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Evaluating options for Balancing the Water-Electricity Nexus in California: Part 1 – Securing Water Availability

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HIGHLIGHTS

- A spatially and temporally resolved model of California's major surface reservoirs is presented.
- The sensitivity to urban water conservation, desalination, and water reuse is examined.
- Under baseline hydrology conditions, individual options secure water availability alone.
- Water savings from individual options other than desalination are insufficient.
- Seawater desalination alone requires extreme capacity installations.

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ABSTRACT

The technical potential and effectiveness of different water supply options for securing water availability in a large-scale, interconnected water supply system under historical and climate-change augmented inflow and demand conditions were compared. Part 1 of the study focused on determining the scale of the options required to secure water availability and compared the effectiveness of different options. A spatially and temporally resolved model of California's major surface reservoirs was developed, and its sensitivity to urban water conservation, desalination, and water reuse was examined. Potential capacities of the different options were determined. Under historical (baseline) hydrology conditions, many individual options were found to be capable of securing water availability alone. Under climate change augment conditions, a portfolio approach was necessary. The water savings from many individual options other than desalination were insufficient in the latter, however, relying on seawater desalination alone requires extreme capacity installations which have energy, brine disposal, management, and cost implications. The importance of identifying and utilizing points of leverage in the system for choosing where to deploy different options is also demonstrated.

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1. Introduction and background

Concerns over climate effects on water availability combined with increasing demands in various regions are driving interest in diversifying the water supply portfolio. Many regions in the world are expected to face decreased water availability due to the impacts of climate change on regional hydrology and weather patterns (Boithias et al., 2014; Charlton and Arnell, 2011; Li et al., 2010; López-Moreno et al., 2013; Olmstead, 2013; Pingale et al., 2014; Vairavamoorthy et al., 2008; Cayan et al., 2010; Hao and AghaKouchak, 2013; Schubert and Lim, 2013; Trenberth, 2001; Wehner, 2013). A number of relevant studies have been performed for the water supply system of California in particular, due to its particular susceptibility to climate change impacts on water supply availability. Connell-Buck et al. (2011), Zhu et al. (2005), Tanaka et al. (2006), and Lund et al. (2003) investigated the effects of warmer and drier climates on water supply using the CALVIN model and outlined potential adaptation measures. More studies have predicted a warmer and drier climate with less snow pack in the future in southwestern United States (Cayan et al., 2010; Seager et al., 2007) that could affect both the water availability and energy production (Madani and Lund, 2010). Coupled with population growth and projected increases in demand in many regions, the need for more prudent water management strategies and alternative options for usable water supply has been identified. Many alternative options for water supply are currently available. The accessibility of these options varies significantly by region, however, reliance on the historical paradigm of precipitation-based surface and groundwater supplies may not be enough to meet increasing demands.

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Water conservation is one option that is encouraged in many sectors and regions. Conservation is considered as the most direct and immediate method for stabilizing the water supply. For example, regions such as California have managed to maintain per-capita water usage at steady levels through improvements in urban and agriculture water use efficiency measures (Hanak et al., 2009; Gleick et al., 2005), offsetting the increase due to population growth. Certain studies have estimated that water conservation measures may be enough to negate the impacts of climate change in particular regions (Boland, 1997). It has also demonstrated beneficial economic impacts by reducing the cost of water and increasing the value of related commodities such as food (Ward, 2014; Smart Savings: Water Conservation Measures that Make Cents, 2008).

Desalination is another option that has been implemented or is being considered as part of the water supply portfolio to combat water shortages in arid regions. As of 2011, a worldwide capacity of about 72 Mm^3/d has been installed, with the largest share of this capacity being located in the Persian Gulf countries in the Middle East region for seawater desalination, and the second largest total capacity in North America, mostly focused on brackish water desalination (Desalination.com: Market data, 2012; Lattemann et al., 2010). Middle Eastern regions have historically relied on thermal desalination, whereas new plants in North America and Australia have relied on membrane technology for large scale operations. For example, a membrane desalination plant was installed in Sydney, Australia as a contingency measure after the effects of the Millennium Drought which impacted the region from 1995 to 2010, with the capability to provide up to 15% of the city's water supply (Review of Operating Regime for Sydney's Water Desalination Plant, 2010). High energy demand is the biggest challenge in desalination installation and operation. Many research efforts in this area focus on reducing the energy and greenhouse gas impacts of this measure (Al-Karaghouli and Kazmerski, 2013; Al-Zahrani et al., 2012) or comparing it with other options (Shrestha et al., 2011; Ghaffour et al., 2013). The use of desalination, however, is limited to coastal regions with access to seawater or inland regions with access to large brackish groundwater reservoirs.

Besides conventional resources, reclaimed wastewater effluent is another alternative resource option to help secure water supplies. Approximately 12 billion gallons (45.4 Mm^3) of municipal wastewater effluent is discharged each day to an ocean or estuary out of the 32 billion gallons per day (121.1 Mm^3/d) discharged in the United States. Reusing these coastal discharges would directly augment available water resources (equivalent to 6% of the estimated total U.S. water use or 27% of public supply) (Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater, 2012). About 5–6% of municipal wastewater effluent in the U.S. is reclaimed and beneficially reused. It is projected that water reuse level will increase from 1.92 BGD (7.27 Mm^3/d) in 2008 to 2.7 BGD (10.22 Mm^3/d) by 2015. In some countries with scarce water resources (e.g. Singapore) up to 30% of the wastewater is reused. In 2009, State of California reused 218 BG (825.2 Mm^3) reclaimed water (National Water Reuse Database, 2013). Among this volume, 36.5% was used for agricultural irrigation, 11.9% for groundwater recharge, 9.7% for industrial reuse, 11.7% for wetlands, and 12.6% for public access irrigation.

