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Response surfaces of vulnerability to climate change: the Colorado River Basin, the High Plains, and California

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Abstract We quantify the vulnerability of water supply to shortage for the Colorado River Basin and basins of the High Plains and California and assess the sensitivity of their water supply system to future changes in the statistical variability of supply and demand. We do so for current conditions and future socio-economic scenarios within a probabilistic framework that incorporates the inherent uncertainties in the drivers of vulnerability. Our analysis indicates that the most sensitive basins to both current and future variability of demand and supply are the Central California and the San Joaquin-Tulare basins. Large sensitivity is also found for the Kansas basin of the High Plains. Within the Colorado River Basin, the Lower Colorado and Gila were found to be the most vulnerable and sensitive sub-basins. By accounting for future uncertainty within the above probabilistic framework, this study unveils and isolates the individual responses of a given basin to changes in the statistical properties of demand and supply and offers a valuable tool for the identification of policy strategies and adaptation measures.

1 Introduction

As human populations expand and the climate changes, it becomes ever more important to assess the vulnerability of current and future water supplies to shortage. Although some attempts at quantifying this vulnerability have been made in the past decade (e.g., Roy et al. 2010; Vörösmarty et al. 2000), those attempts have not accounted for the inherent uncertainty in its drivers (i.e., supply and demand). Incorporating such uncertainty (i.e., stochasticity) requires that the assessment be done probabilistically. In a separate paper (Foti et al. 2014), we

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incorporate the stochastic nature of supply and demand into a probabilistic assessment of the vulnerability of the entire US water supply system. In this paper we demonstrate the utility of that framework for selected basins in the US.

Supply and demand are variably distributed in space and time due to the inhomogeneous space-time superposition of their anthropogenic and climatic components (Oki and Kanae 2006). Historical records and future projections indicate the larger Southwest, including the High Plains, Colorado River Basin, and much of California, as the areas more likely to experience water shortages (Barnett et al. 2004; Barnett and Pierce 2008, 2009; Cayan et al. 2010; Christensen et al. 2004; Dawadi and Ahmad 2012; Lane et al. 1999; Foti et al. 2012). The water resources of the High Plains and California have sometimes been insufficient to meet expanding agricultural needs and are projected to be unable to fully support irrigation within a few decades (Wada et al. 2010), while intense groundwater mining is projected to endanger the Central Valley and Ogallala aquifers (Scanlon et al. 2012). In the Colorado River Basin, the construction of large storage structures has not fully provided water security across the Southwest (Barnett and Pierce 2008), as the annual average flow of the Colorado River had been entirely allocated to sustain the agricultural and urban needs of the Southwest, Mexico and California by the early 1990's (Gleick 2010).

In this paper we assess the future vulnerability and sensitivity of the water supply of a set of basins located in the larger Southwest of the US, specifically: the Niobara-Platte-Loup and Kansas basins of the High Plains; the Colorado-Gunnison, Colorado San Juan, Little Colorado, Lower Colorado and Gila basins of the Colorado River Basin; and the Sacramento-Lahontan, San Joaquin-Tulare, and Central California Coastal basins of California.

The core and novelty of our probabilistic framework lay in accounting for the inherent stochasticity of the vulnerability drivers, both of which crucially depend on a stochastic climate and are correlated in space and time. In addition, we account for the uncertainty in future climatic and socio-economic conditions by exploring, within this probabilistic approach, a set of two climatic models in combination with three global emission scenarios (see Supplemental Material).

2 The US water supply system

We characterize the US water supply system at the spatial scale of 98 Assessment Sub Regions (ASRs) (Figure S1A of the Supplemental Material) which make up the whole conterminous US. The US water supply system is a highly interconnected complex structure that can be represented as a set of networks. Two or more ASRs are considered part of the same network when they are connected by a sequence of water links, either natural (due to natural upstream to downstream flow) or artificial (via water diversions). At the above spatial scale, we identify three multi-ASR networks (of 69, 10, and 4 ASRs) and 15 single-ASR networks (See Figure S1B of the Supplemental Material) (Foti et al. 2012, 2014; Foti 2011). The ten basins analyzed in this paper belong to the 69-ASR network. The determination of inter-ASR water flows, reservoir storage and evaporation and water assigned to each demand at each of the ten study basins, therefore, required the simulation of the entire 69-ASR system for each of the climatic and socio-economic conditions considered in the study.

Annual water supply at each basin (i.e., ASR) is the aggregated annual fresh water yield (i.e., the difference between precipitation and evapotranspiration) plus the water stored within the basin at the beginning of the given year, plus the natural inflow from upstream basins, plus the water artificially diverted from other basins. All those components of water supply are inherently stochastic and are correlated in time and space.

The 69-ASR water supply network was simulated using MODSIM (Labadie et al. 1984; Labadie and Larson 2007). The simulations provide annual values of water flows in any link, storage levels in each ASR, water evaporated from storage, and water assigned to the demand of each ASR. All the above depend both on climate and on the following set of priorities for water allocation: (1) in-stream flow requirements, (2) trans-ASR diversions, (3) consumptive water uses, and (4) reservoir storage.

2.1 Fresh water yield and storage

We use Eagleson's (1978a, b, c, d, e, f, g) one-dimensional, statistical-dynamical physically-based annual water balance model to estimate evapotranspiration, infiltration, groundwater flow and surface runoff as well as fresh water yield (see Supplemental Material). The model was implemented at the annual time step on a 5×5 km grid for the US and calibrated using historical streamflow records of over 2,000 basins making up the conterminous US. For all basins, the calibrated model matches the average historical streamflows within a 1 % tolerance (Foti et al. 2012, 2014; Foti 2011). Results were aggregated at the ASR level to determine probability distribution functions (PDFs) of water yield for historical (1953–2005) and projected future climate (2006–2100). Water yield, *Y*, is the sum of surface and sub-surface flow or, equivalently, the difference between precipitation and evapotranspiration.

