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Urban water sustainability: an integrative framework for regional water management

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Abstract

Traditional urban water supply portfolios have proven to be unsustainable under the uncertainties associated with growth and long-term climate variability. Introducing alternative water supplies such as recycled water, captured runoff, desalination, as well as demand management strategies such as conservation and efficiency measures, has been widely proposed to address the long-term sustainability of urban water resources. Collaborative efforts have the potential to achieve this goal through more efficient use of common pool resources and access to funding opportunities for supply diversification projects. However, this requires a paradigm shift towards holistic solutions that address the complexity of hydrologic, socio-economic and governance dynamics surrounding water management issues. The objective of this work is to develop a regional integrative framework for the assessment of water resource sustainability under current management practices, as well as to identify opportunities for sustainability improvement in coupled socio-hydrologic systems. We define the sustainability of a water utility as the ability to access reliable supplies to consistently satisfy current needs, make responsible use of supplies, and have the capacity to adapt to future scenarios. To compute a quantitative measure of sustainability, we develop a numerical index comprised of supply, demand, and adaptive capacity indicators, including an innovative way to account for the importance of having diverse supply sources. We demonstrate the application of this framework to the Hetch Hetchy Regional Water System in the San Francisco Bay Area of California. Our analyses demonstrate that water agencies that share common water supplies are in a good position to establish integrative regional management partnerships in order to achieve individual and collective short-term and long-term benefits.

1 Introduction

Changing climate and rapidly growing populations are threatening urban water supplies in the western United States. California in particular, as the most populated state in the country and with variable precipitation patterns and unevenly distributed water supplies, is facing the need to address the long-term sustainability of its urban water resources (CDWR, 2013; Grantham and Viers, 2014). Traditional water supply portfolios in California are heavily dependent on imported sources that are transported from Northern California and the Colorado River to the rest of the state through an extensively engineered distribution system. This over-reliance on imported supplies places undue stress on supply sources that are themselves sensitive to seasonal precipitation changes, periodic droughts, and infrastructure degradation (Brozovic et al., 2007; Cayan et al., 2010; Diffenbaugh et al., 2015; Viviroli et al., 2011). Risks of intensified regional water scarcity can have severe economic impacts (Brozovic et al., 2007; Khater, 1993). Thus, the water sector has to rethink its water supply and demand priorities.

Diversifying water supply portfolios can help reduce stress on regional water resources (Hering et al., 2013; Luthy and Sedlak, 2015). Alternative water management practices such as incorporating water recycling and reuse, stormwater and rainwater capture, desalination, groundwater banking, as well as demand management measures such as water use efficiency and conservation, can introduce more flexibility and resilience to both local and regional water systems (Fernandez et al., 2010; Makropoulos et al., 2008; Newman et al., 2014; Tarroja et al., 2014). Innovative holistic approaches and enhanced collaboration are needed to make this happen while addressing the complexity of physical and social stressors on water resources (Liu et al., 2015; Re, 2015; Srinivasan, 2015; Srinivasan et al., 2010, 2012; Thompson et al., 2013), diverse stakeholders (Carr et al., 2012; Grantham and Viers, 2014), and fragmented water governance (Hughes and Pincetl, 2014; Kallis et al., 2009; Lubell and Lippert, 2011).

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In this paper, we develop an integrative sustainability framework that incorporates the variety of factors affecting urban water resources. First, we explore the supply, demand, and adaptive capacity of individual water agencies urban water portfolios to generate numerical sustainability indices (Ajami et al., 2008; Juwana et al., 2012; Loucks, 2005; Sandoval-Solis et al., 2011). In the process we introduce the concept of the Gini–Simpson index (Simpson, 1949), typically used in biodiversity studies, as an innovative method to measure water supply diversity. Then, we analyze the socio-economic and governance dynamics that affect the sustainability of water portfolios. We recognize the role of people as endogenous agents in the water cycle (Padowski and Jawitz, 2009; Savenije and Van der Zaag, 2008; Sivapalan et al., 2012, 2014) who affect the reliability of resources based on their own water use (Mini et al., 2014; Panagopoulos, 2014), collective behaviors (Fielding et al., 2015; Hornberger et al., 2015), and diffusion of information (Galan et al., 2009). Similarly, we build on previous observations that the discrepancy between watershed and political boundaries adds complexity to water management issues (Hughes and Pincetl, 2014; Kauffman, 2002). Finally, we integrate these hydrologic, socio-economic, and governance layers to analyze the challenges and opportunities for enhancing portfolio sustainability at a regional scale. We illustrate the application of our framework to the Hetch Hetchy Regional Water System (RWS) in the San Francisco Bay Area. Our proposed framework adds to existing literature by providing a critical analysis of the limitations of traditional water supply portfolios. We also provide an innovative perspective to harvest the unique characteristics of individual water agencies and use them as opportunities for re-defining the scope of integrative regional water sustainability.

2 Methodology: urban water sustainability framework

2.1 Framework components

Sustainability refers to a utility's capacity to satisfy the needs of all its water users on a consistent basis, not only with reliable existing supplies but also providing the flexibility for adaption to future needs (Juwana et al., 2012). Sustainability frameworks are an important tool that help guide management practices in order to avoid economic losses resulting from potential water supply shortages, either from infrastructure damage, population growth, or climate change (Brozovic et al., 2007; Khater, 1993; Loucks, 2000). Although sustainability indicators and integrative frameworks have been previously developed for the assessment of water resources (Ajami et al., 2008; Loucks, 1997; Sandoval-Solis et al., 2011; van Leeuwen et al., 2012), these tend to be either too narrowly focused on the hydrology of supply sources or to broadly defined to be practical (Brown et al., 2015). Our framework addresses these limitations by integrating three important management components relevant to any urban water resource system: (1) supply, (2) demand, and (3) adaptive capacity, framed in the context of socio-hydrologic stressors (Fig. 1). We define important indicators within these components, quantify their performance, and integrate them into a sustainability index.

2.1.1 Supply

Traditional water supply portfolios are comprised of imported sources, local surface, or groundwater supplies that must be shared among several uses and users. For this reason, analyzing historical hydrologic records of utilities' primary supply sources can provide important insights on the reliability of the existing supplies and any underlying trends. However, as urban areas continue to grow, climate change impacts pose an uncertain future, and pre-established water rights limit availability, hydrologic analyses are only a small part of the urban water picture. Our framework adds to purely hydrological assessments by considering the reliability of supplies as a function of two controllable variables: vulnerability of existing supplies available (Eq. 1), and supply diversity (Eq. 2). When supply portfolios are reliant on imported water, the availability of this water is dependent on contracted allocations from the source. In our analysis, vulnerability is defined in terms of the fraction of the maximum allocation of a given supply source that is being used (indicating an agency's capacity to grow into their existing supplies), and supply diversity is defined by the number of different sources available and their relative abundance (indicating flexibility in times of uncertainty). For this indicator of supply diversity, we propose the use of the Gini–Simpson index, traditionally used as a measure of biodiversity (Simpson, 1949). The Gini–Simpson index has been adopted in other disciplines such as sociology and psychology (Gibbs and Martin, 1962), but to the best of our knowledge this is one of the first studies to introduce the concept in the context of water resources management.

$$\text{Supply vulnerability} = \frac{\text{water use}}{\text{total water availability or allocation}} \tag{1}$$

$$\text{Supply diversity} = 1 - \sum_i \left(\frac{\text{supply source}_i}{\text{total supply}}\right)^2 \tag{2}$$

2.1.2 Demand

Managing water demands effectively can extend availability of water supplies and limit the potential impacts of water shortage, even when the reliability of the supplies themselves is uncertain. Water demand is a result of intrinsic water use behaviors in a community, as well as a function of land use, population density, industrial activities, outdoor irrigation needs, etc. (Hornberger et al., 2015; Mini et al., 2014; Panagopoulos, 2014). Our framework proposes current per-capita water consumption (Eq. 3) as an objective quantifiable measure of these effects, and a main contributor to water stress. This measure indicates how effectively different communities use their water. It also signifies how much room there is for improved demand management practices and conservation strategies to help decrease consumption and consequently improve the reliability of existing supplies.

$$\text{Demand} = \frac{\text{water use in service area}}{\text{population}} \tag{3}$$

2.1.3 Adaptive capacity

In order for water supplies to be sustainable in the long-term, they must have the flexibility and resilience to adapt to future demand needs and potential disruptions (Milman and Short, 2008). Our proposed framework includes three major adaptive capacity opportunities that may be adopted at different time-scales. In short time frames, water agencies have the potential to introduce conservation strategies to make more efficient use of their current water supplies (Eq. 4). Over longer time scales, water providers may augment supply by introducing alternative sources (Eq. 5). Ultimately, utilities may target these alternative sources more efficiently to match the water quality needs of diverse demand sectors (Eq. 6). For example, by using captured rainwater or recycled wastewater for industrial applications such as heating and cooling, higher-quality water resources may be saved for potable uses (Hering et al., 2013).

$$\text{Future conservation capacity} = \frac{\text{conservation potential}}{\text{total demand}} \tag{4}$$

$$\text{Future augmentation capacity} = \frac{\text{augmentation potential}}{\text{total demand}} \tag{5}$$

$$\text{Demand diversity} = 1 - \sum_i \left(\frac{\text{demand sector}_i}{\text{total demand}}\right)^2 \tag{6}$$

When calculating adaptive capacity, future conservation and augmentation potentials are normalized and computed as the fraction of the total demand they would be able to satisfy. Demand diversity is defined in the same manner as supply diversity using the Gini–Simpson index (Simpson, 1949).