All of these available options also have strong implications for regional energy use, greenhouse gas emissions, and the ability to meet renewable energy targets in different regions, and the interface between water and energy is an ongoing research field of importance (California's Water-Energy Relationship, 2005; King et al., 2013; Stillwell et al., 2011). A variety of previous studies have examined particular aspects of interactions within the water–energy nexus. Madani et al. (2014) and Guégan et al. (2012) examined in detail the potential impacts of climate change hydrology on hydropower generation and operation, and implications for sustainable energy policy (Hadian and Madani, 2013). Blasing et al. (2013) investigated the response of hydropower electricity generation to changing temperatures under climate change scenarios.

Depending on the pathway taken and the portfolio composition of water supply measures that different regions use to stabilize their water supply, energy impacts can range from co-beneficial to detrimental to the metrics described previously. Before an evaluation of the interaction of different options with sustainable energy goals can be determined, however, the sense of the scale of these options required must be determined for a given system. Many efforts have characterized only the specific energy consumption of different options. Without an understanding of *how much* of these options would be required to stabilize the water supply of a given system, however, the strength of the synergies or interferences with the energy sector cannot be accurately determined. Additionally, there have been few studies which have holistically compared different available options for securing water availability on common criteria. This study aims to address these topics in two parts.

This paper is the first of two parts, aimed at determining the following for this system:

- The ability of individual options to contribute toward stabilizing the water supply.
- The scale (capacity) of individual and mixed option portfolios required to secure water availability under baseline and climate change augment hydrological conditions.

With a more accurate sense of scale, the strength of the interactions with the energy sector can then be determined. This is the focus of the second part of the study.

For both parts of this study, the system of the state of California is used. California provides a good example system for this type of analysis. The state includes a diverse array of climates. The northern and eastern mountain regions of the state have historically received large amounts of precipitation and provided natural storage in the form of snowpack that drive the flow of major in-state rivers. The northern coastal regions experience moderate temperatures and precipitation rates, and are at the center of the state's water system as most of the major in-state rivers flow into the Sacramento Delta, which is the major distribution point of water supply for the entire state. The highly-populated southern part of the state, however, typically exhibits an arid and desert climate with little natural precipitation, necessitating an extensive reservoir network and aqueduct system to import water from the wetter regions of the state and from out-of-state sources such as the Colorado River. Additionally, water demand in the state is very diverse. High populations give rise to high urban demands, while a thriving agricultural economy gives rise to high agriculture water demands. Finally, exhibiting high populations in addition to being situated on the coast allows the state access to a wide array of water supply options: conservation, desalination, and water reclamation. A recent study based on historical observations indicates a drying precipitation trend in most of the western United States including California (Damberg and AghaKouchak, 2013). Climate model simulations of future climate exhibit different wetting and drying patterns. However, most model simulations show a drier future for California (Seager et al., 2007). In addition, highly progressive energy policies for reducing greenhouse gas emissions and increasing renewable energy usage are also present in the state, as well as access to a diverse array of renewable resources. This allows many aspects of the interplay between energy and water to be examined.

2. Model description

To accomplish the objective of determining the scale of available options to stabilize major reservoir levels and therefore the water supply, an integrated modeling platform was developed. This includes two major classes of components: 1) a model of major surface reservoir behavior and their network and 2) modeling and characterization of the behavior and potential for different water supply stabilization measures in the state. Each of these components will be described as follows.

2.1. Individual reservoir model

Before the reservoir network is modeled, the behavior of the individual reservoir dispatch must be captured. A simple model for an individual reservoir that takes inputs of temporally resolved inflow, temporally resolved reservoir demand, initial fill level, maximum discharge rate, and minimum/maximum fill level limits is used. The fundamental concept of the model is based on a monthly reservoir model introduced by van Beek et al. (2011), Haddeland et al. (2006), and Hanasaki et al. (2006), but has been updated for use with a daily time step. For a given time step, the model is described as follows.

The reservoir storage state is defined by:

$$S_i = S_{i-1} + \int_{i-1}^{i} \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{add}$$

where $\dot{Q}_{in}$ represents the introduced inflow. $\dot{Q}_{out}$ represents the reservoir release to meet the demand, which is calculated as follows:

$$\dot{Q}_{out} = max\left(min\left(\dot{Q}_d, \dot{Q}_{lim}\right), F(s) * \dot{Q}_{avg}\right).$$

$\dot{Q}_{lim}$ is the limit on the amount of discharge available, limited by the amount of water stored. $\dot{Q}_{avg}$ is the average inflow for the entire dataset. $\dot{Q}_d$ represents the reservoir release to meet the reservoir demand only. Net losses due to evaporation are taken into account as additions to the demand profile.

$$\dot{Q}_d = min\left(1, \frac{S_{i-1}}{S_{min}}\right) * Demand_i$$

where S_{min} is the minimum fill level of the reservoir. $F(s)$ represents the ratio of the potential release relative to the amount stored at the given time step:

$$F(s) = min\left(1, \max\left(0, \frac{S_{i-1} - S_{min}}{S_{max,o} - S_{min}}\right)\right).$$

$\dot{Q}_{add}$ represents the additional release from the reservoir for auxiliary concerns such as flood and river level management, considering the available buffer between maximum operating fill level ($S_{max,o}$) and maximum absolute fill capacity (S_{max}):

$$\dot{Q}_{add} = max\left(0, \frac{S_{i-1} - S_{max,o}}{S_{max} - S_{max,o}}\left(\dot{Q}_b - \dot{Q}_{out}\right)\right) + max\left(0, S_{i-1} - S_{max}\right)$$

where $\dot{Q}_b$ is the bank-full discharge.

This process is carried out sequentially for every time step in the dataset for the analysis period. More details on the datasets will be described in a later section.

2.2. Reservoir system model

A model of California's reservoir system is developed to capture the sensitivity of deploying different technologies in hydrologic regions of the state. California is selected as the system of interest due to its many unique characteristics, including a high population, a diverse array of water demands, spatially diverse precipitation patterns, and a highly managed water conveyance system. This model captures 13 major surface reservoirs: 12 are managed by the California Department of Water Resources and Lake Mead. The included surface reservoirs and their capacity are presented in Table 1 with their locations presented in Fig. 1.