Water storage capacity for each ASR was determined by aggregating storage capacities of natural and man-made impoundments. Only the 1,196 reservoirs with a normal surface area of at least 5 km^2 (excluding tailings ponds, cooling ponds, and reservoirs whose only purpose is flood control) were selected among those listed in the June 2009 version of the National Inventory of Dams from the US Army Corps of Engineers (Foti et al. 2012).

2.2 Water demands and diversions

We individuated three classes of water use for each ASR: in-stream flow requirements, trans-ASR water diversions and consumptive uses. All of them are incorporated in the water supply network simulation. Nevertheless, in the analysis of the results, what will be referred as "demand" is only the consumptive use.

In-stream flow requirements refer to the magnitude and temporal distribution of flows required to ensure adequate supply for ecosystems maintenance. Careful determination of in-stream flow requirements involves a complicated mix of socio-economic, biological and environmental factors, which is not practical at the ASR scale. In this study we adopt the general guidelines delineated by Tennant (1976) and set the in-stream flow requirement of each ASR for both current and future conditions as 10 % of its average streamflow calculated over the years 1953–1985.

Trans-ASR diversions represent water diverted from one ASR to another as the result of legal agreements between the jurisdictions involved. The information regarding inter-basin diversions was taken from USGS publications covering the western (Petsch 1985) and eastern (Mooty and Jeffcoat 1986) US and aggregated by ASR. For the Colorado River Basin and California, the above information was updated with more recent sources (California Department of Water Resources 1998; Colorado Water Conservation Board 1998, 2010; Litke and Appel 1989).

County-level estimates of water withdrawals across the US, necessary to compute water demand (i.e., consumptive use) at each ASR, are available at 5-year intervals from the USGS for the period 1985–2005 (Hutson et al. 2004; Kenny et al. 2009; Solley et al. 1988, 1993, 1998). These data, along with data on water use drivers and water use efficiency rates, were used to simulate past and current conditions and as a basis for projecting future levels of desired water withdrawal (from surface and ground water combined) by ASR. Consumptive use proportions from the USGS for years 1985, 1990, and 1995 were then used in converting estimates of withdrawal to estimates of water demand. The analysis of the projections of future demands, by GCM-SRES scenario combination, is presented in a separate paper (Brown et al. 2013) and briefly summarized in the Supplemental Material.

3 Vulnerability assessment

We define and quantify the vulnerability of the US water supply to shortage as the probability that water demand exceeds water supply (Foti et al. 2014; Korchendorfer and Ramirez 1996). This is done by using the time-dependent probability distribution functions of supply *(S)* and demand *(D)* to estimate vulnerability (*V*) for each ASR as:

$$V(t) = \Pr[S(t) < D(t)] \tag{1}$$

Surplus is then defined as the difference between supply and demand, *S-D* (note that in this context, surplus can be negative).

The vulnerability of water supply to shortage, therefore, is a function of all the statistical moments of the probability distributions of supply and demand. In a context of hydro-climatic and socio-economic variability, then, it is not sufficient to quantify the effects of changes in the mean values of hydro-climatic and socio-economic variables of interest; it also is necessary to quantify the effects of changes in their inherent variability (i.e., variance, covariance and higher order moments).

Empirical probability distributions were fitted to the demand and supply obtained by simulating the US water supply network. Using Eq. 1, these distributions of *D(t)* and *S(t)* allowed a probabilistic assessment of vulnerability for each ASR for the current conditions as well as for each one of the projected futures. All simulations of the period 1953–2100 began with reservoirs half full. Current vulnerability was evaluated for each ASR over the 20-year period of 1986–2005. Future vulnerability was estimated for four 20-year periods centered at 2020, 2040, 2060 and 2080 assuming no changes in storage capacity, in installed trans-ASR diversion capacity, in in-stream flow requirements, and in the physical structure of the water supply network.

3.1 Sensitivity of vulnerability to changes in the drivers

Changes in vulnerability depend not only on the projected changes in supply and demand, but also on the sensitivity of vulnerability to changes in supply and demand. We express the total change in vulnerability as the following differential:

$$dV = \frac{\partial V}{\partial \mu_S} d\mu_S + \frac{\partial V}{\partial \mu_D} d\mu_D + \frac{\partial V}{\partial \sigma_S} d\sigma_S + \frac{\partial V}{\partial \sigma_D} d\sigma_D + \frac{\partial V}{\partial \mathrm{cov}(S,D)} d\mathrm{cov}(S,D) \tag{2}$$

where the partial derivatives represent the sensitivities of vulnerability to changes in the probabilistic characteristics of supply and demand. Those sensitivities are also functions of the mean, variance and covariance of *S* and *D* (Foti et al. 2014).

3.2 Response surfaces

We characterize the ten selected basins in terms of climate response surfaces. These surfaces represent the first order response of a system to changes in two major system components (in our case supply and demand) and allow a general analysis of the impact that future variations in those components have on the system itself (e.g., Weiβ and Alcamo 2011). We present response surfaces for vulnerability, and for sensitivity of vulnerability to changes in the mean and standard deviation of supply and demand, for each of the selected basins and for the CGCM-A1B scenario. The analytical expressions for vulnerability and the corresponding sensitivities as functions of the mean and standard deviation of supply and demand are provided in the Supplemental Material.