2.1.4 Social context

Socio-economic factors are well known to affect water use behaviors including consumption patterns, willingness to accept alternative supplies and technologies and responsiveness to conservation and adaption incentives in times of water shortage (Hornberger et al., 2015; Mini et al., 2014). Each service area has unique underlying factors affecting water use. The specific relationships between socio-economic factors and water use should be further explored on a case-by-case basis using methods such as multidimensional linear regression, principal component analysis, or factor analysis (Loch et al., 2014; Mini et al., 2014; Panagopoulos, 2014). In this framework, we propose exploring these relationships, but rather than defining external quantifiable metrics, we consider them as endogenous factors implicit in the previously defined metrics for supply, demand, and adaptive capacity.

2.2 Sustainability index

We propose a quantitative index that assesses the performance of different water agencies and that helps us to better understand the stressors of and improvement opportunities for urban water sustainability. Our aggregate sustainability index (SUSi) incorporates supply, demand, and adaptive capacity variables as previously described. For this purpose, metrics are normalized by linearly re-scaling them from their observed A–B range to a 1–10 range (Eqs. 7 and 8). We chose this 1–10 range to avoid a multiplication by zero when indicators are at their lowest value. In the resulting 1–10 scale, higher values are associated with increased sustainability. Two of the indicators used in our framework, vulnerability and water use per capita, are by definition negative indicators, meaning that in their observed scale higher values would actually decrease overall sustainability. For consistency, these values are transformed into a relative scale in the same 1–10 range. Therefore, all re-scaled values are positive indicators after using the following transformation:

For positive indicators (I_{P}):

$$\text{Re-scaled } I_{\mathrm{P}} = 1 + (10-1) \cdot \frac{(I_{\mathrm{P}} - A)}{(B - A)} \tag{7}$$

For negative indicators (I_{N}):

$$\text{Re-scaled } I_{\mathrm{N}} = 1 + (10-1) \cdot \left[1 - \frac{(I_{\mathrm{N}} - A)}{(B - A)}\right] \tag{8}$$

Re-scaled indicators are then aggregated into their respective components (supply, demand, and adaptive capacity) (Eqs. 9–11), and the three components are subsequently aggregated into an overall index (Eq. 12), using the geometric mean. The final aggregate index is multiplied by ten with the purpose of providing higher resolution in a 1–100 scale.

$$\text{Supply}_i = [(\text{vulnerability}_i) \cdot (\text{supply diversity}_i)]^{1/2} \tag{9}$$

$$\text{Demand}_i = [(\text{water use per capita}_i)] \tag{10}$$

$$\text{Adaption}_i = [(\text{conservation}_i) \cdot (\text{augmentation}_i) \cdot (\text{demand diversity}_i)]^{1/3} \tag{11}$$

Overall index:

$$\text{SUSi}_i = [(\text{Supply}_i) \cdot (\text{Demand}_i) \cdot (\text{Adaption}_i)]^{1/3} \cdot 10 \tag{12}$$

Our index is calculated using the geometric mean to address the challenge of assigning specific weights to each criterion. This approach has previously been proposed for water resources management (Ajami et al., 2008; Loucks, 1997; Sandoval-Solis et al., 2011) because the multiplicative form allows us to weigh all criteria as non-substitutable while giving implicit weighing to the indicators with worse performance and maintaining an intuitive scale (Juwana et al., 2012). This form also allows the index to be easily adapted to different contexts, since additional indicators may be added or re-defined within the supply, demand, and adaption components before being integrated into the overall sustainability index. Thus, the multiplicative approach provides a flexible and practical tool to measure sustainability with respect to the indicators of interest while maintaining a holistic view.

2.3 Regional scope

Current supply reliability and long-term sustainability can be enhanced through a combination of supply augmentation and demand management measures implemented at a variety of different scales (regions). These measures may include different active and passive conservation programs, water reuse and recycling, stormwater and rainwater capture, desalination, groundwater recharge and banking, or water transfers. While individual water agencies may implement projects best suited to their needs, diversifying supply portfolios in general can help reduce stress on imported supplies, common resources, and regional sustainability overall, benefitting all utilities (Hering et al., 2013; Luthy and Sedlak, 2015; Tarroja et al., 2014). Thus, regions may be defined based on scales that are consistent with common water needs or opportunities. To identify the impact of local sustainability on the regional scale, we propose a weighted average of sustainability indices (Eq. 13).

$$\text{Regional sustainability} = \sum_{i} \frac{d_{\mathrm{i}}}{D} \cdot \mathrm{SUSi}_{i} \tag{13}$$

Where, weights correspond to the fraction of the total regional demand (D) that is attributed to an agency's individual demand (d_{i}).

3 Study site: the Hetch Hetchy Regional Water System

To illustrate our methodology, we apply the water sustainability framework to a subset of the San Francisco Bay Region comprised of agencies dependent on the Hetch Hetchy Regional Water System. This region provides a good study site because it encompasses several water agencies highly reliant on a common pool of imported and local supplies, and who are represented by an existing coordinating agent: the Bay Area Water Supply and Conservation Agency (BAWSCA).

The RWS, owned and operated by the San Francisco Public Utilities Commission (SFPUC), plays a key role in water delivery to 2.6 million residents, businesses, and community organizations in the San Francisco Bay Area. The majority of the water in this system originates in snowmelt from the Sierra Nevada Mountains and is then moved through an extensive distribution system. Of the potential maximum daily water load, 81 mgd (million gallons per day) are designated for retail use in the city of San Francisco, while the remaining 184 mgd are distributed to wholesale customers throughout the Bay Area. BAWSCA represents the interests of the 24 cities and water districts, an investor-owned utility, and a university, that purchase water wholesale from the RWS (Fig. 2). These member agencies represent a diverse group of service areas. For example, based on 2013 data (BAWSCA, 2013), population size and water use per capita span the range of 4282–340 000 people and 56.9–358.8 gal capita^{-1} day^{-1}, while the average price of water and median household income vary between 0.41–1.16 cents gal^{-1} and USD 50 142–236 528 a month, respectively. BAWSCA has the authority to coordinate water conservation, supply and recycling activities for its member agencies, acquire water supplies, finance projects, and build facilities.

4 Analysis and results

4.1 Supply factors affecting sustainability

Following our framework, urban water supplies in the BAWSCA service area are sensitive to the hydrologic reliability of their imported supplies from Hetch Hetchy, the vulnerability of their allocations from this source, and the availability of alternative supply sources. We explore these factors as well as the underlying role of management and governance dynamics.

4.1.1 Hydrology of the Hetch Hetchy Regional Water System

The RWS is dependent on rainfall and snowmelt to maintain inflows to upcountry reservoirs in the Tuolumne River watershed. In addition to Hetch Hetchy, other mountain reservoirs and Bay Area reservoirs as well as a water bank are managed by SFPUC to supply water to urban users. The water bank, located in the Don Pedro Reservoir downstream of Hetch Hetchy, allows SFPUC some flexibility in maximizing the use of water from Hetch Hetchy Reservoir while meeting the entitlements of senior water rights holders to divert water from the Tuolumne River (SFPUC, 2013). Releases from upcountry reservoirs on the RWS to Don Pedro Reservoir above the irrigation districts' entitlements add water to the RWS water bank account. Conversely, SFPUC debits water from its account whenever it diverts or stores water from the Tuolumne River that would otherwise be within the entitlements of the irrigation districts. This adaptive management strategy has provided flexibility for the RWS to meet its water demands over time. Nevertheless, the three-year period of 2012–2014 was the driest three-year period in the 97-year hydrologic record of this system (CDWR, 2015). As a result, at the end of the water year 2014, the cumulative effects of low precipitation years led to a sharp decrease in the amount of water available to SFPUC and its customers. If drought conditions prevail, alternative management actions will be required to offset the depleting supplies in storage.

