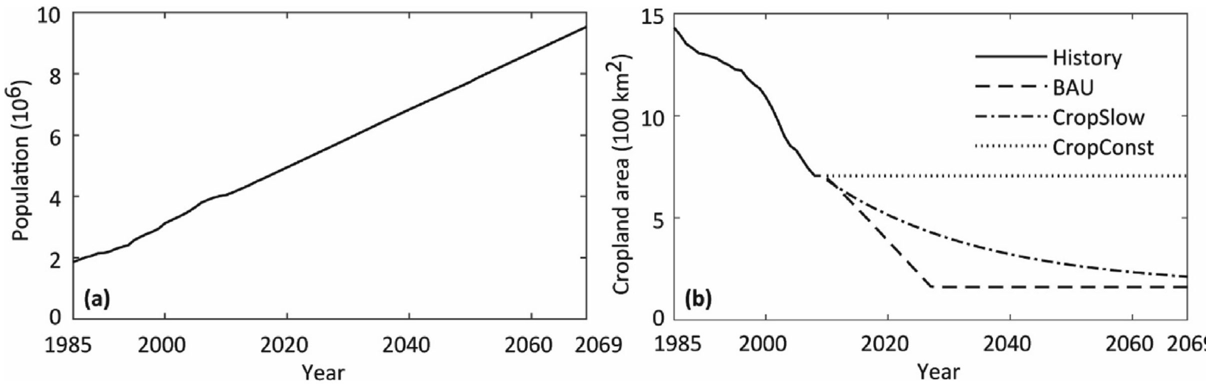

Fig. 5. (a) Population estimation and projection in the Phoenix AMA from 1985 to 2069. Estimates from 1985 to 2014 were obtained from ADWR10 and Office of Economic Opportunity State of Arizona (2018). This agency also provided the projections from 2015 to 2050, which were extended linearly through 2069. (b) Estimation of cropland area from ADWR10 from 1985 to 2009 and projections from 2010 to 2069 in BAU, CropConst, and CropSlow scenarios.

water availability in the allocation of water resources in the Phoenix AMA. Our "CropSlow" scenario assumes that the cropland area would decrease at a slower rate compared to the BAU scenario, following an exponentially decreasing relation (Fig. 5b and Table S8). Our "CropConst" scenario hypothesizes instead that the cropland area would remain constant to the value observed in 2009. For both CropSlow and CropConst scenarios, we used the same projections of water supply and demand for other sectors of the BAU scenario (Table 3). Following Mounir et al. (2019), we designed a "Renewable" scenario to assess the impact of increased electrical generation from renewable sources on the FEW nexus response for the region. This scenario aims at a renewable portfolio standard (RPS) of 50% by 2030 and a carbon-free generation by 2060 that will be achieved by replacing existing power plants fueled by coal or natural gas with plants based on solar photovoltaic (PV) technologies (see Mounir et al. (2019) for details). This scenario is inspired by the RPS adopted in the neighboring states of Nevada and California (Ballotpedia, 2018; Dillon, 2018). We computed the water demand for power generation based on energy demand as a function of population, and water use rates of the power plants existing in each year (EIA, 2019b). The future water supply and demand for other uses were assumed to be the same as BAU (Table 3).

Finally, our "Shortage" scenario simulates the impacts of an extreme drought (hereafter, megadrought) on the SRP and CAP systems under the same demand projections of the BAU scenario. To simulate megadrought conditions, we followed the approach of Gober et al. (2016), who used runoff reduction estimates from paleo reconstruction data for the Colorado, Salt and Verde Rivers (Meko et al., 2012; Meko & Hirschboeck, 2008). Thus, we generated 1000 time series of inflow into the SRP reservoirs by applying a reduction of 19% to the time series created for the BAU scenarios. From these, we derived the volume of surface water and groundwater allocated to the SRP members as described in Text S1. We applied a reduction of 12% in the Colorado River flow to generate Lake Mead elevations using the reservoir operations model described by Sampson et al. (2016, Appendix C). We generated a total of 1000 time series of water volume delivered by CAP to Arizona following the normal delivery and shortage rules found in USBR (2007).

3.5. Metrics for scenario comparison and quantification of FEW interactions

We compared results for the future scenarios by computing (i) sectorial water allocations from each supply source, (ii) percent change of such allocations compared to BAU, and (iii) cumulative net recharge of groundwater. The latter was used as a proxy for safe-yield, i.e. the difference between groundwater recharge and withdrawals, and was calculated each year by applying the method suggested by ADWR10 with the WEAP outputs. The approach accounts for incidental recharge from all demand sectors, natural recharge through mountain front recharge, streambed infiltration, inflow and outflow fluxes of the aquifer, canal seepage, and artificial recharge. Due the lack of studies on environmental flows in the Salt River downstream of Granite Reef dam and the complicated mechanisms regulating CAP water allocations, we did not compute any measure of water stress related to low environmental flows despite its recognized importance (Vanham et al., 2018).

We quantified FEW interactions in the different scenarios by computing three variables related to food, water and energy. For water, we used the net cumulative recharge at the end of the simulation period. For food, we estimated the total production of wheat through 2069 by assuming the same crop portfolio (wheat is grown in 16% of the total cropland area) and yield intensity (0.67 kg/m^2) (USDA NASS, 2019a) throughout the simulation period. For simplicity, we named this variable "food production". For energy, we calculated the electricity required to pump, convey, treat, and distribute water using the energy intensities (in kWh/m^3) reported in Table 4 and obtained from Hoover (2009). For each scenario, we calculated the electricity demand as the sum of the products between each energy intensity and the corresponding water volumes modeled by WEAP for the entire simulation period. In addition, for each scenario we calculated the sustainability index, SI, following the method of Daher & Mohtar (2015) and Daher et al. (2019). SI for each scenario is defined as $SI_S = \sum_{i=1}^{4} IRS_{S,i}$, where $IRS_{S,i}$ is the individual resource sustainability for the resource i, calculated as $IRS_{S,i} = \frac{R_{S,i}}{R_{BAU,i}} \times w_i$, with $R_{S,i}$ ($R_{BAU,i}$) being the resource i in a given scenario S (BAU) and w_i being a weight coefficient. We considered four resources, including (i) total food production (kg), (ii) total water use (m^3), (iii) cumulative groundwater net recharge (m^3), and (iv) cumulative energy demand embedded in water (kWh). The weight w was assumed equal 0.25, i.e., the same weight was assumed for the four resources. IRS_i for resources (ii) and (iv) was multiplied by -1 to reflect the negative impact on the sustainability. As a result, a larger positive SI implies a more sustainable scenario.