4 Results and discussion

4.1 Vulnerability: the CGCM-A1B future

The response surfaces of Fig. 1 show the individual impact on vulnerability of projected changes in the means of supply and demand for the ten selected basins. With the exception of

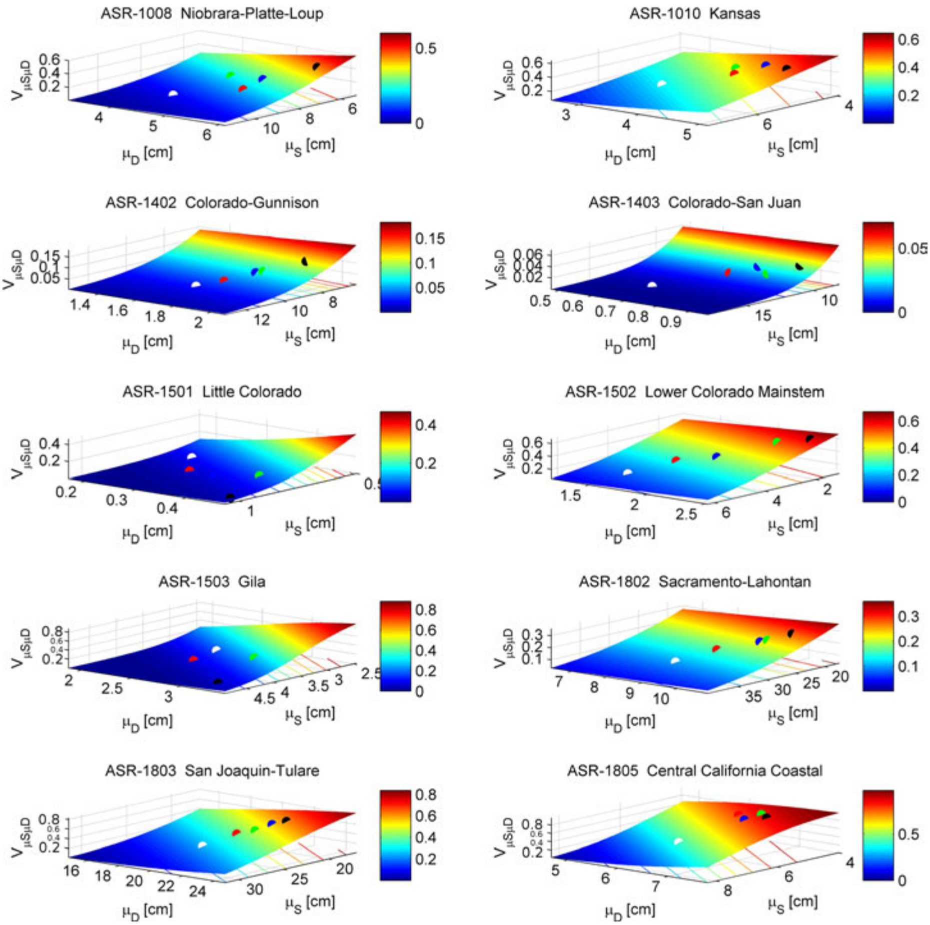

Fig. 1 Response surfaces of vulnerability as function of mean water supply and water demand for the ten study basins. Current status is represented for each surface by the *white marker*. *Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

the Little Colorado and Gila basins, the projected decreases in water supply over the course of the 21st century will contribute towards an increase in vulnerability. The projected changes in the variability (i.e., standard deviation) of water supply, on the other hand, are expected to decrease vulnerability for eight of the basins (again, the only exceptions are the Little Colorado and Gila basins). This decrease in vulnerability occurs because the variability of water supply is projected to decrease, along with the mean water supply itself, for those eight basins. Noticeably, projected changes in mean demand always contribute to an increase in future vulnerability. The effect of changes in the standard deviation of demand, on the other hand, increases vulnerability only in the basins of the High Plains and in the Colorado-Gunnison, Lower Colorado and Gila basins.

Compounded projected changes in mean supply and demand are expected to cause increases in the vulnerability of all basins throughout the 21st century, with the exception of the Little Colorado and Gila. The highest increases in vulnerability are expected in the Lower