4.1.2 Vulnerability of SFPUC allocations

Each BAWSCA member agency is subject to an individual water sales contract from SFPUC, which specifies an Individual Supply Guarantee (ISG) for that agency. These allocations are unevenly distributed among water entities depending on the timing and stipulations of their individual contracts, and water deliveries are subject to cutbacks in times of shortage (BAWSCA, 2015). For example, as shown in Fig. 3 both Purissima Hills Water District and the city of Menlo Park are solely dependent on Hetch Hetchy water, but Purissima Hills is currently using up the entirety of its allocated supply, while Menlo Park's demand accounts only for 80 % of their allocation, meaning Menlo Park is less vulnerable in their projections for future needs. Furthermore, water availabilities from the RWS could be impacted by competing demands, infrastructure damage, climate change and the ensuing hydrologic conditions, policy decisions, and regulatory actions (SFPUC, 2013). In January 2014, the SFPUC called for a voluntary reduction of 10 % from all users of the RWS, applied across BAWSCA agencies based on agency-projected use. Further mandatory reductions could greatly impact water agencies that rely heavily on RWS supplies.

4.1.3 Supply diversity among BAWSCA member agencies

Overall, only 60 % of BAWSCA agencies' water supplies come from SFPUC. While some utilities rely solely on the RWS, others have access to other sources such as groundwater, local surface water, recycled water, and imported water from the State Water Project and Central Valley Project. However, it is important to note how this diversity is distributed among BAWSCA agencies (Fig. 2b). Although several of the larger water agencies (Alameda County Water District, Santa Clara, Milpitas, Sunnyvale, and Daly City) have diversified water supplies, most service areas in our study region have a small enough demand that their imported RWS supply is sufficient to cover their present needs and growth projections. This lessens the sense of urgency for these agencies to collaborate or develop alternative supplies. Nevertheless, on an agency-by-agency basis, the long-term reliability of BAWSCA's traditional supply portfolios is highly uncertain (BAWSCA, 2015). The need to diversify supply portfolios is exacerbated by the potential economic consequences of supply shortfalls. Economic losses to businesses and residential users under a 20 % water supply deficiency on the RWS are estimated up to USD 7.7 billion annually (BAWSCA, 2015). This number could almost double under a supply interruption scenario in the RWS such as an earthquake, with economic loss estimates of up to USD 14 billion in damage costs depending on the extent and location of the disruption (Brozovic et al., 2007; Khater, 1993). Based on the potential risks of future shortages, BAWSCA member agencies relying primarily on water from the RWS must diversify their water supply portfolios, even if they have not yet reached the need to supplement their ISG allocations.

4.2 Demand factors affecting sustainability

Demand-side characteristics influence water stress. Utilities in the BAWSCA service area have maintained a steady water demand for the past two decades despite a 13 % population growth thanks to investments on conservation and efficiency measures (BAWSCA, 2014). In order to understand the most influential factors affecting current water use among BAWSCA agencies, and to get a better idea of the underlying trends and correlations in demand behaviors, we performed a principal component analysis (PCA) and a linear regression analysis.

PCA is a well-known method used to reduce large data sets into a smaller number of components grouped by correlated variables. We analyzed data from the 2010 U.S. Census and the BAWSCA annual surveys for overall population, population density, median household income, average water bills as a percentage of household income, median value of homes (as a proxy for the value of land), and diversity of demand sectors as possible socio-economic indicators of water use per capita. The results of this work indicate that these six variables may be grouped into three principal components that account for 77.8 % of explanatory power in the data (Table 1). Within each component, we consider indicators with values higher than 0.5 to be significantly correlated to the principal component. The first principal component (PC1), which is highly correlated to median household income and value of homes, all indicators of wealth, is by far the most important driver of variability in the data (40.5 %). The second principal component (PC2) is related to population density, price of water, and diversity in the demand sectors, all characteristics that may systematically bias water use. The third principal component (PC3) is related to the net size of the service area as measured by the total population served.

With a better understanding of the correlations between indicators, we also explore how these factors relate to per-capita water use in single-family residential homes using a multi-dimensional linear regression analysis on the same elements we explored in PCA. While all characteristics may directly or indirectly influence water use, income is the only statistically significant variable (p value < 0.05) in our analysis (Table 1). Figure 4 displays the relationship between water use and the three most significant indicators (lowest p values, corresponding to income, water bills, and population density). The plot shows a strong linear correlation between income (x axis) and water use (y axis), and a less marked trend of water pricing (size of the circles) and population density (color scale).

The results of this PCA and linear regression are consistent with intuitive expectations about the relationships between socio-economic characteristics and water use – higher income residents use more water. The reasons behind these correlations reveal important information. Previous studies found that high-income water users are typically located in areas with lower population densities, larger housing units, and consequently greater indoor and outdoor water use (Harlan et al., 2009; House-Peters et al., 2010). Our analysis suggests that the relationship between variables is more complicated than just a function of dwelling size. In our study area, the Hillsborough, Bear Gulch, and Purissima Hills agencies are outliers in terms of household income among BAWSCA member agencies, with median values between USD 120 K and USD 240 K per year. These three outliers are made up of almost completely residential demands with some of the lowest population densities and highest water use levels. Nevertheless, other service areas also have relatively low population densities, and even pay less on average per gallon of water than residents in the outlier utilities, but these factors are of lower significance than the direct effect of income as shown in Table 1 and Fig. 4. This observation suggests that beyond basic needs, water use behavior is highly related to people's perspective on water as an economic good, and is more likely to be used in excess when users have greater disposable income levels. This means that a given water use efficiency policy or conservation incentive may be effective to different extents in different service areas. Understanding each location's socio-economic characteristics would be a good opportunity to develop targeted drivers for demand management and help BAWSCA maintain its steady demands in the future.

4.3 Opportunities for adaptive capacity

The diversity of supply and demand characteristics and existing agency interconnections within BAWSCA present several opportunities for the efficient implementation of conservation programs, supply augmentation, and targeting projects to suit different demand sectors. Furthermore, we explore hydrologic, socio-economic, and governance characteristics that could add flexibility to the region as a whole when choosing among sustainability enhancement mechanisms.

4.3.1 Conservation potential

Water use behaviors and socio-economic factors can be used to develop more efficient demand management mechanisms (Hornberger et al., 2015; Mini et al., 2015). Water use among some BAWSCA agencies may not be sustainable in the long-term, particularly in high-income communities. Even though BAWSCA-agency retail water prices have increased by 58 % from 2005 to 2013 (BAWSCA, 2014), water bills are only a small percentage of household income (less than 1 % for the majority of BAWSCA agencies (Pacific Institute, 2013), and therefore many consumers may not be properly aware of the true value of water in times of shortage. Structuring water rates, water use efficiency policies, and conservation incentives that take into account each service area's diverse characteristics can help manage water demand as well as provide an opportunity for funding mechanisms. The BAWSCA Regional Water Demand and Conservation Projections study (BAWSCA, 2014) reports expected water savings from both active and passive conservation measures as identified by each water agency. These projections were calculated based on the intention to implement specific water conservation and efficiency programs, as well as leak management, suitable to each water agency, and is thus used to quantify conservation potential in this study.

4.3.2 Supply augmentation and sharing

Land use patterns determine both need and opportunity for supply augmentation projects (Inamdar et al., 2013; Srinivasan et al., 2013). Areas with low population density and low cost of land may be better equipped to implement new water infrastructure projects, while areas with higher water use and faster growth rates are the ones in greater need of securing new supplies. However, the locations of opportunity and need therefore do not necessarily overlap. Given this discrepancy, the distribution of water supplies could be more effective through the development of flexible market mechanisms that take advantage of common supply pools (Anderson, 2015; Grafton et al., 2011; Palazzo and Brozovic, 2014; Stern, 2010). In the BAWSCA region the distribution of supplies could be leveraged by the uneven contract allocations from the RWS. For example, many agencies are starting to outgrow their RWS allocations, whereas others like Palo Alto and Menlo Park have contracts for significantly more water than they are currently using (excess amounts that translate into 84 and 61 unused $\mathrm{gal\,capita^{-1}\,day^{-1}}$ for these agencies, respectively) (Fig. 3). This unused water remains in the RWS until claimed (assuming 100 % level of service). As BAWSCA agencies work on diversifying their supply portfolios, the existing infrastructure of the RWS is an opportunity for sharing these supplies, acting as a bank account. This type of collaborative management solution is particularly relevant for BAWSCA given the existing overlap in natural resource and political boundaries among agencies, as well as established governance and coordination layers.