The Lake Mead reservoir serves Arizona and Nevada in addition to California, therefore not all of its capacity can be treated as a California reservoir. The allocations of water from this reservoir are governed by the Colorado River compact (Hoover, 1922), and are fixed by contract. Therefore, to include Lake Mead in the model, an effective reservoir representing the portion of Lake Mead that serves California is created by scaling down the reservoir capacity of the Lake Mead reservoir according to the allocation distribution in the Colorado River compact.

Table 1
Major Surface Reservoirs Managed by CA DWR + Lake Mead. Designation of the hydrologic region directly served by the each reservoir and their connection to the Sacramento Delta is included.

Reservoir	Capacity (TAF)	Hydrologic Region Directly Served	Connection to Delta
Don Pedro (DP)	2030	San Joaquin River San Francisco Bay	Tuolumne River
Exchequer (EX)	1025	San Joaquin River San Francisco Bay	Merced River San Joaquin River
Folsom Lake (FS)	977	San Joaquin River	American River
Millerton Lake (ML)	520	Tulare Lake South Lahontan	San Joaquin River
New Melones (NM)	2420	San Joaquin River San Francisco Bay	Stanislaus River
Lake Oroville (OR)	3538	Sacramento River	Feather River
Pine Flat (PF)	1000	Tulare Lake South Lahontan	San Joaquin River
Lake Shasta (LS)	4552	North Coast Sacramento River	Sacramento River
Trinity Lake (TL)	2449	North Coast Sacramento River	Sacramento River
San Luis (SL)	2039	Central Coast San Francisco Bay	State Water Project (Supply)
Lake Mead (CA Effective) (LM)	10867	South Coast Colorado River	N/A
Castaic Lake (CL)	325	South Coast	N/A
Pyramid Lake (PL)	171	South Coast	N/A
CA Statewide Aggregate	**31913**		

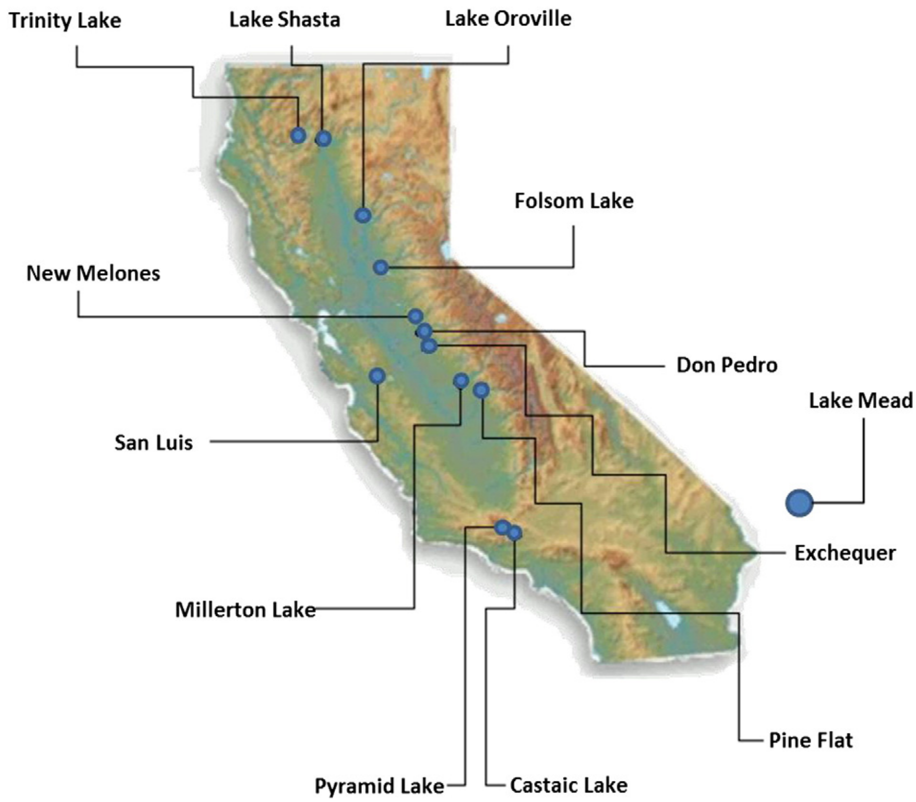

Fig. 1. Location of major surface reservoirs in model (California Data Exchange Center — Reservoirs, 2013).

The inflows to the Lake Mead reservoir that are relevant to this downscaled effective reservoir are also apportioned from the total Lake Mead inflow based on the Colorado River Compact allocation distribution, reflecting actual water sharing rules for this reservoir.

Each reservoir is tasked with primarily serving the water needs of a given hydrologic region. Water conservation or production measures that are implemented in a given region will directly displace demand on the reservoirs serving it. In addition, the included reservoirs are