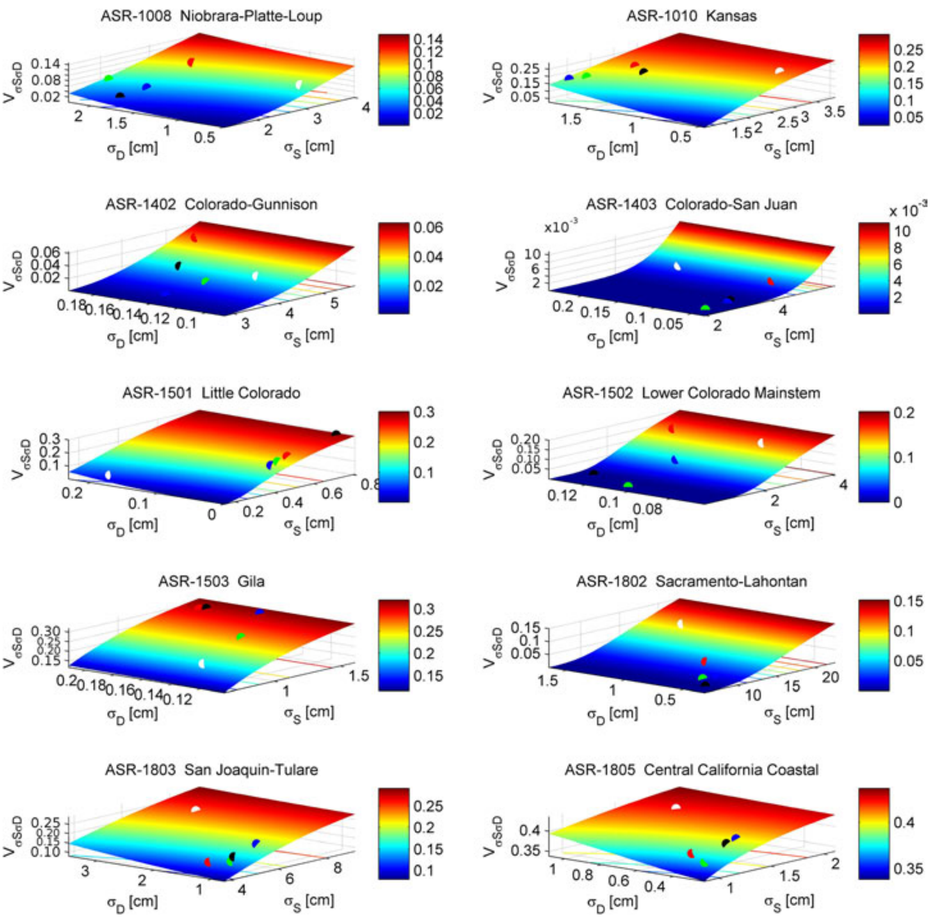

Fig. 2 Response surfaces of vulnerability as function of the standard deviation of water supply and water demand for the ten study basins. Current status is represented for each surface by the *white marker*. *Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

Colorado, Kansas and Central California basins. In these three basins, the average demand is projected to exceed the supply (i.e., $V>0.5$) respectively by 2060, 2040 and 2020. On the other hand, when only the effect of changes in the standard deviation of supply and demand is considered, only the Little Colorado and Gila are projected to experience progressive vulnerability increases (Fig. 2). In the case of the Gila basin the increase in vulnerability is due to the simultaneous increase in the standard deviation of both supply and demand, whereas in the Little Colorado basin the increase in vulnerability is driven by the increase in the standard deviation of water supply, which offsets the projected decrease in the standard deviation of demand.

The volume under the response surfaces, calculated as shown in Figure S2 of the Supplemental Material, is a measure of the current sensitivity of basin vulnerability to changes in the PDFs of water supply and demand. The greater the volume is, the more sensitive the given basin is to future changes in supply and demand (e.g., Weiβ and Alcamo 2011), as large volumes under the surface indicate that changes in the drivers would more strongly impact the basin's vulnerability. In order to use this indicator to directly compare the responses of the selected basins to projected changes in supply and demand, the surfaces were created using ranges of [μ_S - σ_S, μ_S+ σ_S], [μ_D - σ_D, μ_D - σ_D], [$0.5 \cdot \sigma_S$, $1.5 \cdot \sigma_S$] and [$0.5 \cdot \sigma_D$, $1.5 \cdot \sigma_D$] for each basin. Volumes under the response surfaces were then normalized by their respective averages. As shown in Fig. 3, the Central California Coastal ASR is by far the most sensitive basin to changes in supply and demand, followed by the San Joaquin-Tulare and Kansas basins, while the Colorado-Gunnison and Colorado-San Juan basins are the least sensitive. Normalized sensitivities to changes in mean water supply and demand are very close to the normalized sensitivities to changes in the standard deviation of supply and demand for most of the basins. However, this does not suggest that each basin is equally sensitive to changes in the means of supply and demand as it is to changes in their standard deviations; rather the normalized sensitivities indicate how the sensitivities (either to the mean or to the standard deviation of supply and demand) compare to each other among basins.

Our findings are in overall agreement with those of other regional studies (Barnett et al. 2004; Cayan et al. 2010; Clow 2009; Dettinger et al. 2004; VanRheenen et al. 2004), despite the fact that the time step of our analysis prevents us from characterizing seasonal patterns.

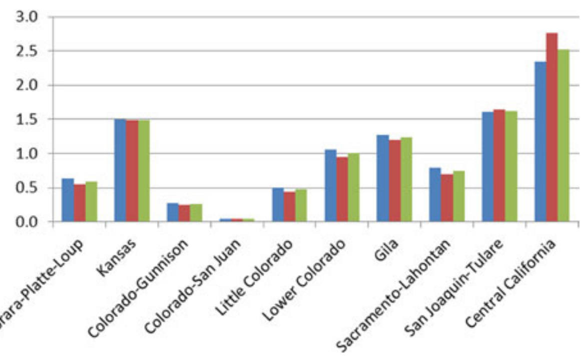

Fig. 3 Normalized volumes under the response surfaces of vulnerability for the ten study basins for the current conditions. *Blue histograms* correspond to the volume under the response surfaces of vulnerability changes as function of mean supply and demand. *Red histograms* correspond to the volume under the response surfaces of vulnerability changes as function of standard deviation of supply and demand. *Green histogram* corresponds to the sum of the previous two volumes

4.2 Sensitivity of vulnerability: the CGCM-A1B future

Response surfaces showing the sensitivity of vulnerability to changes in mean water supply and mean water demand for CGCM-A1B scenario are shown in Fig. 4. Sensitivities to changes in mean water supply are always negative, meaning that as mean water supply increases the probability of shortage decreases. The magnitude of the sensitivity, however, is found to vary in both space and time.

Notably, all selected basins, with the exception of the Little Colorado, Gila, and Central California Coastal basins, are projected to become more sensitive over time to changes in average water supply. The same is true for the sensitivity to changes in mean water demand, as indicated in the response surfaces of Fig. 5. Because the magnitudes of the sensitivities to mean demand and mean supply reach a maximum when average demand equals average supply (see eqs. S.2a and S.2b in the Supplemental Material), in those basins where the average surplus diminishes over time the magnitude of sensitivity to vulnerability increases