4. Results

4.1. Model performance

Our simulated estimates of water deliveries to demand nodes in the Phoenix AMA for the calibration and validation periods capture reasonably well the observed estimates from ADWR10. As an

Table 4
Energy intensities (kWh/m^3) used in the calculation of electricity demand for pumping, conveying, treating, and distributing water in the Phoenix AMA.

	Agricultural and Indian		Municipal and Industrial		Power Plant	
SRP	Conveyance	0	Conveyance	0	–	
	WTD	0	WTD	0.32		
	Total	0	Total	0.32		
CAP	Conveyance	1.24	Conveyance	1.24	–	
	WTD	0	WTD	0.32		
	Total	1.24	Total	1.56		
GW	Pumping	0.75	Pumping	0.75	Pumping	0.75
	WTD	0	WTD	0.32	WTD	0
	Total	0.75	Total	1.07	Total	0.75
RW	Total	2.42	Total	2.42	Total	2.42
WW collection and treatment	0.42					

Note: Data were obtained from Hoover (2009); the Indian sector was grouped with the agricultural sector because 97% of its demand is for agricultural use; GW represents groundwater; RW represents reclaimed water; WW represents waste water; WTD represents water treatment and distribution.

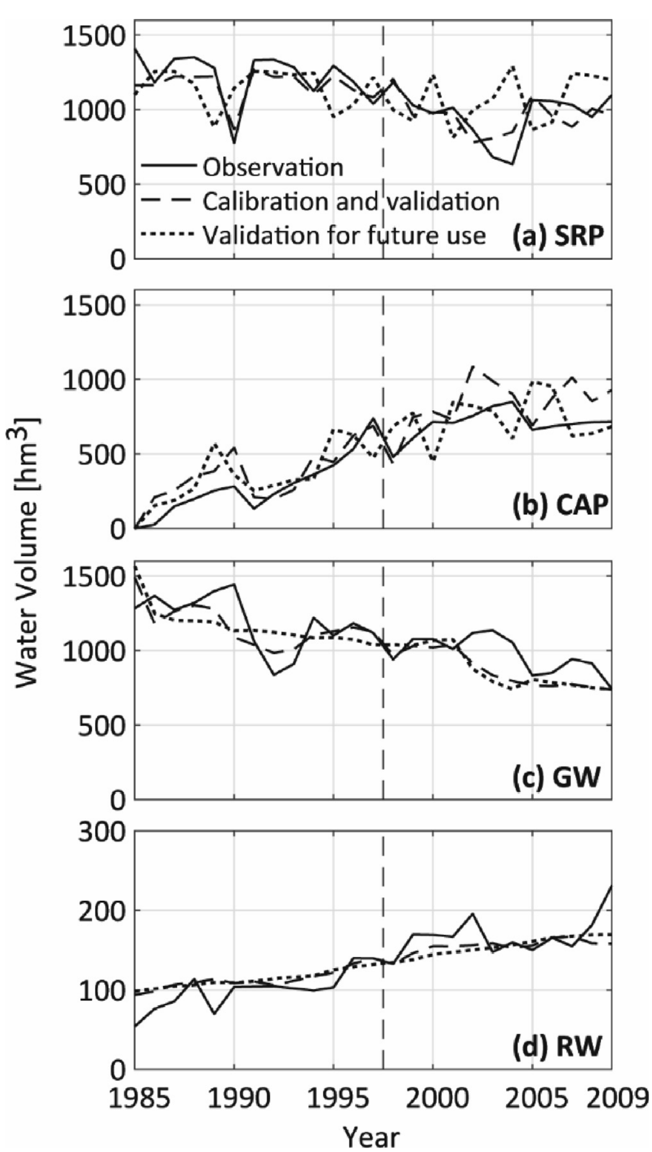

Fig. 6. Comparison between the annual water volume supplied to all sectors by (a) SRP, (b) CAP, (c) groundwater (GW), and (d) reclaimed water (RW) estimated by ADWR (observation) and simulated by WEAP in two settings: (i) using observed estimates of water demand and supply (calibration and validation), and (ii) using the relations developed to apply WEAP in future scenarios (validation for future use). The calibration and validation simulations include a calibration period from 1985 to 1997 and a validation period from 1998 to 2009, which are separated by vertical dashed lines.

example, Fig. 6 shows the observed and simulated time series of total deliveries from each supply source (results for each sector are reported in Fig. S6). To quantify the performance, we calculated root mean square error (RMSE), correlation coefficient (CC), and bias (B) between the time series (Fig. 7; Table S10). From these results we conclude that: (i) WEAP is able to simulate well the overall trend of water deliveries from each source to the distinct demand sectors even if, in some cases, it does not fully capture the interannual fluctuations, as revealed by low or negative CC; (ii) RMSE (B) for SRP, CAP and groundwater (hereafter GW) have similar order of magnitude ranging from 3 to 252 hm^3 (−108 to 135 hm^3); and (iii) given the relatively lower volume of water supplied (demanded), the magnitudes of RMSE and B for reclaimed water (industrial sector) are much smaller than those of CAP, SRP, and GW (municipal and agricultural).