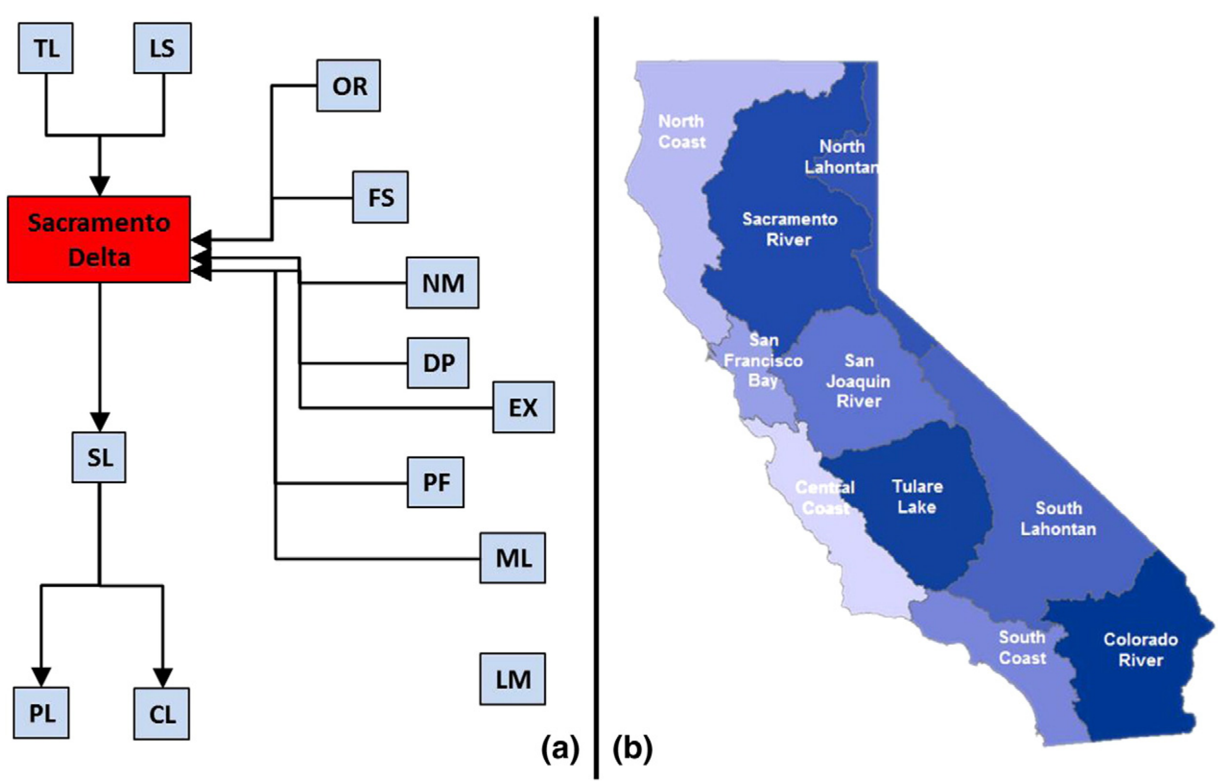

Fig. 2. (a) Reservoir connections in California. (b) Hydrologic regions in California.

linked either by natural river flows or by artificial canals, and this structure forms the basis for how changes in the demand on one reservoir affect demands on other reservoirs. Therefore, a unit volume of water saved in an area served by one reservoir also affects the demands on all of the reservoirs that supply it. A simplified schematic of how these major surface reservoirs are linked in the model and the location of hydrologic regions are presented in Fig. 2 (2010 Urban Water Management Plan Data, 2013). A table of the assumptions for the demand region directly served by each reservoir is presented in Table 1. The designation of directly-served demand regions are based on the location of the reservoirs and their main river outflows. The designation of reservoir linkages is based on the river topography of the state and constructed major canals, which is tied together by the Sacramento Delta (California State Water Project Facilities, 2013). The connections of major reservoirs to the Delta are also presented in Table 1.

It is important to highlight, however, that this model is not a water management model such as those represented by the CALFED (Healey et al., 2004) or CALVIN (Lund and Howitt, 2001) models. These aforementioned models are aimed at examining different water management paradigms for watershed management, flood control, and water allocation policies. This model does not attempt to capture changes in the paradigm of water transfers in the state, other than allowing the presence of water savings due to water stabilization options to free up allocations in the reservoir chain. Otherwise, historical management practices and groundwater demand are embedded in the baseline case of the model.

Inflow data for each of the reservoirs was obtained from the California Data Exchange Center (California Data Exchange Center, 2013), State Water Project operation reports (State Water Project Monthly Operations Data, 2012), and USGS data (National Water Information System: Web Interface, 2013), for the time period of 2000–2010 with a daily temporal resolution. The demand vector on each reservoir was scaled based on the profile of the outflow data, spanning of model parameters for each reservoir was conducted to evaluate reservoir performance, and parameters were selected tuned to best resemble normal historical reservoir operation. Overall, while the mean fill level errors for some individual reservoirs vary between 2% and 20%, the statewide aggregate fill condition matches quite well with an error of only 3.884%.

2.3. Characterization of water stabilization measures

This study considers five different individual measures for stabilizing water availability in California: Urban water conservation, water reuse, thermal desalination with waste heat, thermal desalination with direct natural gas, and membrane desalination. The manner in which these options are characterized in terms of their potential and integration into the model is described here.

2.3.1. Urban water conservation (UC)

The potential for urban water conservation used in this study is taken from an analysis conducted by the Pacific Institute (Gleick et al., 2003), which examined the potential for conservation in different regions in California. The nature of water conservation measures consists of the following:

- Improvements to water use of indoor appliances such as toilets, sinks, and showers, by the installation of low-flow appliances in residential sectors
- Water savings from reducing losses and inefficiencies in the water distribution system such as leakages and providing adequate maintenance
- Efficient hardware and management improvements for outdoor urban water use. This primarily consists of reducing water usage for watering lawns, gardens, and other landscaping items
- Reductions in the water usage in various commercial and industrial processes such as manufacturing of products.

With all of these measures combined, the authors concluded that the minimum cost effective urban water conservation potential statewide is about 2.02 million acre-feet per year or 6.824 Mm^3/d. This figure was set as the 100% potential mark for this study, and spanning cases are carried out up to this limit. The water savings or reduction in demand is distributed spatially across the hydrologic regions according to population (California Water Plan Update 2009 - Volume 3: Regional Reports, 2009). Temporally, the water savings are assumed to follow the profile of the reservoir demands that are serving the corresponding region.

2.3.2. Water reuse (PR)

The potential for water reuse was calculated by using appropriate wastewater treatment capacity in the state and current reuse efforts to set a limit on the additional capacity for water reuse. This is calculated as follows.