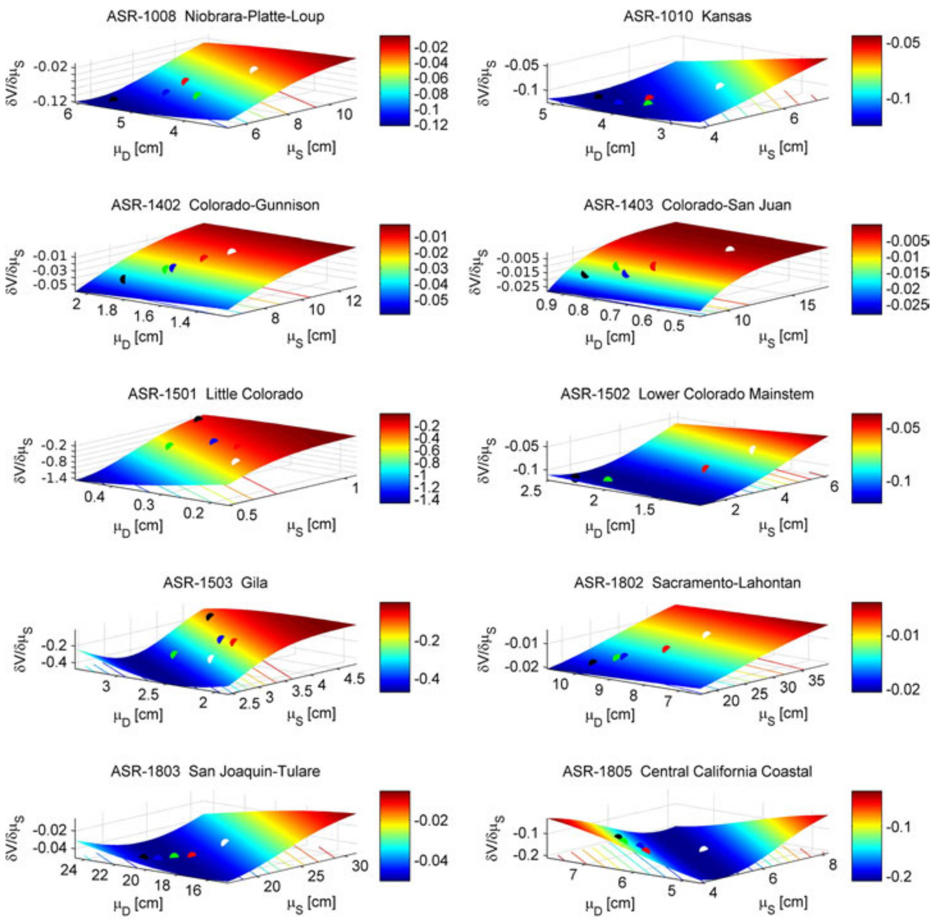

Fig. 4 Response surfaces of sensitivity of vulnerability to changes in mean water supply for the ten study basins. Current status is represented for each surface by the *white marker*. *Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

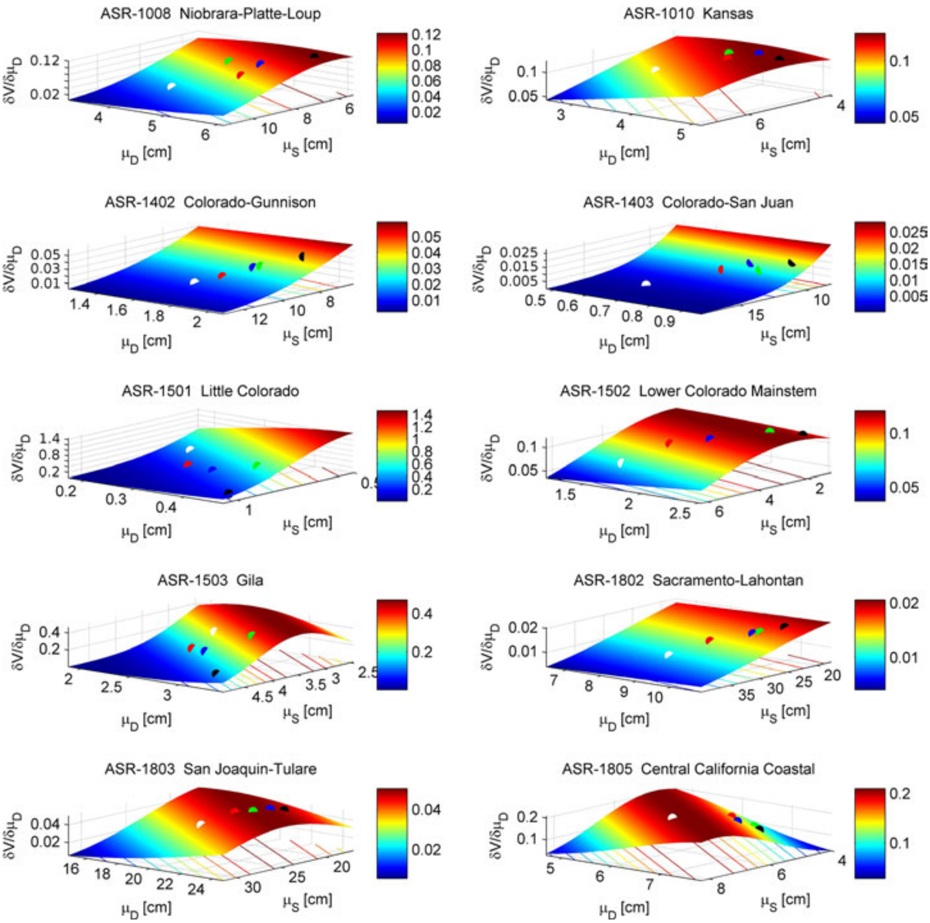

Fig. 5 Response surfaces of sensitivity of vulnerability to changes in mean water demand for the ten study basins. Current status is represented for each surface by the *white marker. Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

(negatively for sensitivity to supply and positively for sensitivity to demand). For current conditions (i.e., $\mu_S > \mu_D$), surplus may diminish either because supply decreases for a given demand, or because demand increases for a given supply, or because supply decreases and demand increases. Those basins for which the magnitude of the difference between μ_S and μ_D increases exhibit decreases in the magnitude of their sensitivity. For most basins, where $\mu_S > \mu_D$, this may result from increases in supply for a given demand, or decreases in demand for a given supply; however, for basins where $\mu_S <= \mu_D$ (e.g., Little Colorado River Basin, Gila River Basin and Central California Coastal basins), this may result from increases in the demand.