4.3.3 Targeting demand diversity

Though BAWSCA serves mostly residential customers, other sectors including commercial, industrial, governmental uses, and dedicated irrigation account for 40 % of the total demand in the region (Fig. 2c). Having a diverse set of customers is important because using water in different demand sectors offers an opportunity to match alternative supply sources of different quality levels to non-potable uses (Hering et al., 2013). This is consistent with the concept of more efficient sharing of common pool resources. For example, SFPUC already has an established program that promotes the development of in-building and shared, or district-scale, non-potable water reuse systems in San Francisco (SFPUC, 2015), thus enhancing the reliability of the city's supplies. Overall, increased collaboration at the regional scale would allow agencies to work together and use their resources and opportunities more efficiently, making cost-effective investments on water quality, supply augmentation, and demand management projects while matching capacity and need.

4.4 Sustainability index

Applying our sustainability index methodology to BAWSCA allows us to do a comparative analysis of its member agencies and identify strengths and weaknesses. This work also informs us of potential management strategies that could introduce more flexibility and resilience into local water portfolios, and to assess their regional impact. Figure 5 shows the performance of individual water agencies listed in decreasing order of their computed sustainability indices for the year 2013. The figure also shows how these agencies compare in terms of supply, demand, and adaption components of the index. Table 2 provides more detailed information on the performance of individual indicators that were used to compute sustainability indices in this case study. Integrated index values range from 20 to 56 (on an scale of 1 to 100). Overall, most agencies scored high in the demand component, indicating relatively efficient water use. Supply and adaption components show wider variability and present additional opportunities for sustainability enhancement, primarily through supply diversification. It is notable from these results that the range of demand performance is inherently wider (from as low as 2.59 to as high as 9.76) than those of supply and adaption performances, which only go up to 7.19 and 3.89 respectively. This is a result of both the performance of BAWSCA agencies with respect to each component, but is also dependent on the indicators used in this analysis and the way each of those indicators was quantified. For example, since many agencies are completely dependent on a single supply source, they have a supply diversity score of 1 in a 1 to 10 range, which brings down their overall score. Similarly, only supply augmentation projects listed under BAWSCA's Long-Term Reliable Water Supply Strategy (Table 3) were included in these calculations, whereas individual agencies may also have plans to implement additional projects independently of BAWSCA. Since only one indicator (water use per capita) was included in the calculations of the demand score, this number does not display the same variability. This approach is suitable for the case study because it emphasizes weaknesses and allows us to do a comparative analysis of agencies with respect to the indicators that need to be addressed, primarily related to low supply diversity and a lack of adaptation capacity.

The service areas with the highest sustainability scores were Daly City, San Bruno, Sunnyvale, Milpitas, and Alameda County Water District. These agencies have proactively developed diverse supply portfolios (e.g., additional imported supplies, local surface supplies, groundwater, and recycled water), managed demand as a priority component of supply reliability, and are considering additional adaptation strategies. In contrast, agencies like Purissima Hills Water District, California Water Service-Bear Gulch district, and the Town of Hillsborough have low indices as they are heavily dependent on the RWS (low supply diversity), have a high use of their allocated supplies (vulnerability), high water use per capita, and low adaptation potential (no existing plans for supply augmentation, and low demand diversity). These agencies with low sustainability scores are at high risk in times of water shortage. While these utilities could improve their performance through independent supply augmentation and demand management efforts, higher sustainability could also be achieved through collaborations with neighboring agencies. For example, while the Town of Hillsborough has one of the lowest sustainability indices in our framework, it only accounts for 1.5 % of the total water use among the BAWSCA agencies, giving it some flexibility to share alternative supply projects with other small agencies or to negotiate small portions of a larger project.

We explored the regional impacts of agencies individual sustainability performance by computing a BAWSCA-wide index. For this purpose, each component (supply, demand, and adaptive capacity) was calculated as a weighted average of individual agencies, with weights corresponding to water use. Adaptive capacity scenarios were added as either agency-specific, in which case local sustainability is directly enhanced and correspondingly weights into the sustainability of the region, or regional projects meant to benefit BAWSCA as a whole. Potential augmentation projects included in these future sustainability scenarios are listed in Table 3. The list of projects, identified by BAWSCA in its Long-Term Reliable Water Supply Strategy (BAWSCA, 2015), includes only projects that are considered feasible and have the potential to contribute to the long-term reliability of urban water supplies. Local projects identified by agencies comprise several recycled water projects and a groundwater project. Regional projects include local capture and reuse of rainwater, greywater, and stormwater, desalination of bay water and brackish groundwater, and water transfers. Figure 6 shows the performance of BAWSCA as a whole from 2002 to 2013. The time series shows a steady, though very slow, increase in sustainability attributed mainly to water conservation and efficiency measures, as supply and demand portfolios have not changed significantly. Using our framework, we compare this business-as-usual scenario to alternative cases that include adaptive capacity measures (Table 4). There are clear performance benefits of including both local and regional supply augmentation and diversification projects, all of which can help reduce stress on existing supply sources and thus benefit agencies that rely on the same common pool of water resources. The regional sustainability index has the potential to increase from 34.79 to 51.19 if all local and regional projects continue in the pipeline, while only 5 out of 27 agencies could reach this score independently.

5 Discussion and conclusions

Water shortages are a prevalent risk in many parts of the world as a result of a changing climate, rapidly growing populations, and over-reliance on imported supplies. Regional coordination, defined by common socio-hydrological water issues and opportunities as exemplified by our framework, can greatly contribute to better resource management, promote supply diversification, and help address the risks associated with water shortages. While integrative water management is not a new idea (Fernandez et al., 2010; Makropoulos et al., 2008; Mitchell, 2006; Paton et al., 2014; Rahaman and Varis, 2005; Savenije and Van der Zaag, 2008; van Leeuwen et al., 2012), there is a need for a better understanding of how existing social dynamics interplay with the technical and operational advancements proposed in the literature (Anderson, 2015; Brown et al., 2015; Gober and Wheater, 2014). For example, traditional cost-benefit analyses focus on economic or system optimization and fail to account for existing governance structures (Beh et al., 2014; Kirsch and Maxwell, 2015; Tarroja et al., 2014). Similarly, initiatives for collaborative programs have had mixed impacts on pre-existing organization and management structures (Booher and Innes, 2010; Hughes and Pincetl, 2014; Innes et al., 2007; Kallis et al., 2009; Lubell and Lippert, 2011). When developed strictly under either hydrological or political incentives, without regard for the holistic picture, collaborative programs are likely to fall short of their intended potential. This work develops a generalized socio-hydrologic framework that can help bridge the science-policy gap for sustainable water management and enhanced collaboration.

The methodologies proposed in this research provide a systematic approach for water agencies to identify opportunities for sustainability enhancement, taking advantage of local characteristics to design regional solutions. BAWSCA member agencies are an example of how an adequate match between hydrologic, socio-economic, and governance dynamics can be used to coordinate bottom-up regional initiatives. Our results strongly suggest that water agencies reliant on a common pool of water supplies have a particular advantage for collaborative management. Rather than being competitors for a limited resource, these agencies have the opportunity to be partners in a dynamic system of adaptive capacity building. Our analysis of diverse characteristics among BAWSCA's service areas exemplifies that although not all service areas may have the economic, social and governance capacity to implement the required steps to increase their own supply reliability, there are many opportunities for the region as a whole to do so. Urban water resource systems could benefit from the addition of alternative supply sources such as rainwater, stormwater and greywater capture and reuse, recycled water, desalination, as well as demand management practices. The diversification of supply portfolios would help reduce stress on existing supplies, thus improving the reliability, flexibility, and resilience of water resources. Our study not only emphasizes the importance of supply diversity, but also provides an innovative approach to measure such diversity, bringing the Gini–Simpson index, commonly used in biodiversity studies, to the field of water management.

This framework can be used to systematically identify sustainability enhancement mechanisms in complex socio-hydrologic systems, and to guide the development of future decision support tools. One limitation of this work is its lack of guidance on choosing between possible adaptation mechanisms, which is likely influenced by economic and financial considerations. Agencies may be hesitant to develop new supplies due to the financial risks and the hydrologic uncertainties that influence the potential outcomes of such an investment. Our work shows that under more collaborative dynamics, these risks could be reduced by sharing costs and benefits of these projects among several agencies, since the benefits of increased reliability would be extended to the regional level. Future research should investigate how the hydro-socio-economic framework in a region could support more effective allocations of risks and benefits, and how stakeholder dynamics could be leveraged to develop the necessary financing strategies for enhanced sustainability.