During the calibration period (1985–1997): (i) the time series of the total water volume (Fig. 7a) are highly correlated (CC > 0.63), with a maximum RMSE of 142 hm^3 for GW, and a positive B of + 78 hm^3 for CAP that is offset by a negative B of −64 hm^3 for SRP; (ii) results for the municipal use (Fig. 7b) are similar to those obtained for total use, although with lower CCs; and (iii) WEAP simulates quite well the allocation of water to the agricultural and industrial sectors (Fig. 7c,d). The validation (1998–2009; Fig. 7-e-h) estimates have, overall, lower CCs across all sectors, suggesting lower model ability to capture inter-annual variability in water supply deliveries. However, the model performs well in allocating water for municipal and industrial sectors, as demonstrated by the lower magnitude in B (with the exception of total). Finally, performances of the simulations conducted to evaluate the model skill for future scenarios (1985–2009; Fig. 7i–l) are similar to those obtained in the calibration and validation periods, except for the allocation of SRP water. For this source of water supply, in fact, performances tend to degrade (higher RMSE and lower CC) since they are affected by the routine that simulates water rights and reservoir management of this utility.

4.2. Future projections for the BAU scenario

Results of the future water demand and allocation under the BAU scenario are summarized in Fig. 8. The water demand of the municipal sector (Fig. 8a) exhibits a hyperbolic curve increasing to 1625 hm^3 by 2036 (+23% when compared to 2009) but then decreasing to 1224 hm^3 by 2069, below the 2009 estimate (−7%) as a result of the combined effect of increasing population and decreasing per capita water consumption. The population growth leads to a steady increase of industrial (from 133 to 262 hm^3) and power plants demand (from 104 to 243 hm^3), while the agricultural demand declines from 908 hm^3 to 350 hm^3 in 2028 (−62%) and then remains constant. The Indian demand is assumed

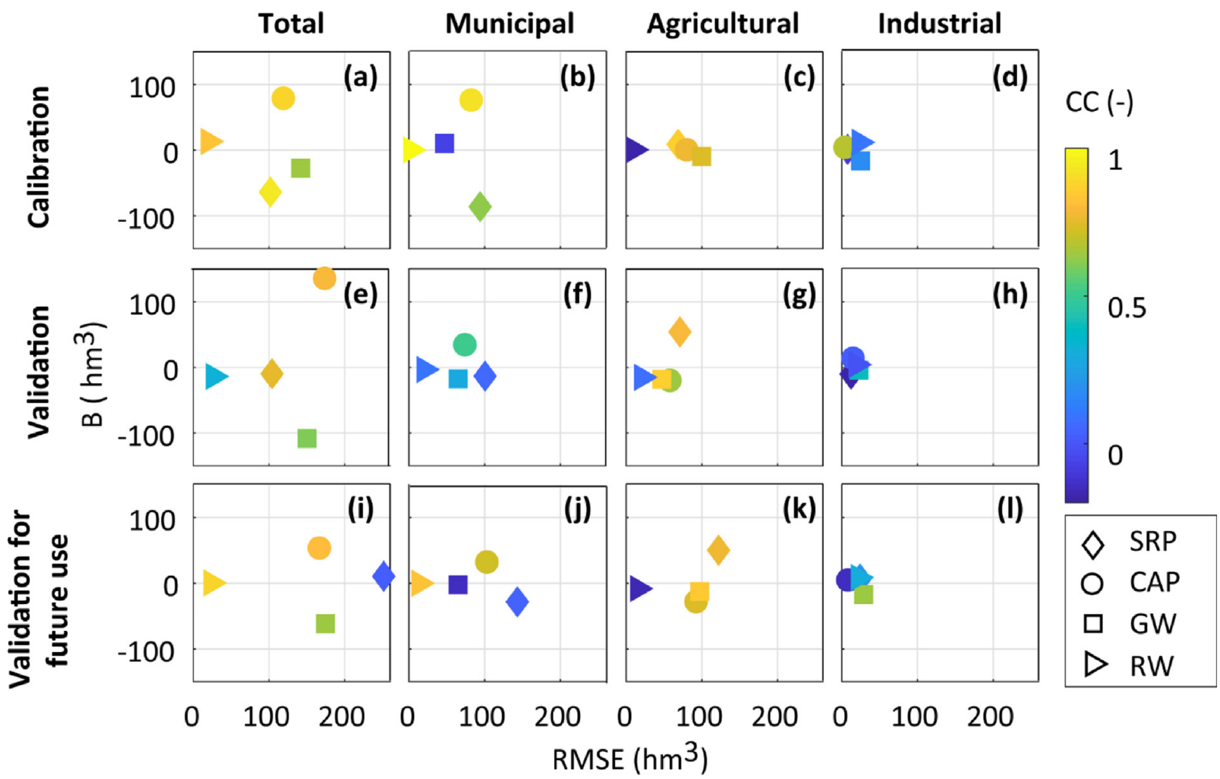

Fig. 7. Overview of the metrics summarizing performances of the WEAP simulations in the (a)–(d) calibration period, (e)–(h) validation period, and (i)–(l) validation for future model use. The metrics are the root mean square error, $RMSE = \sqrt{(\sum_{i=1}^{n}(x_i - y_i)^2)/n}$, correlation coefficient, $CC = (\sum_{i=1}^{n}[(x_i - \overline{x})(y_i - \overline{y})])/(\sqrt{[\sum_{i=1}^{n}(x_i - \overline{x})^2][\sum_{i=1}^{n}(y_i - \overline{y})^2]})$, and bias, $B = (\sum_{i=1}^{n}(x_i - y_i))/n$, where x_i and y_i are the simulated and observed water volumes in year i, respectively, n is the number of years, and $\overline{x}$ and $\overline{y}$ are the corresponding means. Note that Industrial sector includes power plants.