The projected behavior of the sensitivity of vulnerability to changes in mean supply and demand (see Figs. 4 and 5) is consistent across all basins examined and results from the fact that supply is generally projected to decrease while demand is projected to increase. Those basins for which the surplus is currently positive will exhibit increases in the magnitude of vulnerability (because their surplus will approach zero), while those whose average surplus is currently negative will also exhibit an increase in vulnerability but, concurrently, a decrease in the sensitivity to further changes (because their surplus will grow negatively). The latter condition is crossed or reached by 2080 by several of the selected basins, namely the Kansas, Lower Colorado, San Joaquin-Tulare, and Central California Coastal basins.

The response surfaces of the sensitivity of vulnerability to changes in the standard deviation of supply and demand for the CGCM-A1B projections are shown in Figs. 6 and 7. Because in all the cases considered mean supply is larger than mean demand, the sensitivity of vulnerability to changes in the standard deviations of supply and demand is always positive, with vulnerability always increasing as a result of a more variable supply or demand. The sensitivity of vulnerability to changes in the standard deviation of water supply (or demand) is zero when the standard deviation of water supply (or demand) is itself zero (see eqs. S.3a and S.3b in the Supplemental Material). Figure 6 shows that the sensitivity of vulnerability to the standard deviation of water supply is projected to decrease throughout the 21st century for all the selected basins, with the exception of the San Joaquin-Tulare and Central California Coastal

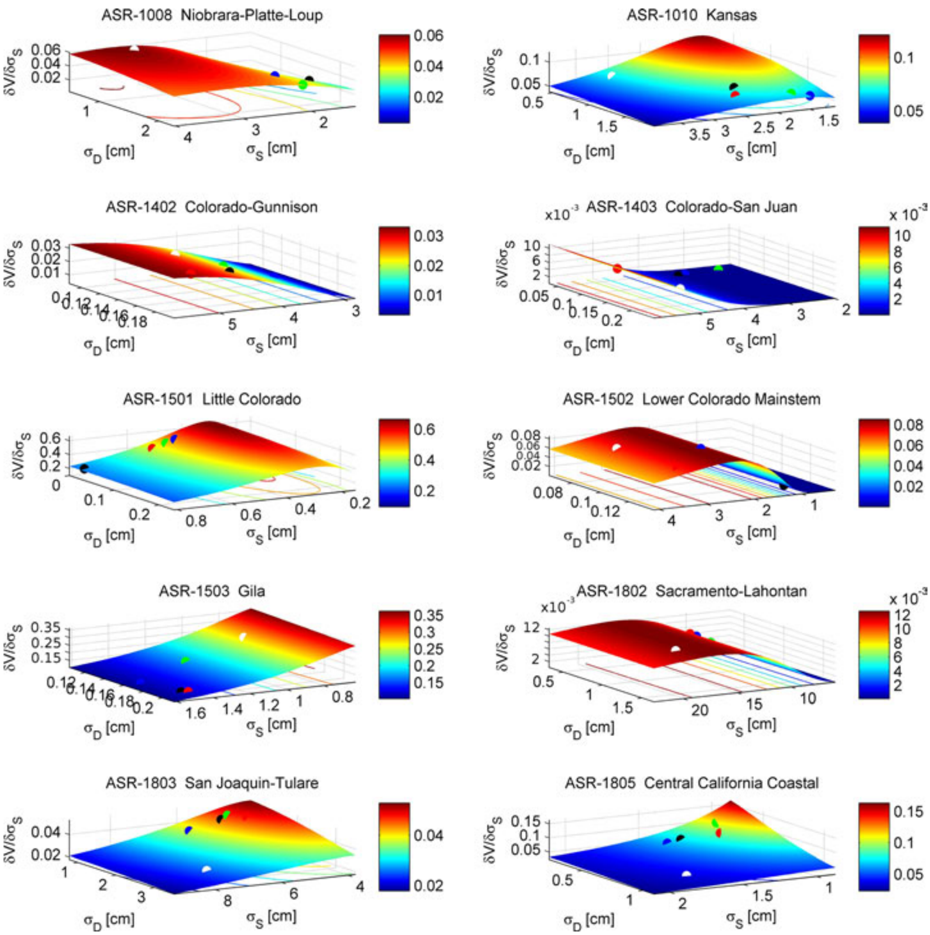

Fig. 6 Response surfaces of sensitivity of vulnerability to changes in standard deviation of water supply for the ten study basins. Current status is represented for each surface by the *white marker*. *Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