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References

Ajami, N. K., Hornberger, G. M., and Sunding, D. L.: Sustainable water resource management under hydrological uncertainty, Water Resour. Res., 44, W11406, doi:10.1029/2007WR006736, 2008.

Anderson, T. L.: Dynamic markets for dynamic environments: the case for water marketing, Daedalus, 144, 83–93, 2015.

BAWSCA: Annual Survey FY 2013–14, Bay Area Water Supply and Conservation Agency, Web site, available at: http://www.bawsca.org/docs/BAWSCA_FY13-14_AnnualSurvey.pdf), 2013.

BAWSCA: Regional Water Demand and Conservation Projections, Bay Area Water Supply and Conservation Agency, Web site, available at: http://www.bawsca.org/docs/BAWSCA%20Demand%20and%20Conservation%20Projection%20FINAL%20REPORT.pdf, 2014.

BAWSCA: Long-Term Reliable Water Supply Strategy Phase II – Final Report, Bay Area Water Supply and Conservation Agency, Web site, available at: http://bawsca.org/water-supply/long-term-reliable-water-supply-strategy/, 2015.

Beh, E. H. Y., Dandy, G. C., Maier, H. R., and Paton, F. L.: Optimal sequencing of water supply options at the regional scale incorporating alternative water supply sources and multiple objectives, Environ. Modell. Softw., 53, 137–153, 2014.

Berkes, F.: Evolution of co-management: role of knowledge generation, bridging organizations and social learning, J. Environ. Manage., 90, 1692–1702, 2009.

Booher, D. E. and Innes, J. E.: Governance for resilience: CALFED as a complex adaptive network for resource management, Ecol. Soc., 15, 45, http://www.ecologyandsociety.org/vol15/iss3/art35/, 2010.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W., and Brekke, L.: The future of water resources systems analysis: toward a scientific framework for sustainable water management, Water Resour. Res., 51, 6110–6124, 2015.

Brozovic, N., Sunding, D. L., and Zilberman, D.: Estimating business and residential water supply interruption losses from catastrophic events, Water Resour. Res., 43, W08423, doi:10.1029/2005WR004782, 2007.

Cai, X. M., Lasdon, L., and Michelsen, A. M.: Group decision making in water resources planning using multiple objective analysis, J. Water Res. Pl.-ASCE, 130, 4–14, 2004.

Carr, G., Bloeschl, G., and Loucks, D. P.: Evaluating participation in water resource management: a review, Water Resour. Res., 48, W11401, doi:10.1029/2011WR011662, 2012.

Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M., and Gershunov, A.: Future dryness in the southwest US and the hydrology of the early 21st century drought, P. Natl. Acad. Sci. USA, 107, 21271–21276, 2010.

CDWR: California Water Plan Update 2013. Volume 1 – The Strategic Plan, California Department of Water Resources, Sacramento, CA, Web site, available at: http://www.waterplan.water.ca.gov/docs/cwpu2013/Final/0a-Vol1-full2.pdf, 2013.

CDWR: California's Most Significant Droughts: Comparing Historical and Recent Conditions, Report, available at: http://www.water.ca.gov/waterconditions/docs/California_Signficant_Droughts_2015_small.pdf, 2015.

Diffenbaugh, N. S., Swain, D. L., and Touma, D.: Anthropogenic warming has increased drought risk in California, P. Natl. Acad. Sci. USA, 112, 3931–3936, 2015.

Fernandez, B., Weaver, K., and Daverin, J.: An integrated approach to water resource planning in southern California, innovations in watershed management under land use and climate change, in: Proceedings of the 2010 Watershed Management Conference, Madison, Wisconsin, USA, 23–27 August 2010, 929–939, 2010.

Fielding, K., Gardner, J., Leviston, Z., and Price, J.: Comparing public perceptions of alternative water sources for potable use: the case of rainwater, stormwater, desalinated water, and recycled water, Water Resour. Manag., 29, 4501–4518, 2015.

Galan, J. M., Lopez-Paredes, A., and del Olmo, R.: An agent-based model for domestic water management in Valladolid metropolitan area, Water Resour. Res., 45, W05401, doi:10.1029/2007WR006536, 2009.

Gibbs, J. P. and Martin, W. T.: Urbanization, technology, and the division of labor: international patterns, Am. Sociol. Rev., 27, 667–677, 1962.

Gober, P. and Wheater, H. S.: Socio-hydrology and the science–policy interface: a case study of the Saskatchewan River basin, Hydrol. Earth Syst. Sci., 18, 1413–1422, doi:10.5194/hess-18-1413-2014, 2014.

Grafton, R. Q., Libecap, G., McGlennon, S., Landry, C., and O'Brien, B.: An integrated assessment of water markets: a cross-country comparison, Rev. Environ. Econom. Pol., 5, 219–239, 2011.

Grantham, T. E. and Viers, J. H.: 100 years of California's water rights system: patterns, trends and uncertainty, Environ. Res. Lett., 9, 084012, doi:10.1088/1748-9326/9/8/084012, 2014.

Hahn, T., Olsson, P., Folke, C., and Johansson, K.: Trust-building, knowledge generation and organizational innovations: the role of a bridging organization for adaptive comanagement of a wetland landscape around Kristianstad, Sweden, Hum. Ecol., 34, 573–592, 2006.

Harlan, S. L., Yabiku, S. T., Larsen, L., and Brazel, A. J.: Household water consumption in an arid city: affluence, affordance, and attitudes, Soc. Natur. Resour., 22, 691–709, 2009.

Hering, J. G., Waite, T. D., Luthy, R. G., Drewes, J. E., and Sedlak, D. L.: A changing framework for urban water systems, Environ. Sci. Technol., 47, 10721–10726, 2013.

Hornberger, G. M., Hess, D. J., and Gilligan, J.: Water conservation and hydrological transitions in cities in the United States, Water Resour. Res., 51, 4635–4649, 2015.

House-Peters, L., Pratt, B., and Chang, H.: Effects of urban spatial structure, sociodemographics, and climate on residential water consumption in Hillsboro, Oregon, J. Am. Water Resour. As., 46, 461–472, 2010.

Hughes, S. and Pincetl, S.: Evaluating collaborative institutions in context: the case of regional water management in southern California, Environ. Plann. C, 32, 20–38, 2014.

Inamdar, P. M., Cook, S., Sharma, A. K., Corby, N., O'Connor, J., and Perera, B. J. C.: A GIS based screening tool for locating and ranking of suitable stormwater harvesting sites in urban areas, J. Environ. Manage., 128, 363–370, 2013.

Innes, J. E., Connick, S., and Booher, D.: Informality as a planning strategy – collaborative water management in the CALFED Bay-Delta Program, J. Am. Plann. Assoc., 73, 195–210, 2007.

Juwana, I., Muttil, N., and Perera, B. J. C.: Indicator-based water sustainability assessment – a review, Sci. Total Environ., 438, 357–371, 2012.

Kallis, G., Kiparsky, M., and Norgaard, R.: Collaborative governance and adaptive management: lessons from California's CALFED Water Program, Environ. Sci. Policy, 12, 631–643, 2009.

Kauffman, G. J.: What if. . . the United States of America were based on watersheds?, Water Policy, 4, 57–68, 2002.

Khater, M., Scawthorn, C. and Rojahn, C.: A model methodology for assessment of seismic vulnerability and impact of disruption of water supply systems, in: Earthquake Hazard Reduction in the Central and Eastern Unites States: a Time for Examination and Action (Socioeconomic Impacts: 1993 National Earthquake Conference), edited by: Tierney, K. J. and Nigg, J. M., Cent. U.S. Earthquake Consortium, Memphis, Tenn., 605–614, 1993.

Kirsch, B. R. and Maxwell, R. M.: The use of a water market to minimize drought-induced losses in the Bay Area of California, J. Am. Water Works Ass., 107, 104–104, 2015.

Liu, D., Tian, F., Lin, M., and Sivapalan, M.: A conceptual socio-hydrological model of the co-evolution of humans and water: case study of the Tarim River basin, western China, Hydrol. Earth Syst. Sci., 19, 1035–1054, doi:10.5194/hess-19-1035-2015, 2015.

Loch, A., Adamson, D., and Mallawaarachchi, T.: Role of hydrology and economics in water management policy under increasing uncertainty, J. Hydrol., 518, 5–16, 2014.