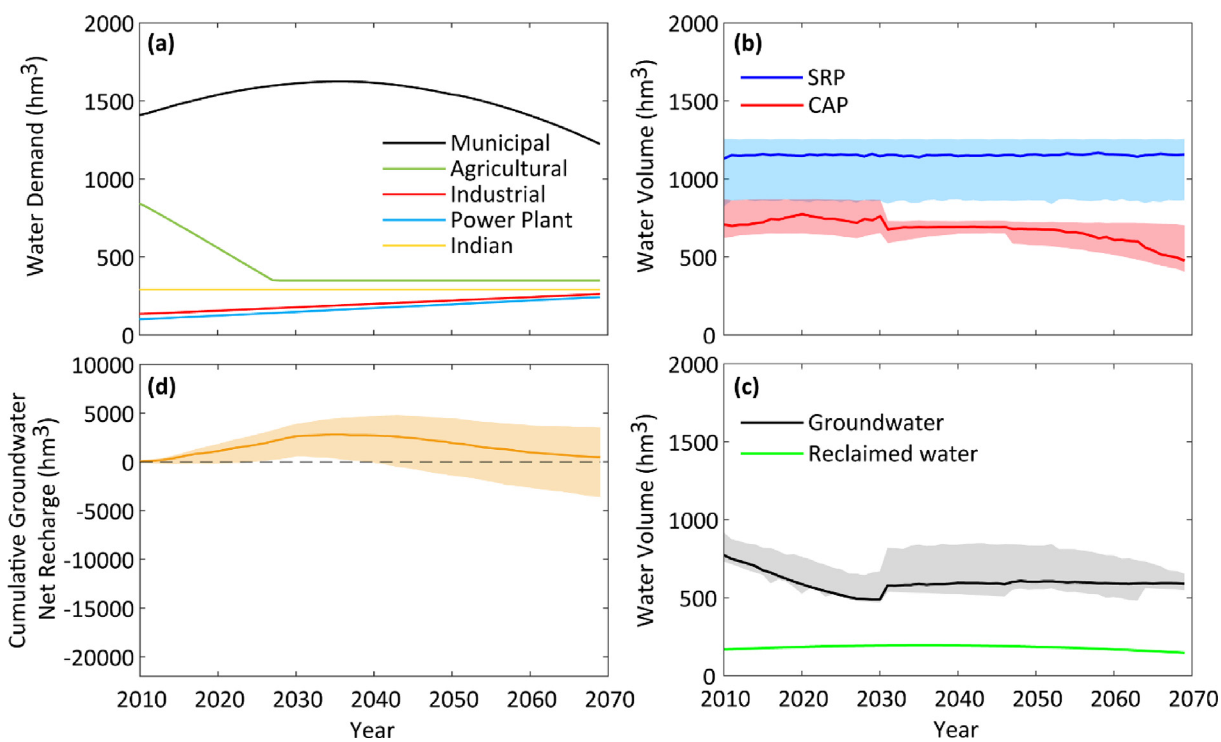

Fig. 8. Results of WEAP simulations in the BAU scenario. (a) Annual water demand for the different sectors. (b) Median (line) and 90% confidence intervals (shaded area) of annual water volume supplied by CAP and SRP. (c) Same as (b) but for groundwater and reclaimed water. (d) Same as (b) but for the cumulative net recharge to the aquifer.

constant throughout the simulation period (292 hm^3/year). The water volumes supplied by each source to satisfy the future water demand are plotted in Fig. 8b,c through the median and 90% confidence interval (CI) of the stochastic ensemble simulations. Allocations of SRP water appear relatively constant throughout the simulation period, with a positively skewed CI. The water volume supplied by CAP is fairly constant through 2030 and, then, it sharply drops in 2031 and gradually decline afterwards; the associated CI is symmetric with variable width (Fig. 8b). Results for GW resources depict decreasing allocations until 2030 and, after a sharp increase, a leveling around 593 hm^3. Overall, the median decrease of GW use is 23% when compared to 2009. In this case, the CI is negatively skewed with respect to median allocation (Fig. 8c). The use of reclaimed water reflects the municipal water demand curve (Fig. 8a), although with a much less pronounced peak. Finally, the median value of the cumulative GW net recharge increases with time until ~2035, where it reaches 2792 hm^3, and then gradually declines until the end of the simulation period remaining always positive (Fig. 8d). Variability around the median estimates indicates a balanced CI with a positive upper bound and a lower bound that is positive until 2039 and negative afterwards approaching −3600 hm^3 in 2069.

4.3. Future projections for alternative food and energy scenarios

Our simulations of future scenarios indicate that impacts on water allocations with increasing food production and a different portfolio of electricity generation are significantly different (Figs. 9 and 10). Agricultural demands for the CropSlow and CropConst scenarios follow similar patterns as the cropland area, resulting in larger water demand as compared to BAU (Fig. 9a). The percent changes in GW and CAP water deliveries when compared to the BAU scenario are positive for both sources with divergent supply-use dynamics (Fig. 9b). CAP water differences are generally consistent between the two scenarios, with only minor increased use for CropConst near the end of the simulation period. In contrast, the percent changes of GW use in CropConst are much larger