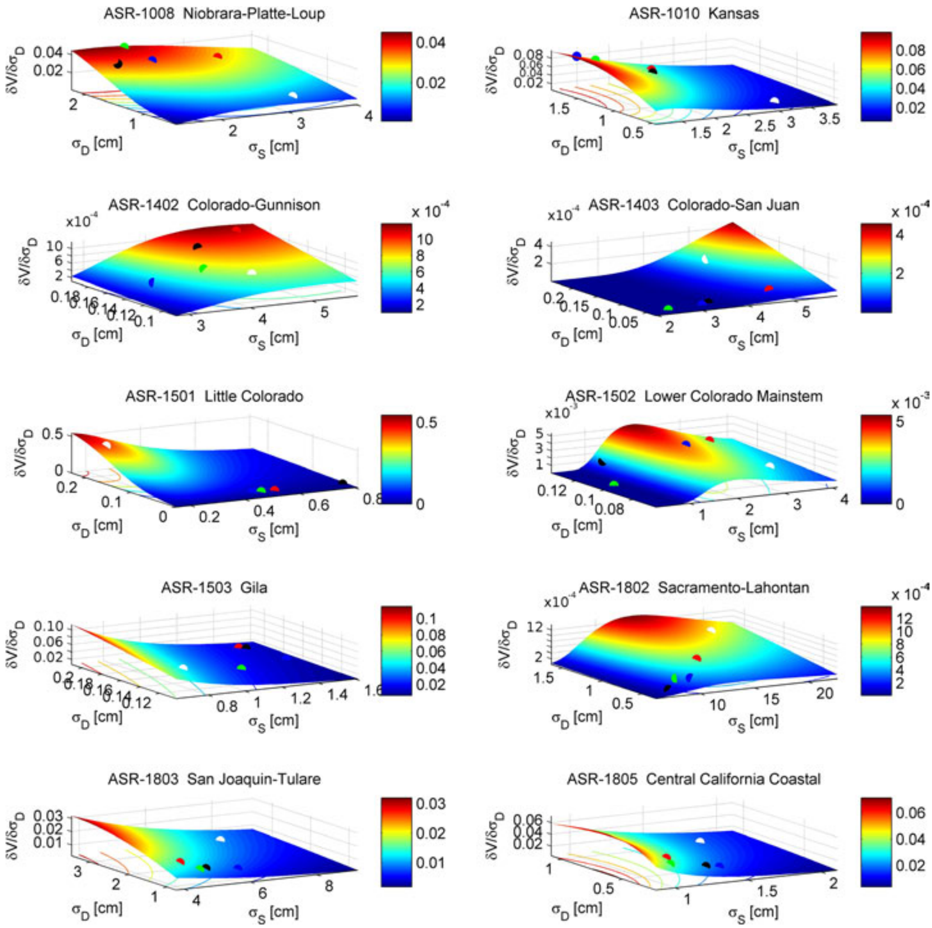

Fig. 7 Response surfaces of sensitivity of vulnerability to changes in standard deviation of water demand for the ten study basins. Current status is represented for each surface by the *white marker. Red*, *blue*, *green* and *black markers* indicate respectively the 2020, 2040, 2060 and 2080 periods. Maps are relative to the CGCM-A1B future

basins. Sensitivity to the standard deviation of water demand, on the other hand, is expected to decrease in the Colorado-San Juan, Little Colorado, Gila, and Sacramento-Lahontan basins (Fig. 7).

4.3 GCM and Scenario dependence

The analysis presented so far is based on the CGCM-A1B hydro-climatic and socio-economic projections. Obviously, different pictures of the future arise when other GCMs or scenarios are used. Normalized volumes below the response surfaces of vulnerability for future target years and six GCM-SRES scenario combinations are presented in Fig. 8 for each of the selected basins. The analysis of Fig. 8 shows that the projected response of individual basins varies significantly among alternative futures. Such dissimilarities are largely due to discordances in the projections of climatic variables by the different GCMs, which in turn affect the projections of future supply and demand and result in complicated mixtures of future conditions.