Loucks, D. P.: Quantifying trends in system sustainability, Hydrolog. Sci. J., 42, 513–530, 1997.

Loucks, D. P.: Sustainable water resources managagement, Water Int., 25, 3–10, 2000.

Loucks, D. P.: Decision support systems for drought management, in: Drought Management and Planning for Water Resources, edited by: Vela, A., Rossi, G., Andreu, J., and Vagliasindi, F. CRC Press, 119–131, 2005.

Lubell, M. and Lippert, L.: Integrated regional water management: a study of collaboration or water politics-as-usual in California, USA, Int. Rev. Adm. Sci., 77, 76–100, 2011.

Luthy, R. G. and Sedlak, D. L.: Urban water-supply reinvention, Daedalus, 144, 72–82, 2015.

Makropoulos, C. K. and Butler, D.: Distributed water infrastructure for sustainable communities, Water Resour. Manag., 24, 2795–2816, 2010.

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K., and Butler, D.: Decision support for sustainable option selection in integrated urban water management, Environ. Modell. Softw., 23, 1448–1460, 2008.

Milman, A. and Short, A.: Incorporating resilience into sustainability indicators: an example for the urban water sector, Global Environ. Chang., 18, 758–767, 2008.

Mini, C., Hogue, T. S., and Pincetl, S.: Patterns and controlling factors of residential water use in Los Angeles, California, Water Policy, 16, 1054–1069, 2014.

Mini, C., Hogue, T. S., and Pincetl, S.: The effectiveness of water conservation measures on summer residential water use in Los Angeles, California, Resour. Conserv. Recy., 94, 136–145, 2015.

Mitchell, V. G.: Applying integrated urban water management concepts: a review of Australian experience, Environ. Manage., 37, 589–605, 2006.

Newman, J. P., Dandy, G. C., and Maier, H. R.: Multiobjective optimization of cluster-scale urban water systems investigating alternative water sources and level of decentralization, Water Resour. Res., 50, 7915–7938, 2014.

Pacific Institute: Water Rates: Water Affordability, Report, available at: http://www.pacinst.org/wp-content/uploads/2013/01/water-rates-affordability.pdf, 2013.

Padowski, J. C. and Jawitz, J. W.: The future of global water scarcity: policy and management challenges and opportunities, The Whitehead Journal of Diplomacy and International Relations, 10, 99–114, 2009.

Palazzo, A. and Brozovic, N.: The role of groundwater trading in spatial water management, Agr. Water Manage., 145, 50–60, 2014.

Panagopoulos, G. P.: Assessing the impacts of socio-economic and hydrological factors on urban water demand: a multivariate statistical approach, J. Hydrol., 518, 42–48, 2014.

Paton, F. L., Dandy, G. C., and Maier, H. R.: Integrated framework for assessing urban water supply security of systems with non-traditional sources under climate change, Environ. Modell. Softw., 60, 302–319, 2014.

Rahaman, M. M. and Varis, O.: Integrated water resources management evolution, prospects and future challenges, Sustainability: Science, Practice & Policy, 1, 15–21, 2005.

Re, V.: Incorporating the social dimension into hydrogeochemical investigations for rural development: the Bir Al-Nas approach for socio-hydrogeology, Hydrogeol. J., 23, 1293–1304, 2015.

Sandoval-Solis, S., McKinney, D. C., and Loucks, D. P.: Sustainability index for water resources planning and management, J. Water Res. Pl.-ASCE, 137, 381–390, 2011.

Savenije, H. H. G. and Van der Zaag, P.: Integrated water resources managagement: concepts and issues, Phys. Chem. Earth A/B/C, 33, 290–297, 2008.

SFPUC: 2013 Water Availability Study for the City and County of San Francisco, San Francisco Public Utilities Commission, 2013.

SFPUC: Non-Potable Water Program, San Francisco Public Utilities Commission, Web site, available at: http://www.sfwater.org/index.aspx?page=686, 2015.

Simpson, E. H.: Measurement of diversity, Nature, 163, 688–688, 1949.

Sivapalan, M., Savenije, H. H. G., and Bloeschl, G.: Socio-hydrology: a new science of people and water, Hydrol. Process., 26, 1270–1276, 2012.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A., Wescoat, J. L., and Rodriguez-Iturbe, I.: Socio-hydrology: use-inspired water sustainability science for the anthropocene, Earth's Future, 2, 225–230, 2014.

Srinivasan, V.: Reimagining the past – use of counterfactual trajectories in socio-hydrological modelling: the case of Chennai, India, Hydrol. Earth Syst. Sci., 19, 785–801, doi:10.5194/hess-19-785-2015, 2015.

Srinivasan, V., Gorelick, S., and Goulder, L.: A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India, Water Resour. Res., 46, W07540, doi:10.1029/2009WR008693, 2010.

Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H., and Rozelle, S.: The nature and causes of the global water crisis: syndromes from a meta-analysis of coupled human-water studies, Water Resour. Res., 48, W10516, doi:10.1029/2011WR011087, 2012.

Srinivasan, V., Seto, K., Emerson, R., and Gorelick, S.: The impact of urbanization on water vulnerability: a coupled human-environment system approach for Chennai, India, Global Environ. Chang., 23, 229–239, 2013.

Stern, J.: Introducing competition into England and Wales water industry – lessons from UK and EU energy market liberalisation, Utilities Policy, 18, 120–128, 2010.

Tarroja, B., AghaKouchak, A., Sobhani, R., Feldman, D., Jiang, S., and Samuelsen, S.: Evaluating options for balancing the water–electricity nexus in California: part 1 – securing water availability, Sci. Total Environ., 497, 697–710, 2014.

Thompson, S. E., Sivapalan, M., Harman, C. J., Srinivasan, V., Hipsey, M. R., Reed, P., Montanari, A., and Blöschl, G.: Developing predictive insight into changing water systems: use-inspired hydrologic science for the Anthropocene, Hydrol. Earth Syst. Sci., 17, 5013–5039, doi:10.5194/hess-17-5013-2013, 2013.

United States Census Bureau: American Community Survey 2013, Web site, available at: http://www.census.gov/, 2013.

van Leeuwen, C. J., Frijns, J., van Wezel, A., and van de Ven, F. H. M.: City blueprints: 24 indicators to assess the sustainability of the urban water cycle, Water Resour. Manag., 26, 2177–2197, 2012.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., and Woods, R.: Climate change and mountain water resources: overview and recommendations for research, management and policy, Hydrol. Earth Syst. Sci., 15, 471–504, doi:10.5194/hess-15-471-2011, 2011.

Table 1. Principal component analysis of socio-economic variables and linear regression on water use. Statistically significant numbers in bold.

Socio-economic variables	Principal Components			Linear Regression		
	PC1	PC2	PC3	Coefficient	Std. error	*P* value
Population	0.284	−0.013	**0.793**	1.95×10^{-5}	6.83×10^{-5}	0.778
Population density	0.278	**−0.562**	−0.476	-2.61×10^{-3}	1.58×10^{-3}	0.116
Income	**−0.554**	0.179	0.069	1.28×10^{-3}	2.38×10^{-4}	**3.49×10^{-5}**
Water bills	−0.300	**−0.558**	0.324	$3.51\times10^{+1}$	$1.92\times10^{+1}$	0.083
Home value	**−0.498**	0.275	−0.161	-7.54×10^{-6}	3.27×10^{-5}	0.820
Demand diversity	0.444	**0.515**	−0.085	$-6.42\times10^{+1}$	$4.65\times10^{+1}$	0.184
				(Intercept: $-1.96\times10^{+1}$. *P* value 0.71)		
Proportion of variance	*0.409*	*0.205*	*0.164*	*R-squared = 0.9035*		
Cumulative variance	*0.409*	*0.614*	*0.778*	*Adjusted R-squared = 0.873*		

Table 2. Individual indicator performance for each BAWSCA member agency. Columns in italics show calculated values for the aggregated supply, demand, and adaptive capacity components.