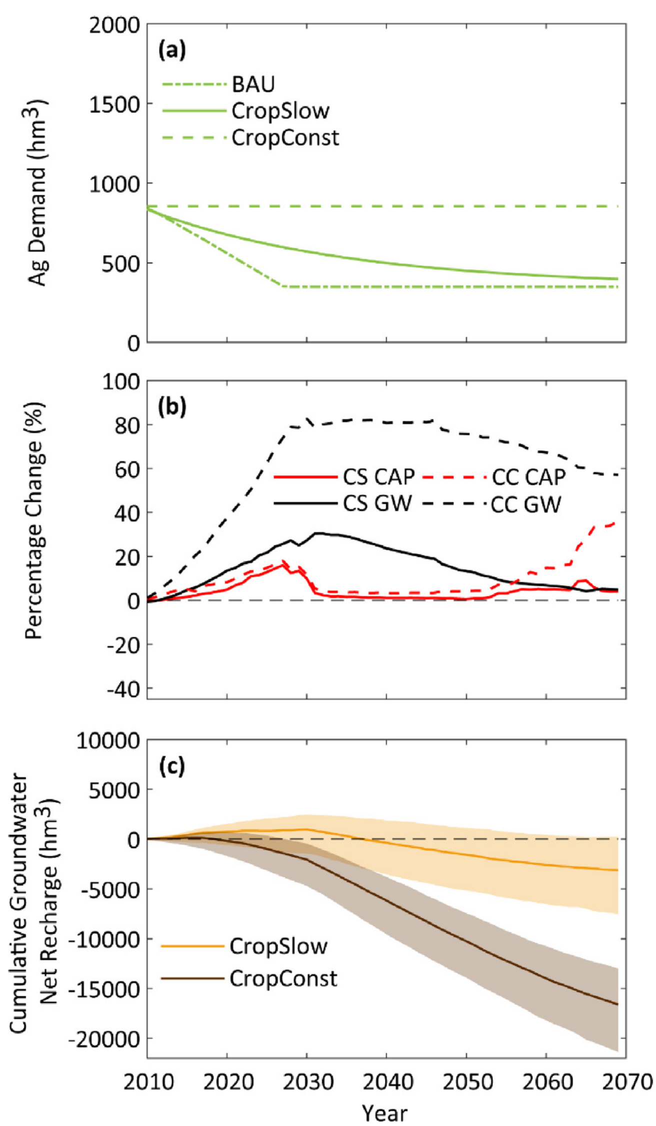

Fig. 9. Results of WEAP simulations in CropSlow (CS) and CropConst (CC) scenarios. (a) Annual water demand from the agricultural sectors in BAU, CropSlow and CropConst scenarios. (b) Median percentage change compared to BAU of annual water supplied by CAP and GW in CropSlow and CropConst scenarios. (c) Median (line) and 90% confidence intervals (shaded area) of the cumulative net recharge to the aquifer in CropSlow and CropConst scenarios.

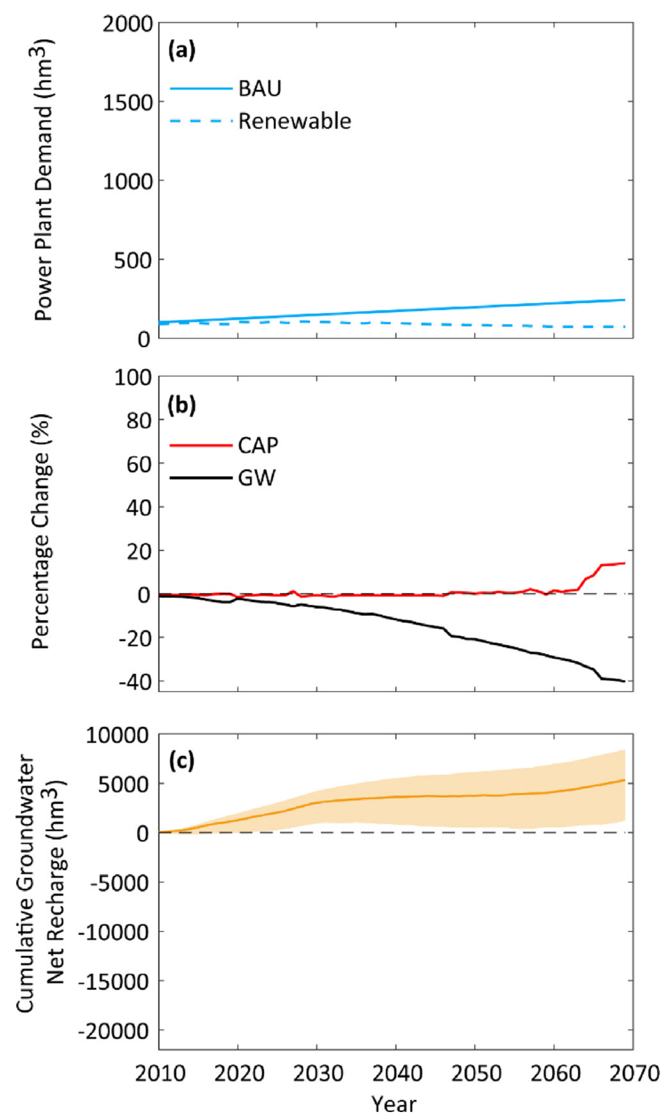

Fig. 10. Results of WEAP simulations in the Renewable scenario. (a) Annual water demand of the power plants in BAU and Renewable scenarios. (b) Median percentage change compared to BAU of annual water supplied by CAP and GW in Renewable scenario. (c) Median (line) and 90% confidence intervals (shaded area) of the cumulative net recharge to the aquifer in Renewable scenario.

than in CropSlow, reaching a maximum of +83% and +30%, respectively. For both scenarios, the change increases up until 2030 and decreases afterwards. Note that SRP and reclaimed water supply (not presented in Fig. 9b) are not affected because they are fully utilized in all cases. The cumulative GW net recharge is largely negative and exhibits a decreasing trend after 2030 (since the beginning of the simulation) for CropSlow (CropConst), approaching a median value of −3103 hm^3 (−16611 hm^3) in 2069 (Fig. 9c). Modifying the energy generation portfolio, as assumed in the Renewable scenario, reduces the water demand for power plants as compared to BAU, with values reaching 74 hm^3 in 2069 (Fig. 10a). This, in turn, causes a steady decrease of GW use with reductions approaching nearly −40% in 2069 (Fig. 10b), and permits achieving safe-yield throughout the simulated period (Fig. 10c).