A list of all of the wastewater treatment plants in California was obtained from the State Water Resources Control Board Regulated Facilities database (Regulated Facility Reports, 2013). This database contains the maximum capacities of each plant, its location, and the thoroughness of its treatment levels. For water reuse, the effluent from a wastewater treatment plant must be fairly contaminant-free before discharging back into the environment, therefore only plants with the highest complexity treatment designation ("A") were included. These plants include primary and secondary stage wastewater treatment processes. The locations of the plants were used to distribute this capacity by hydrologic region.

It is important, however, to account for reuse efforts that are already in operation. To obtain this capacity, data for California for the year 2009 was obtained from the National Water Reuse Database (National Water Reuse Database, 2013). This database contains all of the wastewater treatment plants that are engaged in reuse efforts, including their location. For each hydrologic region, the corresponding capacity was subtracted from the wastewater treatment capacity to obtain the potential for water reuse.

With these datasets, the statewide theoretical capacity for water reuse is calculated to be 18.4 Mm^3/d. This is set as the 100% potential mark for this option. Additionally, the temporal profile of this option is assumed to follow the water demand.

2.3.3. Thermal desalination with waste heat (TDw)

The potential for thermal desalination with waste heat was determined by calculating the waste heat potential from power plants located on the California coast, and using a first principles plant model to determine the specific heat consumption of a representative thermal desalination plant.

The waste heat potential was calculated by data from eGRID 2013 (Emissions and Generation Resource Integrated Database (eGRID), 2013). This database includes all of the power plants in California, its annual generation, and its heat rate on a lower heating value (LHV) basis. The waste heat potential for the Diablo Canyon nuclear power plant, which does not have an LHV heat rate, was calculated from the annual electric generation assuming an efficiency of 30%. This figure is typical of conventional steam turbine cycle power plants. From these parameters, the available waste heat energy can be calculated. Power plants located on the coast were selected and sorted into three hydrologic regions: South Coast, Central Coast, and North Coast, to spatially distribute waste heat potential.

The waste heat potential was converted to a capacity potential by use of a model for a Multi-Effect Evaporation (MEE) power plant constructed by Ettouney (2004). The MEE system was chosen due to its ability to use low temperature waste heat and reduced seawater withdrawals compared to multi-stage flash systems. A representative plant size of 40,000 m^3/d with 12 effects and a heating steam temperature of 60 °C, desalinating seawater with default settings (36 ppt salinity) were used in the computation. The specific heat consumption per cubic meter of water desalinated was calculated by taking the enthalpy difference between the heating steam and the condensate reject from the 1st effect. From these parameters, the waste heat potential was converted to a plant capacity potential.

These datasets set the capacity for thermal desalination with waste heat at 3.632 Mm^3/d. The operating profile of this option is assumed to be steady, which is similar to other desalination plants currently deployed in the world (Desalination Plant Operating Regime, 2010).

2.3.4. Membrane desalination (MD) and thermal desalination with direct natural gas (TD)

These particular options are not characterized by a technical potential, unlike the other options considered in this study. From a technical standpoint, there is not a hard limit on the capacity of these measures, although installing them to extreme capacities has other implications such as energy use, greenhouse gases and brine production. The characteristics of both of these options, however, are also captured using representative plant models by Ettouney (2004).

Thermal desalination with direct natural gas is represented using the same plant model as that for thermal desalination with waste heat, however, the specific heat consumption and installed capacity are converted to a natural gas consumption value assuming an LHV basis. This will be explained in more detail in part 2 of the study.

Membrane desalination is represented using a plant model of a two-stage reverse osmosis membrane system, with a representative plant capacity of 40,000 m^3/d, using seawater feed composition (36 ppt salinity) as the input.

Both of these measures are spatially distributed into three regions: South Coast, Central Coast, and North Coast. In this case, the distribution of capacity is free to be specified.

3. Metrics and approach

3.1. Metrics of analysis

In addition to the characteristics of the raw reservoir system profiles, there are two primary metrics that will be used to evaluate the performance of each individual option or mix of options.

3.1.1. Net reservoir fill change

This represents the difference between the fill level of the aggregate group of reservoirs at the beginning and the end of the 10-year analysis time period. If this metric is positive, this indicates that the reservoirs are able to maintain their levels and are considered stable, whereas a negative value indicates an overall decrease in reservoir levels. The stabilizing capacity of a given option is the minimum capacity required to restore the statewide aggregate net reservoir fill level change to a positive number.

This metric is used as a proxy for the change in water availability in the state. The net reservoir fill level change is a metric that is used to establish a baseline against which the effect of different technologies on the water–electricity nexus can be shown. The primary policy goal is not to keep the reservoirs full for their own sake, but rather to ensure water availability to consumers in all regions in the face of increasingly variable precipitation and runoff patterns. The water reservoir network acts to provide that availability by buffering the effects of droughts/dry spells and variable precipitation patterns from affecting the ability to meet demand. The reservoir level change represents the ability of these reservoirs to continue satisfying these demands into the future. Low water reservoir levels at points in time are not as significant as continued decreases in reservoir levels, which indicate an inability to continue satisfying demands under given demand and climate conditions.

It is also important to recognize that in this study, the reservoirs are not operated to keep levels as high as possible, but rather to satisfy urban, agriculture, and environmental water demands. Additional demand components include energy production and flood control. The net reservoir fill level represents the response of water availability to these demands under different inflow conditions. In this study, the reservoir fill level is only used as a baseline to show how different technologies affect water–electricity nexus.

3.1.2. Groundwater demand change

This refers to the change in the amount of water that the system needs to draw from groundwater reservoirs, as a percentage of the total statewide groundwater withdrawals. Water allocations are freed up for recharging groundwater reservoirs when the demand on a given reservoir is reduced below its minimum demand due to the implementation of water supply stabilizing options. While this study does not model the groundwater reservoirs directly, this metric has implications for stabilizing groundwater withdrawal and reducing overdraft.