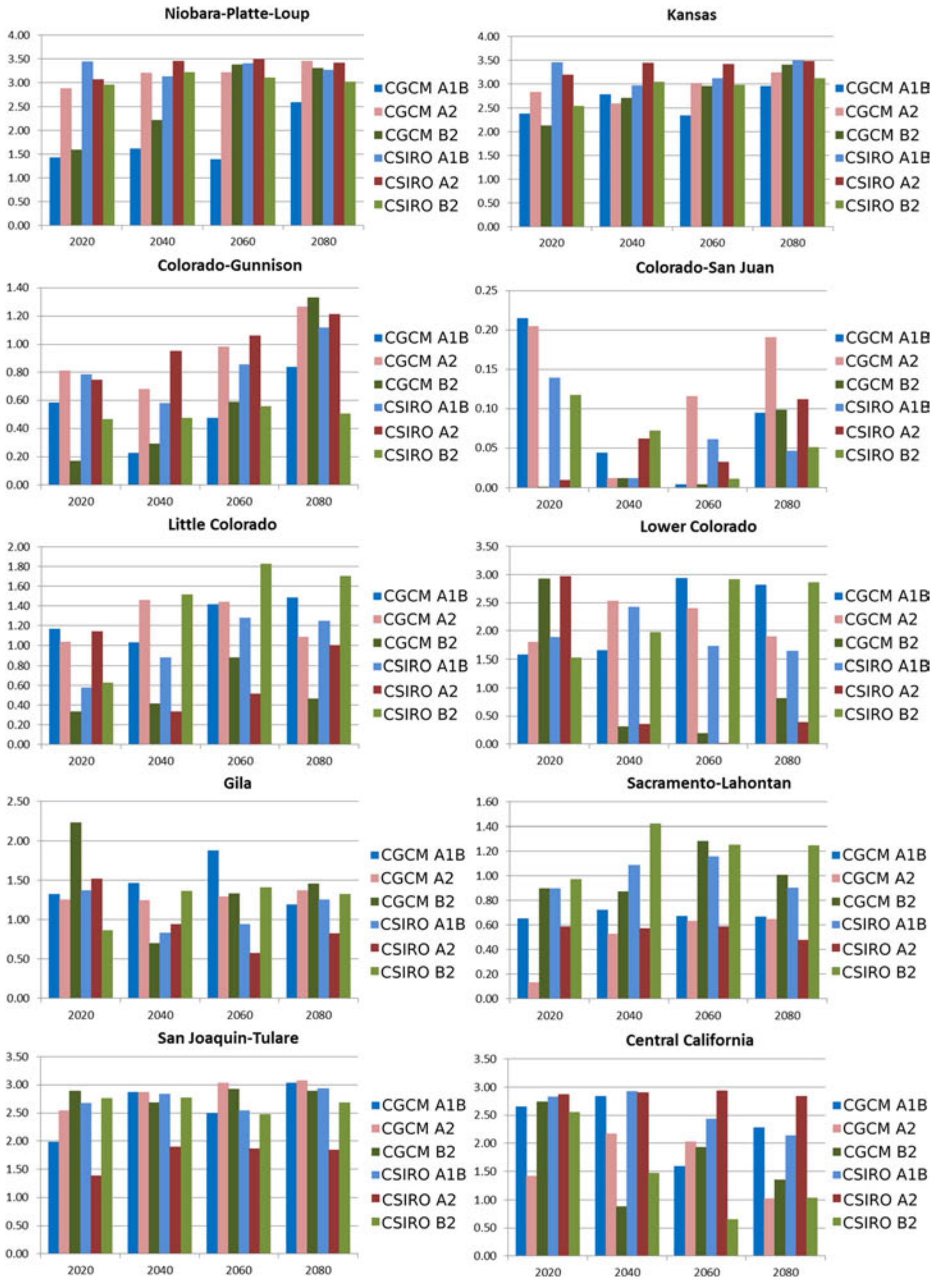

Fig. 8 Projected normalized volumes under the response surfaces of vulnerability for the ten study basins and six GCM-SRES-scenario combinations. Each bar represents the sum of the volumes below the response curves of vulnerability with respect to changes in mean and standard deviation of water supply and demand normalized by the average of the volumes of the ten basins for current conditions

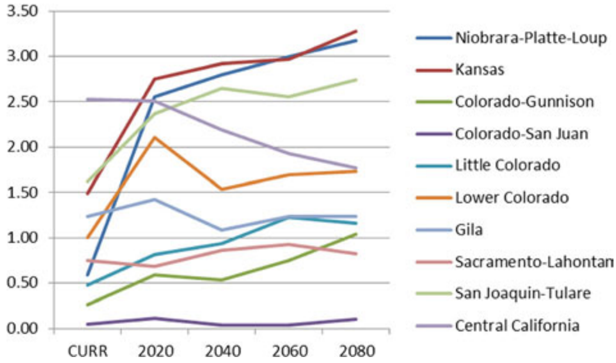

Fig. 9 Projected normalized volumes under the response surfaces of vulnerability for the ten study basins averaged across the six GCM-SRES-scenario combinations

Dissimilarities among GCM-SRES scenario combinations indicate that the uncertainty about the future climatic and socio-economic pathways needs to be carefully examined alongside the inherent uncertainty due to the stochasticity of the vulnerability drivers. Furthermore, a larger number of GCM-SRES scenario combinations may be required to capture the entire distribution of possible futures.

In an attempt to capture the future trends of the response of each basin, we calculated the averages across the six GCM-SRES scenario combinations of the normalized volumes below the response surfaces of vulnerability (Fig. 9). The plot shows that the Central California Coastal basin is expected to become less sensitive overtime, regardless of the fact that during the same time its vulnerability is projected to increase. Therefore, although projected changes in water supply and demand are expected to produce an increase in vulnerability in the Central California Coastal basin, the basin's vulnerability is expected to become less sensitive to further changes in those drivers. In contrast, the High Plains basins (the Kansas and Niobara-Platte-Loup) are projected to become both more vulnerable and more sensitive. As for the other basins, particularly those in the Colorado River Basin, future sensitivity is not expected to change significantly in the future.

5 Summary and conclusions

We have presented a detailed analysis of the response of the water supply systems of ten selected basins of the High Plains, Colorado River Basin and California to projected climatic and socio-economic changes. The study basins were selected for presentation based on their relatively strong responses to current and future changes in PDFs of supply and demand as projected by the set of GCM-scenario combination analyzed. The analysis, however, is based on a comprehensive effort to project vulnerability to water shortages across the US.

Direct effects of and sensitivities to shifts in the drivers of vulnerability were isolated, compared and tracked through the end of the century. Our findings show that, although the basins of California are projected to undergo the largest increases in vulnerability in the coming decades, it is in the High Plains where projected changes in supply and demand will have the larger impact (i.e., where sensitivity to further changes is expected to increase most). Among the five selected basins within the Colorado River Basin, the Lower Colorado and Gila exhibited the most sensitivity to changes in future supply and demand.

The framework we demonstrate offers a consistent way to assess the vulnerability of a system to changes in inherently variable stressors. While the impact of climatic changes on water supply networks has been the focus of numerous previous studies, (Brekke et al. 2004; Matonse et al. 2013; Quinn et al. 2004; VanRheenen et al. 2004), our work is based on a versatile probabilistic approach that can be applied to any environmental and socio-economic vulnerability analysis and includes a comprehensive effort to project water demands. In particular, by isolating the individual contributions of shifts in the statistical moments of the drivers of the vulnerability of the system as a whole, this approach can help policymakers identify the most appropriate management measures and strategies.

This assessment assumes no modifications to the physical structure of US water networks, nor considers changes in the in-stream flow requirements and trans-ASR diversions, thus neglecting potential changes in surface water distribution. Indeed, isolating those locations where adaptation measures are most needed is one of the primary purposes of this study. Our results only account for the inherent stochasticity of the drivers (i.e., stemming from climatic stochasticity and spatial and temporal correlation of supply and demand), as well as for uncertainty about the future (through the GCM-scenario combinations). Uncertainty due to other sources (e.g., modeling errors, data reliability and consistency in space and time, etc.), although quantifiable in some instances (Foti 2011; Foti et al. 2012), is not explicitly presented in this analysis.

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