4.4. Future projections for megadrought conditions

Results for the Shortage scenario suggest substantial changes in the availability of surface water resources and, in turn, in withdrawals and net recharge of groundwater (Fig. 11). The SRP system provides a fairly constant volume of water with a positively skewed CI, as in the BAU scenario. The median allocation of CAP water increases slightly through 2025, it then abruptly decreases of 137 hm^3 and remains fairly constant until the end of the simulation; the CI is positively skewed, with a width that is small until 2034 and dramatically increases afterwards (Fig. 11a). The median GW volume use steadily decreases until 2025, and then returns close to initial values by 2040 followed by a gradual diminishment until the end of the simulation (Fig. 11b). The associated CI is negatively skewed, with dramatic punctuated increases in the upper bound after 2034. The use of reclaimed water is comparable to the BAU scenario (Fig. 11b). The median SRP allocations are ~8% lower than the value in current climate; the percent changes in CAP water use fluctuate between +17% and −13%; lastly, the percent changes in GW use are always positive with larger values between 2026 and 2060 (up to 30%) (Fig. 11c). The median of the cumulative GW net recharge remains positive through 2034 and, then, steadily decreases to −8037 hm^3, with CI exhibiting the largest width among all scenarios (Fig. 11d).

5. Discussion

5.1. Dynamics of future water allocations and associated controls

Our simulations of historical water deliveries in the Phoenix AMA demonstrate that the WEAP platform is able to adequately capture the main rules and physical features affecting sectorial water allocations from the four sources. As such, this model appears to be a reliable tool for exploring the dynamics of water allocations under future scenarios of water demand. In all scenarios, SRP provides the largest source of water that is predicted to be relatively constant in time, with a magnitude that may decrease under drought conditions. The trends exhibited by future deliveries of CAP water and GW result instead from the combined effect of sectorial water demands, surface water availability, and water management rules. Under BAU conditions, the pattern of GW use largely resembles that of agricultural demand (see Fig. 8a and c). However, the sharp increase suggested in 2030 is caused by the CAP water management rules: in 2030, in fact, CAP will cease allocating water for the so-called "Ag Pool" (see Text S2) and these water needs will be satisfied by groundwater resources. In the CropSlow and CropConst scenarios, GW use changes are mainly affected by increasing water needs for agricultural production and, to a lower extent, by the decrease in municipal demand after 2030 (see Fig. 8a, 9a and 9b). Under megadrought conditions, restrictions of CAP water may occur with different amounts that depend on the distinct time series of stochastically generated

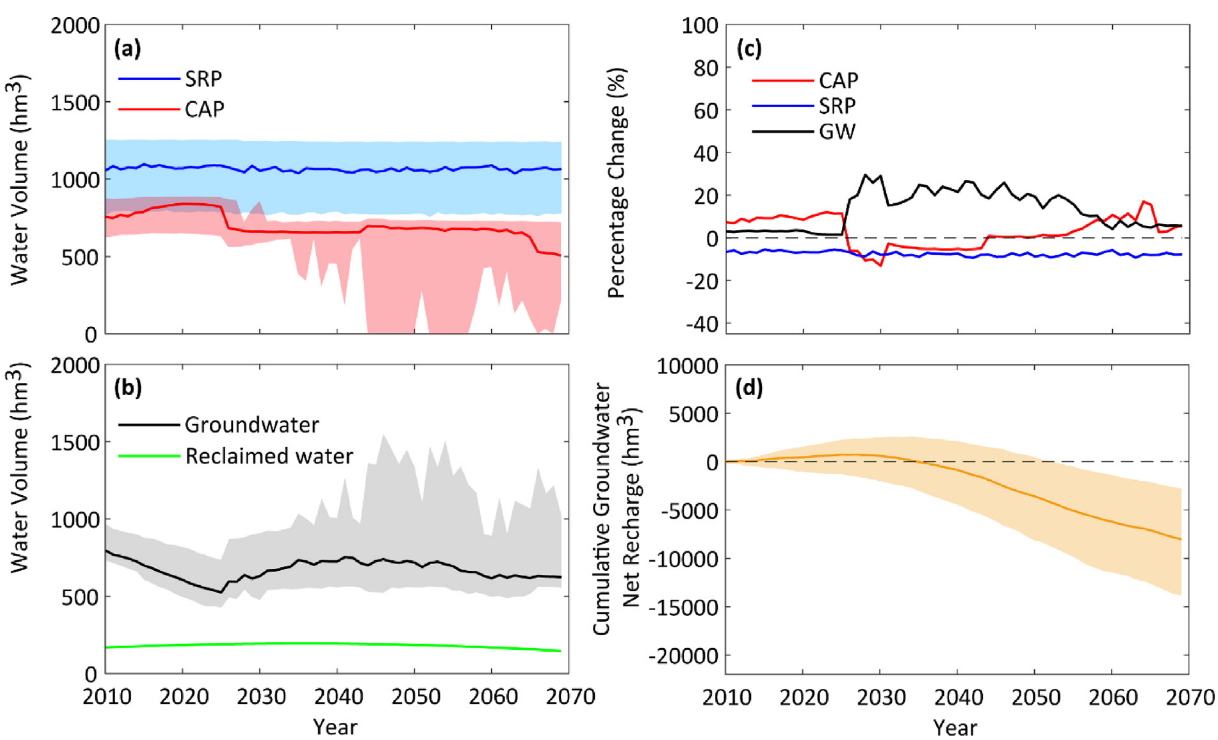

Fig. 11. Results of WEAP simulations in the Shortage scenario. (a) Median (line) and 90% confidence intervals (shaded area) of annual water volume supplied by CAP and SRP in Shortage scenario. (b) Same as (a) but for groundwater and reclaimed water. (c) Median percentage change compared to BAU of annual water supplied by CAP, SRP and GW in Shortage scenario. (d) Same as (b) but for the cumulative net recharge to the aquifer.

levels at Lake Mead, resulting in large width of the CI (Fig. 11a). The lower availability of SRP and CAP water is compensated by larger GW withdrawals (Fig. 11c), whose trend is affected both by municipal and agricultural demands and exhibits large variability across the 1000 series (Fig. 11b).