Groundwater and surface water are intrinsically linked. While an explicit model of the state's extensive groundwater reservoir network would improve the analysis conducted in this paper, there is currently insufficient information to develop an accurate characterization of these reservoirs on a state-wide basis. Information regarding the capacities, locations, and hydrology of these reservoirs on this scale is severely lacking. Additionally, this study focuses on evaluating the relative performance of different technology options relative to a baseline reference. More effective options will better contribute toward water savings and decrease reliance on groundwater resources. With this understanding, quantifying this decreased reliance through this metric is sufficient for the purposes of this study.

3.2. Analysis approach

In this study, reference cases are established under historical and projected future hydrological conditions. The effect of implementing these different options to secure water availability under these conditions is measured by how their implementation affects the metrics described previously.

3.2.1. Inflow and demand conditions

This study evaluates the scale of options needed to secure water availability under two distinct conditions: baseline and climate-change augmented. These are described as follows.

The baseline conditions (BAS) are represented by the January 1, 2000–January 1, 2010 time period. Reservoir inflow data for all of the included reservoirs was obtained from the California Data Exchange Center (CDEC) (California Data Exchange Center, 2013) and historical reports for the operation of the State Water Project (SWP) (State Water Project Monthly Operations Data, 2012), with a daily resolution. The demand vectors for each reservoir are also daily resolved, and are unchanged from the values used in the model verification.

The time period of 2000–2010 was chosen as the analysis period for a number of reasons. This time period includes both wet and dry years, giving a sense of the reservoir network response across multiple years. The ending point of January 1, 2010 was chosen since this corresponds to the middle of a severe drought in the state in order to represent a worst case scenario. Adequate water availability must be present even under drought conditions, and droughts of this severity have already occurred under historical (baseline) hydrology. Under climate change, this can be exacerbated, and therefore this was selected as a baseline from which to introduce the perturbations of climate change. Finally, many of the major reservoirs used in this study did not have data of sufficient resolution or had significant data gaps in years preceding this timeframe.

The climate change augment conditions (CCHa) are chosen to represent the 2040–2050 time period. Reservoir inflows were modified by obtaining spatially-resolved runoff data from four different climate models (ccsm3, cnrm, gfdl, and pcm1) provided by Cal-Adapt Tablular Database (2013). The IPCC Climate Scenario A2: “High Emissions” case was utilized for the runoff data. This case represents a “worst case” scenario of high greenhouse gas emissions and highly exacerbated effects of climate change. This was chosen to set the climate change augment conditions as a bounding worst case. The difference between the runoff data for the 2000–2010 and 2040–2050 time periods was calculated and applied as a modification to the baseline reservoir inflow data. Due to variability in climate model predictions, an average across all four climate models at each time step was used.

In addition to the inflow data, the reservoir demand data was also changed under the CCHa case. Projections for the change in the average yearly urban and agriculture water demand between historical trends and the 2043–2050 time period for the whole state were provided by the California Department of Water Resources (California Water Plan Update 2009 - Volume 3: Regional Reports, 2009). The "Current Trends" scenario was utilized. While the future period refers to 2043–2050 instead of the 2040–2050, the use of an average yearly demand still allows it to be suitable for use in our analysis. These demand changes were distributed spatially in hydrologic regions by urban water demand and irrigated agriculture demand distributions (California Water Plan Update 2009 - Volume 3: Regional Reports, 2009).

3.2.2. Option capacity spanning

A spanning study was performed by increasing the installed capacity of each option until either its maximum capacity potential is reached, or until a given capacity is able to restore the CA statewide reservoir fill condition to positive values, whichever comes first. This was carried out for each of the options discussed in Section 2.3. Option capacity deployment perturbs the reservoir system by reducing the demand placed on the appropriate reservoirs. It is important to note that water produced by any of the measures is *not* placed in the major surface reservoirs. Rather, by displacing reservoir demands, the reservoirs are allowed to store more of their respective inflows, increasing reservoir levels.

The spatial distribution of urban water conservation was set according to the distribution of urban water demand by hydrologic region (California Water Plan Update 2009 - Volume 3: Regional Reports, 2009). For water reuse, the spatial distribution is set by that of wastewater treatment plant capacity using the locations of wastewater treatment plants. For thermal desalination with waste heat, capacity is distributed along the three coastal regions according to calculated waste heat potential, while for all other desalination measures, it is set according to the urban population distribution along the coastal regions. In addition, a case which biases membrane desalination capacity more so toward the South Coast region is also included.

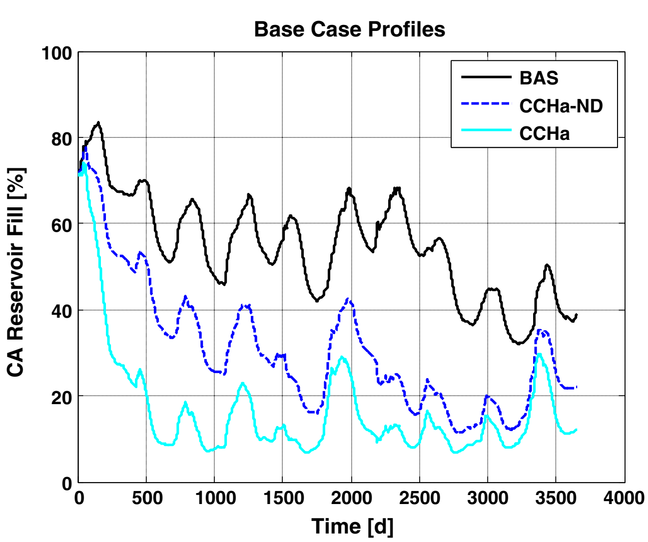

Fig. 3. No option reservoir fill profiles. BAS = baseline conditions, CCHa-ND = climate change conditions with no demand change, CCHa = climate change conditions with demand change.