Agency	Relative vulnerability	Supply diversity	*Supply*	Relative demand	*Demand*	Conservation potential	Augmentation potential	Demand diversity	*Adaption*	SUSI
Alameda County WD	6.65	6.39	*6.52*	8.84	*8.84*	1.97	1.00	5.56	*2.22*	**50.40**
Brisbane/GVMID	8.25	1.00	*2.87*	9.73	*9.73*	1.90	1.00	7.22	*2.39*	**40.60**
Burlingame	7.12	2.14	*3.90*	8.84	*8.84*	1.92	1.00	5.76	*2.23*	**42.52**
CWS- Bear Gulch	4.93	1.00	*2.22*	5.85	*5.85*	2.01	1.00	2.99	*1.82*	**28.67**
CWS- Mid-Peninsula	4.37	1.00	*2.09*	8.93	*8.93*	2.13	1.00	4.74	*2.16*	**34.28**
CWS- South San Francisco	5.96	3.04	*4.26*	9.75	*9.75*	1.79	1.00	5.84	*2.19*	**44.94**
Coastside County WD	6.37	1.97	*3.54*	9.19	*9.19*	2.23	1.00	6.28	*2.41*	**42.81**
Daly City	6.86	5.84	*6.33*	9.79	*9.79*	2.42	2.12	4.55	*2.86*	**56.17**
East Palo Alto	7.36	1.00	*2.71*	9.68	*9.68*	2.44	1.00	4.02	*2.14*	**38.31**
Estero MID	7.94	1.00	*2.82*	9.06	*9.06*	2.17	1.00	6.06	*2.36*	**39.21**
Hayward	7.89	1.00	*2.81*	9.52	*9.52*	1.84	1.00	6.32	*2.26*	**39.27**
Hillsborough	6.99	1.00	*2.64*	3.17	*3.17*	1.82	1.00	1.54	*1.41*	**22.76**
Menlo Park	7.04	1.00	*2.65*	8.50	*8.50*	2.00	1.00	6.86	*2.39*	**37.80**
Mid-Peninsula WD	7.44	1.00	*2.73*	8.91	*8.91*	1.97	1.00	4.65	*2.09*	**37.05**
Millbrae	7.46	1.18	*2.97*	9.14	*9.14*	1.82	1.00	5.22	*2.12*	**38.60**
Milpitas	7.68	5.47	*6.48*	9.37	*9.37*	2.00	1.00	7.00	*2.41*	**52.69**
Mountain View	8.01	3.67	*5.42*	8.99	*8.99*	2.04	1.25	6.29	*2.52*	**49.73**
North Coast County WD	7.45	1.00	*2.73*	9.59	*9.59*	2.06	1.00	3.74	*1.97*	**37.24**
Palo Alto	7.96	2.07	*4.06*	8.35	*8.35*	2.06	1.43	6.41	*2.66*	**44.85**
Purissima Hills WD	3.74	1.00	*1.93*	2.59	*2.59*	1.95	1.00	2.16	*1.61*	**20.06**
Redwood City	6.80	2.14	*3.82*	9.03	*9.03*	3.54	2.96	5.61	*3.89*	**51.19**
San Bruno	9.31	5.56	*7.19*	9.57	*9.57*	2.18	1.00	4.74	*2.18*	**53.14**
San Jose MWS- North	1.00	3.31	*1.82*	8.49	*8.49*	1.40	1.00	6.96	*2.14*	**32.07**
Santa Clara	1.00	6.38	*2.53*	8.79	*8.79*	2.08	1.00	6.34	*2.36*	**37.43**
Stanford	7.80	5.04	*6.27*	8.05	*8.05*	1.59	1.00	7.47	*2.28*	**48.65**
Sunnyvale	8.06	5.91	*6.90*	8.84	*8.84*	2.04	1.76	6.03	*2.79*	**55.39**
Westborough WD	7.95	1.00	*2.82*	9.76	*9.76*	3.00	1.00	4.09	*2.31*	**39.88**

Table 3. BAWSCA's Long-Term Reliable Water Supply Strategy (BAWSCA, 2015) projects considered for calculating supply augmentation potential.

Strategy project type	Strategy project	Yield (AFY)	Range of unit cost (USD/AF)	Schedule
Agency Identified Projects – Recycled Water	City of Daly City – Colma Expansion Project	1060	USD 3310	3-4 years
	City of Mountain View – Increase Recycled Water Supply from Palo Alto Regional Water Quality Control Plant	429	USD 1950–2450	3–4 years
	City of Palo Alto – Recycled Water Project to Serve Stanford Research Park	900	USD 2830	3–4 years
	City of Redwood City – Regional Recycled Water Supply*	Up to 3200	Not determined	3–4 years
Agency Identified Projects – Groundwater	City of Sunnyvale Groundwater Project	1880–2350	USD 1230–1350	4 years
Regional Projects – Local Capture and Reuse	Rainwater Harvesting	210–680	USD 2900–44 700	On-going
	Greywater Reuse	1240–3000	USD 550–4530	On-going
	Stormwater Capture*	Not determined	Not determined	Not determined
Regional Projects – Desalination	Open Bay Intake Desalination	16 800	USD 2100–4950	5–12 years
	Brackish Well Desalination	780–7280	USD 1400–7090	5–12 years
Regional Projects – Transfers	Water Transfers	10 000–31800	USD 950–1750	2–5 years

* Redwood City Regional Recycled Water Supply project and stormwater capture were dropped for further consideration due to limited information currently available on key criteria of cost and potential demand.

Table 4. BAWSCA-wide adaptive capacity scenarios. Scenarios show the potential for increasing the sustainability index under different adaptive capacity measures.

Scenario	SUSi
No adaptive capacity	34.79
Adding local projects only	46.67
Adding local + regional projects	51.19

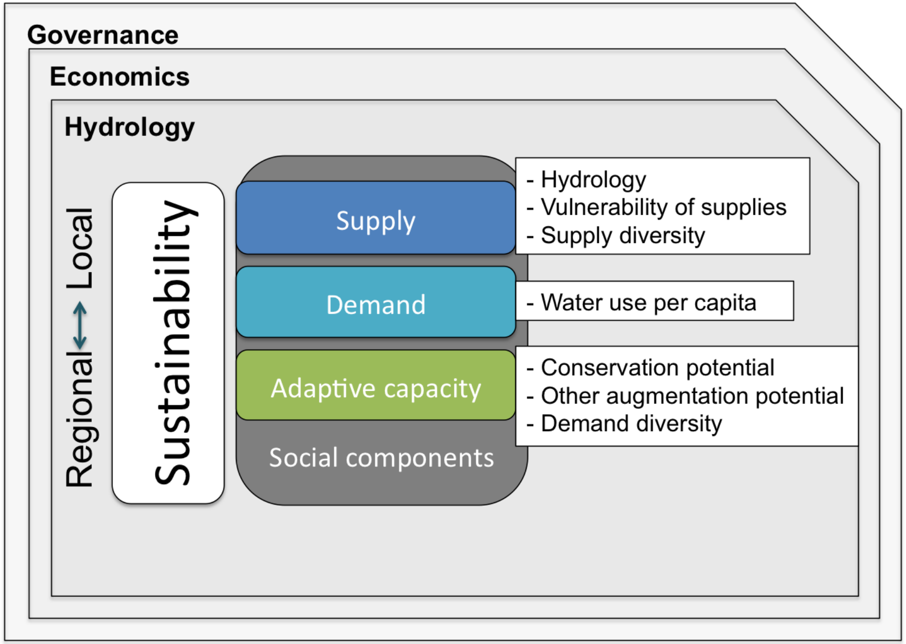

Figure 1. Sustainability framework for urban water systems.

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Urban water sustainability

P. Gonzales and N. K. Ajami

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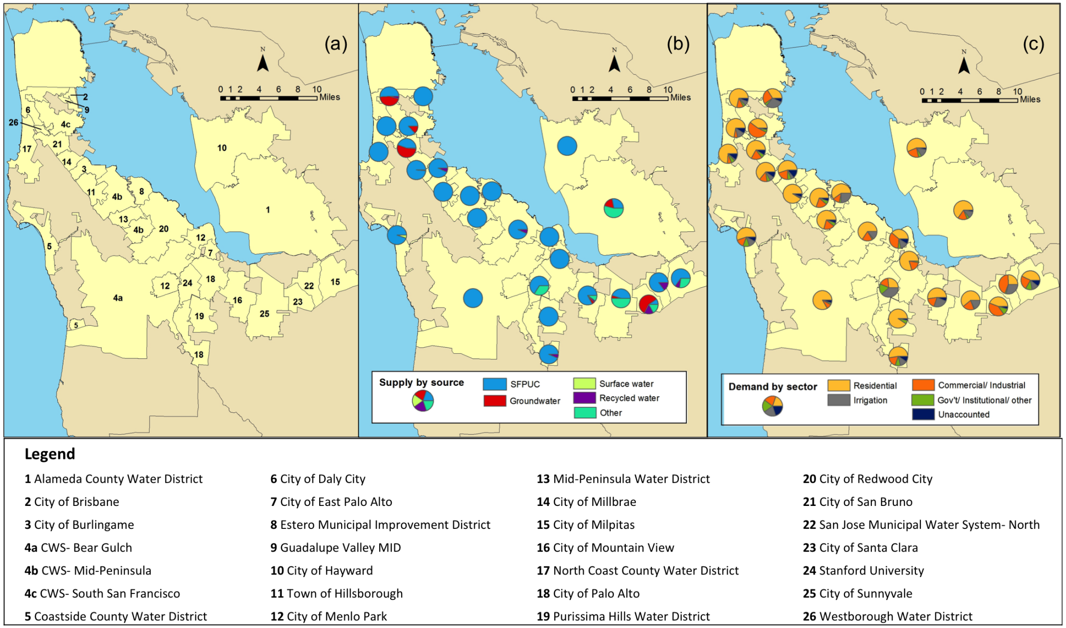

Figure 2. (a) BAWSCA members map, **(b)** supply, and **(c)** demand portfolios by agency for FY 2013–2014.