Finally, the trends of cumulative GW net recharge are mainly affected by agricultural water demand and CAP management rules. This effect can be examined in the BAU scenario, where the cumulative net recharge increases in time through 2038 and, then, decreases steadily (Fig. 8d). Prior to 2030, both GW withdrawals and recharge decrease with time. Specifically, GW withdrawals decline much faster than GW recharge, due to the sustained reduction of agricultural demand. This leads to a positive GW net recharge and an increase of its cumulative value. In 2030, GW withdrawals sharply increase because CAP water is not available anymore for the agricultural sector (Fig. 8c). After eight years, the combination of this increase in withdrawals and the decreasing recharge results in a negative GW net recharge and a steady decline of its cumulative value. Similar considerations can be made for the other scenarios.

5.2. Future changes of the FEW nexus

Simulations with a water management model like WEAP can provide useful insights on the possible future changes of the FEW nexus. Fig. 12a compares cumulative GW net recharge, food production, and energy required for water (see definition in Section 3.5) calculated using the median values of WEAP outputs for the BAU, CropSlow and CropConst scenarios. Under BAU, the cropland area is projected to decrease at the fastest rate, leading to the lowest food production and, at the same time, the smallest energy demand for water. As we consider scenarios where the cropland area decreases less abruptly (CropSlow) or stays constant (CropConst), food production increases three-fold when compared to BAU. However, GW resources are heavily exploited and the energy demand rises up to 15% because water is supplied by GW and CAP (Fig. 9b) that are energy-intensive sources. Figs. 12b and c summarize the effects of a severe drought and an increasing use of renewable energy, respectively. In both cases, food production is not modified because the same cropland area of BAU is assumed. Drought conditions reduce the availability of less energy-intensive SRP water, so that GW (and when available CAP water) must be used to satisfy demand. As a result, energy needs for water increase by 5%. This increase is comparable to that simulated for the CropSlow scenario, but GW overdraft under megadrought conditions is predicted to be ~2.5 times larger. On the other hand, increasing renewable energy with water efficient PV solar plants allows a ten-fold increase of GW recharge and a reduction of 2% of the energy needs of water.

The sustainability index, SI, for all scenarios is presented in Fig. 13. For the BAU scenario, SI is 0 by definition. The stress on water resources induced by entirely preserving food production in the CropConst scenario results in the lowest SI of −8.5. The decline of food production at a slower rate leads instead to slightly less sustainable conditions as compared to BAU (SI = −1.8). An extreme drought is also expected to cause a negative SI (−4.4) by depleting nonrenewable GW resources. In contrast, the transition to renewable energy sources is projected to lead to more sustainable conditions than BAU, with a positive SI of 2.5.

5.3. Comparison with previous relevant studies

Our work complements and expands previous studies on FEW and water-energy systems focused on the same region or conducted elsewhere with a similar approach. A recent study by Mounir et al. (2019) used our simulated water allocations from

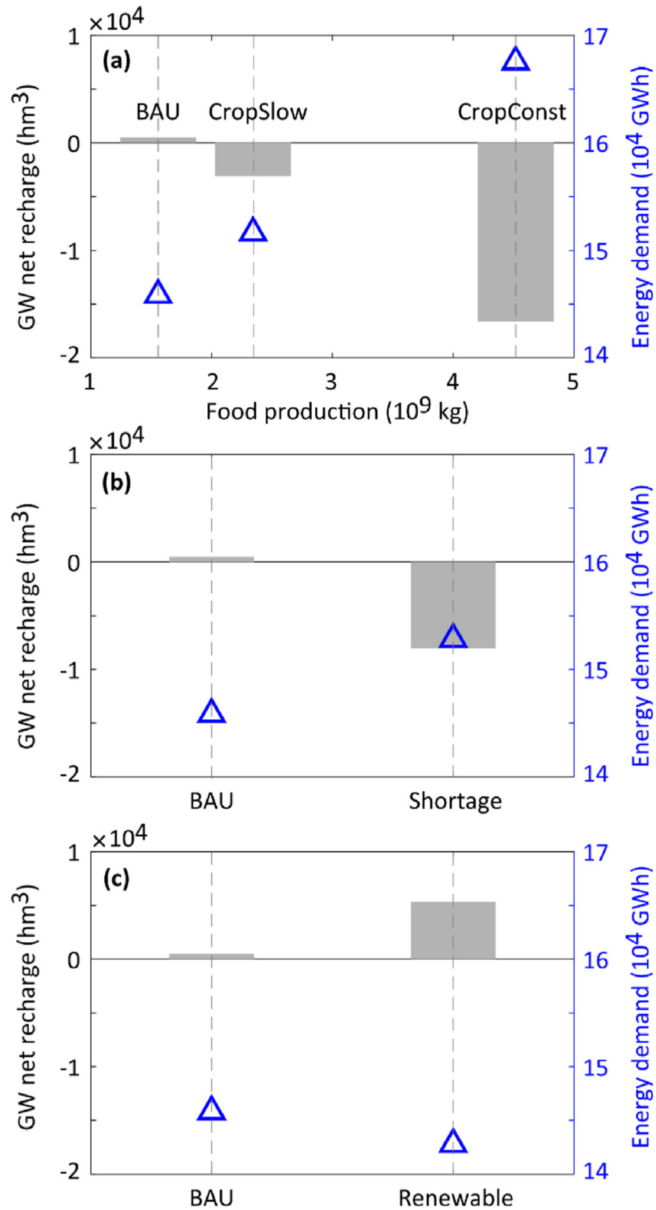

Fig. 12. Cumulative groundwater net recharge (filled bars), food production, and energy demand (triangles) over the period 2010–2069 for the future scenarios simulated by WEAP. (a) Comparison of food production (x-axis), cumulative groundwater net recharge (bars) and energy demand embedded in water (triangles) in BAU, CropSlow and CropConst scenarios. (b) Comparison of cumulative groundwater net recharge and energy demand of BAU and Shortage scenarios. (c) Same as (b) but for BAU and Renewable scenarios. Metrics are obtained using the median values of WEAP outputs.