Based on the results of the individual option capacity spanning, hybrid mixes of available options are also developed. These cases are explained and presented in the results section.

4. Results

4.1. No-option reservoir fill levels

To establish a reference for the reservoir system, the reservoir fill profiles for the 10-year period for three hydrological conditions are presented in Fig. 3. In addition to the BAS and CCHa cases described previously, an additional case (CCHa-ND) shows the reservoir fill profiles with climate-change augmented inflows but no demand change, to highlight the effect of climate change alone.

For baseline inflow and demand conditions, the reservoir levels gradually decrease over the 10-year period. The overcommitting of available water resources combined with drought periods has caused reservoir levels to decrease. Lake Mead is particularly at risk due to overcommitting. The aggregate reservoir fill level drops from about 71% to 38%, for a net change of −33%.

For the case with climate change augmented inflows but no demand change, the prediction of reduced precipitation in the northern and easternmost regions of California which supplies the Sacramento Delta causes further reductions in the statewide reservoir fill condition. This is especially pronounced during the latter end of the time period, where the aggregate reservoir levels drop below 20%. The net change in statewide reservoir fill condition is exacerbated to −49%.

When climate change augmented inflows and demand increases are considered, the situation worsens. Reservoir levels drop to very low levels almost instantly, and remain low for the entirety of the time period, with a net reservoir fill change of −59.8%. It is important to highlight that the additive effects of the increase in demand and climate change affected inflows that potentially cause a water crisis in the state.

4.2. Securing capacities — individual options

For individual options, the progression of the net reservoir fill level change in the statewide reservoir fill condition is presented in Fig. 4 for baseline conditions.

Under these conditions, most of the individual options are able to secure or nearly secure surface reservoir levels. The exception is thermal desalination with waste heat which does not have enough potential in

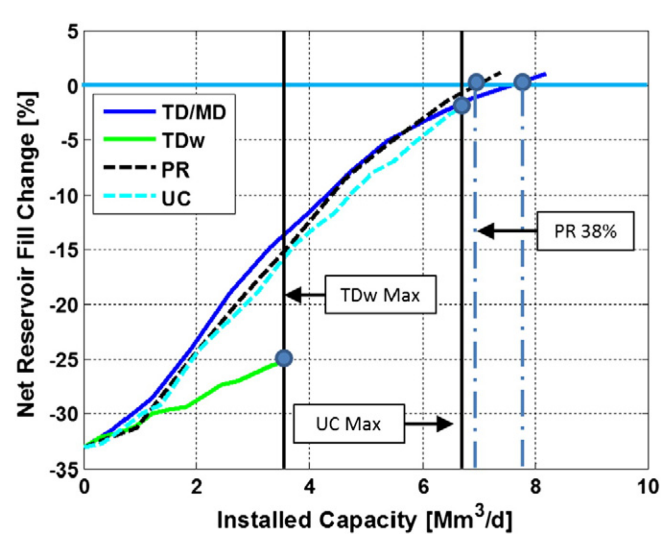

Fig. 4. Net reservoir fill change vs. individual option installed capacity — baseline conditions. TD/MD = thermal desalination/membrane desalination, TDw = thermal desalination with natural gas, PR = water reclamation (purification) and reuse, UC = urban conservation.

California to secure reservoir levels. Due to the shutdown of the San Onofre Nuclear Power Plant, the majority of capacity is due to the waste heat from the Diablo Canyon Nuclear Power Plant. This measure also increases net reservoir fill levels at a lower rate than other technologies due to its spatial distribution, since most of its capacity is located in the central coast, which has less leverage in the system compared to the south coast region.

The spatial distribution of all of the other measures is highly concentrated in Southern California, which is a point of leverage in the system. Southern California imports most of its water through a canal system, therefore its local reservoirs tend to be supplied by other reservoirs preceding it in the system. Therefore, a gallon of water saved in southern California does not only increase the reservoir fill levels of local reservoirs, but also for all of the reservoirs that supply them. This allows it to have a multiplicative effect on raising the statewide reservoir fill condition.

The use of urban water conservation alone with the potential used in this analysis is not quite sufficient to secure water availability statewide, although it does get fairly close to doing so. At 100% of the potential considered here, the statewide reservoir fill condition is raised from −33% to −1.712%. Additional conservation measures that were not taken into account may be enough to secure water availability under baseline hydrological conditions.

The remaining options of wastewater purification/reuse and the other types of desalination considered in this study are able to secure water availability under these conditions. Water reuse is able to do so while utilizing only 38% of its potential capacity. The difference between the progression for wastewater purification/reuse and that for desalination is due to slight differences in their spatial distribution, but more importantly, differences in their operating profile. Water reuse follows the profile of the reservoir demand and works to reduce it, while desalination is steady state and does not dispatch. At lower reservoir levels, desalination is more effective by providing water during periods of low and high demand, whereas at higher reservoir levels, water reuse reduces peak demands and becomes more effective.

Profiles of the statewide aggregate reservoir fill condition for wastewater purification/reuse and for thermal and membrane desalination are presented in Figs. 5 and 6, respectively. These profiles show that when the net reservoir fill levels are raised to their initial conditions, the reservoir levels remain high during the entire analysis period. Additionally, the incremental increase in average reservoir levels is fairly linear for an incremental increase in option capacity.

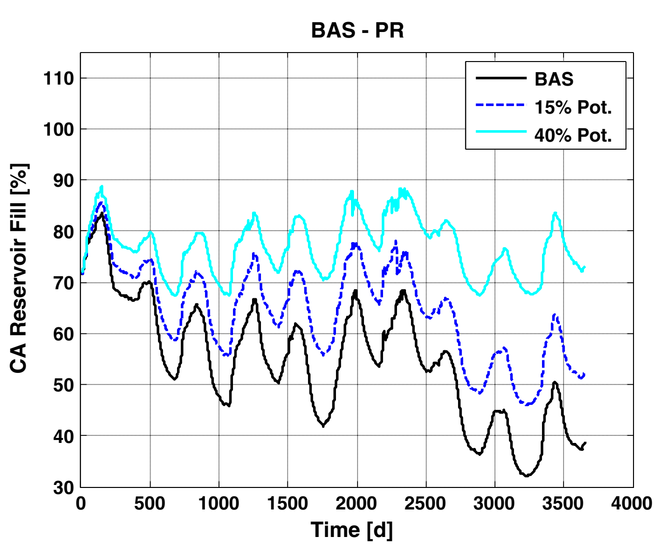

Fig. 5. Reservoir fill profiles for water reuse (PR) under baseline (BAS) conditions.