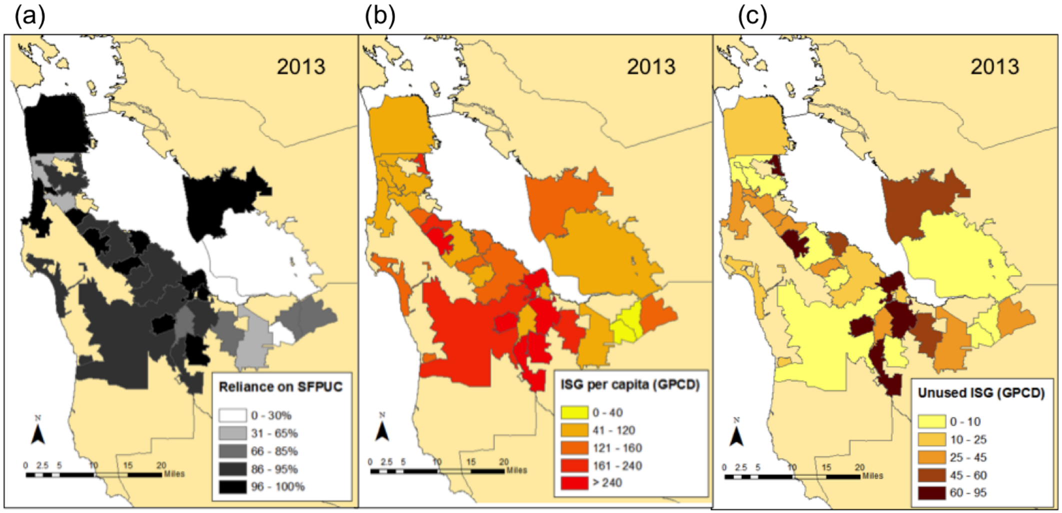

Figure 3. (a) Reliance on SFPUC as a percentage of total supplies, **(b)** distribution of individual supply guarantee among agencies, normalized by population, and **(c)** unused supplies (individual supply guarantee minus actual water purchases) normalized by population.

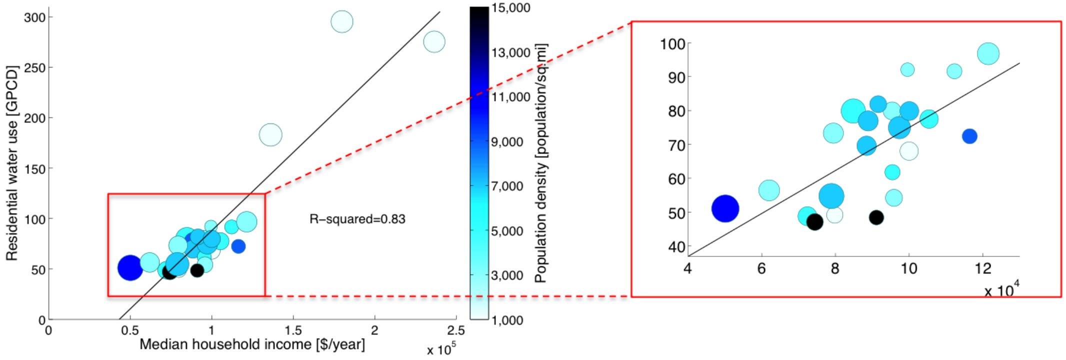

Figure 4. Linear regression of median household income (*x* axis) on residential water use (*y* axis). Relationship with water pricing (circle size) and population density (color scale) is also shown. Insert displays a closer look at the relationship when outliers are removed.

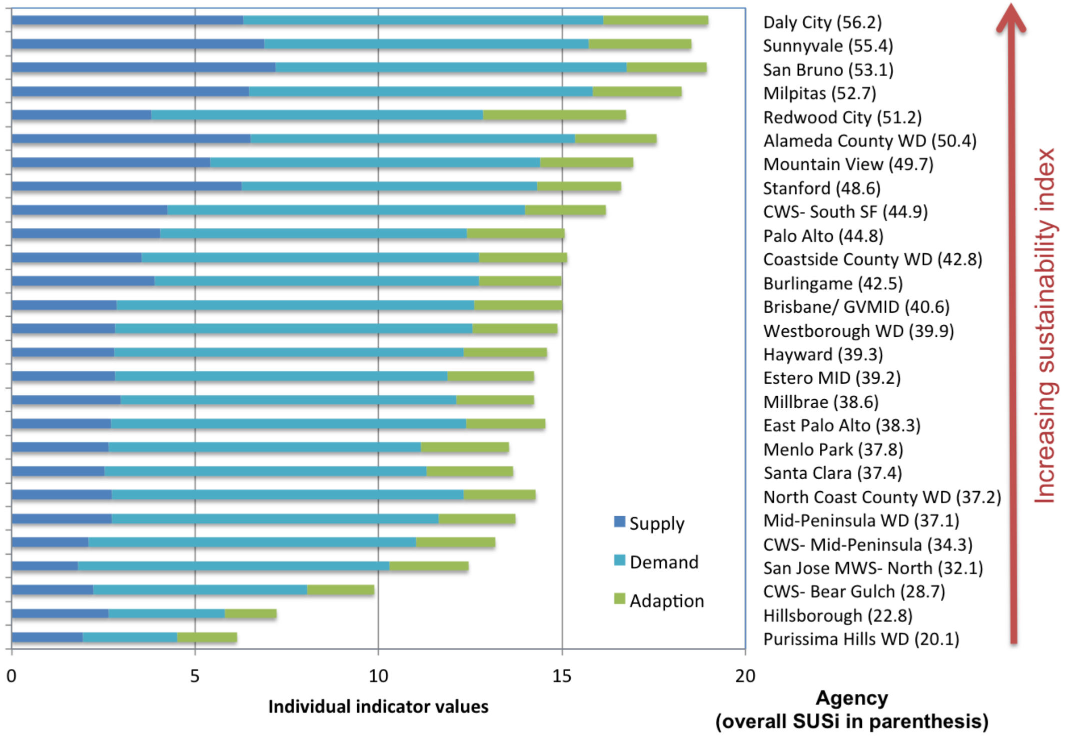

Figure 5. Sustainability indicator values and overall index by agency as of Fiscal Year 2013–2014.

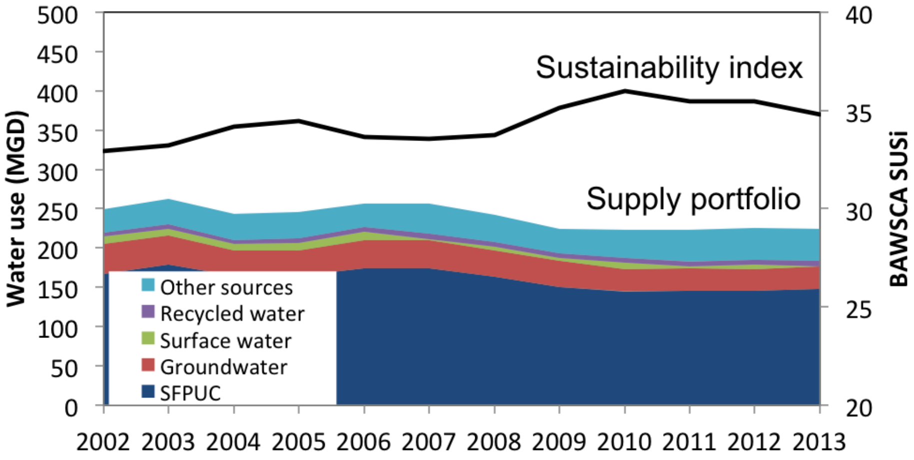

Figure 6. BAWSCA-wide sustainability index and supply portfolios from 2002 to 2013.