the supply sources to the demand sectors to investigate the impacts of future energy portfolios on the water-energy nexus. Yates et al. (2013b) applied WEAP to investigate the water-energy nexus in southwestern U.S., finding that investing in renewable technologies could lead to significant water savings. Our study confirms this result and provides additional quantitative details at higher spatial resolution. Two recent efforts focused in Arizona analyzed conservation strategies in the water-energy nexus (Bartos and Chester, 2014), and the impact of increasing temperature on crop production, irrigation requirements and on-farm energy use (Berardy and Chester, 2017). Our work complements these studies by (i) increasing the spatial granularity of the analyses from the state to the metropolitan region scale; (ii) explicitly

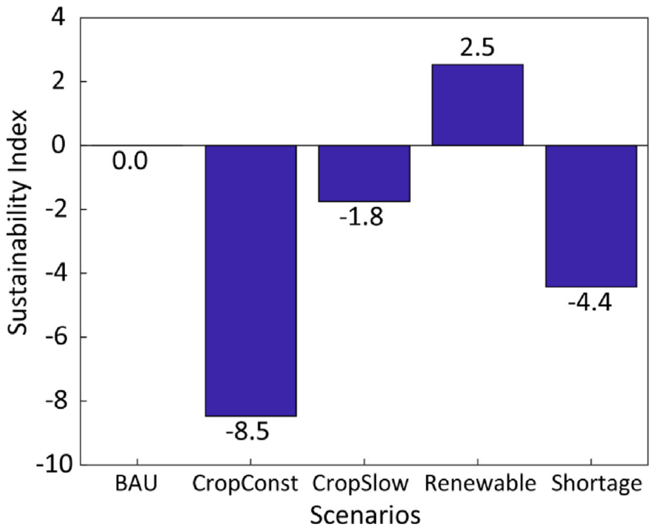

Fig. 13. Sustainability index, SI, for the different scenarios.

considering the water management rules; (iii) providing information on how demand is satisfied by the different supply sources; and (iv) evaluating the impacts of an extreme drought. WEAP has also been applied in other regions of the world to explore similar FEW-related questions. For example, Momblanch et al. (2019) used this platform to model a regional water resources system in India, finding that the impacts on the nexus caused by socio-economic factors (e.g. population, water consumption per capita, cropland area) are greater than those determined by climate change. Our study confirms this result, as the CropConst scenario leads to higher groundwater overdraft than the Shortage scenario.

5.4. Limitations of the modeling approach and future work

Assessing FEW systems is a complicated task that requires the integration of highly heterogenous data sets and multiple models with different spatial and temporal resolutions. Our effort is a preliminary attempt to quantify FEW feedbacks in the Phoenix AMA by explicitly modeling one resource, i.e. water, under different scenarios driven by the other resources, i.e. energy and food. As such, we are aware that this approach has limitations that we aim to address in future work. First of all, separate models should be adopted to simulate the energy and food systems and integrated with the water model to capture the exchange of fluxes shared among the systems. For example, the MABIA method (Jabloun and Sahli, 2012) could be used to quantify irrigation requirements and crop yield within WEAP, and the Long Range Energy Alternatives Planning (LEAP) system (Heaps, 2012) could be coupled to WEAP-MABIA to simulate the energy-water and energy-food feedbacks. Second, an economic model could be adopted to simulate the change of crop portfolios in future scenarios as in Esteve et al. (2015). Third, the configuration of WEAP could be improved to capture with more fidelity the management rules and physical constraints controlling water allocation in the study region. This involves: (i) increasing the spatial granularity of the WEAP network to simulate the access to different water sources by each municipal water provider, irrigation district and power plant; (ii) incorporating the credit system implemented by ADWR to manage groundwater (Sampson et al., 2016); and (iii) increasing the time resolution of the model forcings to–at least–monthly scale to account for the seasonal variability of supplies and demands. This last point will be crucial to model the crop growing seasons, including the effects of seasonal precipitation and evapotranspiration fluxes. Finally, local stakeholders should be actively involved through a participatory modeling process that will make the modeling tools more credible and useful to support decision-making.

6. Conclusions

The Phoenix AMA is a compelling case study to explore the interactions of the FEW systems at the scale of metropolitan regions. In this water-scarce area, population is expected to increase at a rate of ~0.9 million people every 10 years, most likely causing changes in agricultural activities as well as in the energy and water demands. In this study, we quantified some of the FEW interactions in the Phoenix AMA using the WEAP water management model. We first used historical data to show that WEAP is able to reliably simulate the allocation of water from surface water and groundwater sources to the main demand sectors. Next, we applied this model under possible future (2009–2069) scenarios of water and energy demand and supply, as well as of food production. Under BAU conditions where population is expected to increase and agricultural activities to gradually decrease, our results indicate a reduction in the use of groundwater of ~23% that, in turn, will likely allow achieving safe-yield. If the decrease in agricultural activities will be less drastic or remain constant in time (i.e., more food will be produced locally), additional water from more energy-intensive water sources (groundwater and CAP) will be needed. This will considerably compromise the ability to reach safe-yield and, at the same time, increase the energy demand up to 15% as compared to BAU, resulting in less sustainable conditions. The transition to an energy portfolio with a larger fraction of renewable sources will reduce the environmental impacts of electricity generation from traditional fossil fuels, increase the probability of reaching safe-yield, and diminish the energy demand for water of 2%. Finally, the occurrence of a mega-drought under BAU demand conditions will cause shortages in surface water resources that will be largely compensated by groundwater, leading to the need of additional energy (5%) and significant groundwater overdraft. To our knowledge, our study is one of the few efforts aimed at investigating and quantifying the FEW interactions at the scale of a metropolitan region. While the characteristics of FEW systems tend to be highly site-specific, we believe that some of the assumptions made and the analytical approach that we have adopted provide valuable support to quantify FEW interactions at other locations and scales.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134478.

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