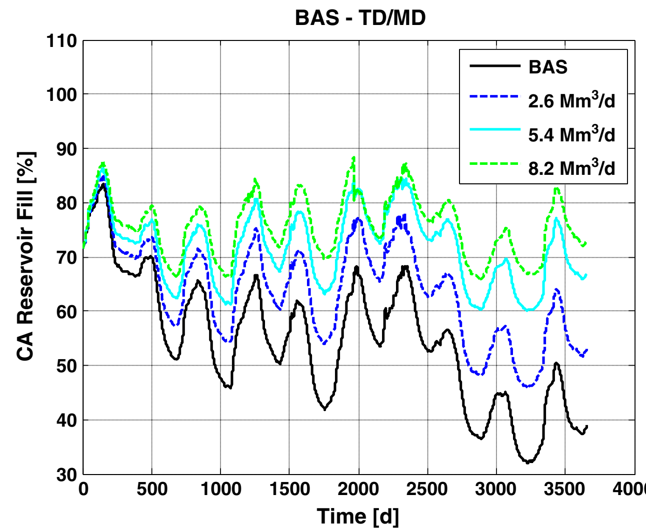

Fig. 6. Reservoir fill profiles for thermal/membrane desalination (TD/MD) under baseline (BAS) conditions.

For individual options, the progression of the net reservoir fill level change in the statewide reservoir fill condition is presented in Fig. 7 for climate change augmented conditions.

Under climate change, the situation changes considerably. Combination of reduced inflow and increased urban demand significantly reduces reservoir levels. Over the 10-year period considered, the net reservoir fill change is −59.8%. This causes the scale of technologies required to secure water availability to be significantly increased.

Of the individual options considered, only desalination is able to eventually stabilize reservoir levels. This makes sense since direct thermal desalination and membrane desalination are the only options that do not have a hard, technical limit on the scaling up of its installed capacity. However, relying solely on this measure requires an extreme amount of capacity. For context, the total amount of desalination capacity in the world is around 78 Mm^3/d. Urban water conservation is limited by the demand requirements, and water reuse is limited by the amount of wastewater effluent available, which is in turn limited by demand requirements.

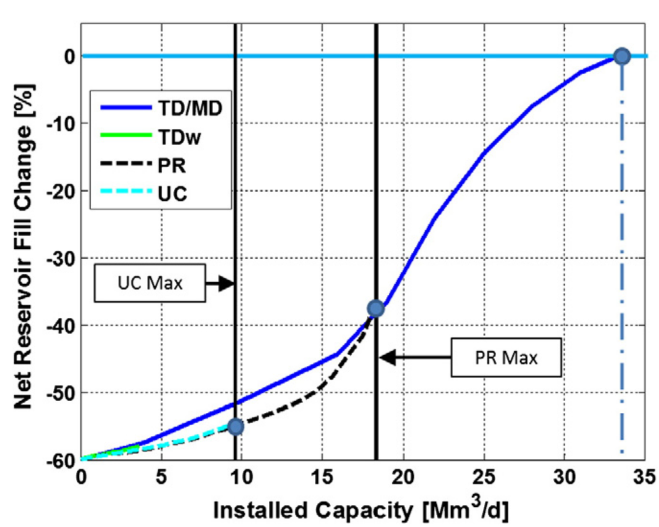

Fig. 7. Net reservoir fill change vs. individual option installed capacity — climate change augmented conditions. TD/MD = thermal desalination/membrane desalination, TDw = thermal desalination with natural gas, PR = water reclamation (purification) and reuse, UC = urban conservation.

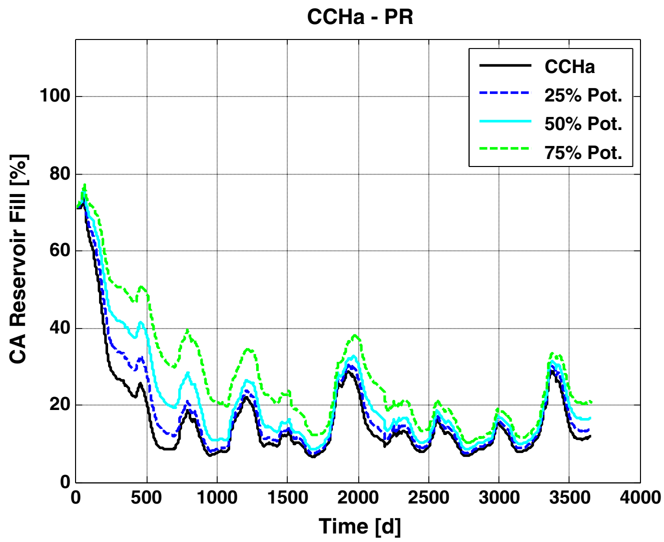

Fig. 8. Reservoir fill profiles for water reuse (PR) under climate change augment (CCHa) conditions.

Under these conditions, the shape of the curve to reach stabilizing capacities has two distinct regions, evident in the desalination curve and somewhat in the wastewater purification/reuse curve. At the lowest reservoir fill levels, the incremental increase in the net reservoir fill change due to technology deployment is lower compared to that at higher reservoir fill levels. This occurs since at low reservoir levels, small displacements of reservoir demand do not significantly increase reservoir levels, since the demand is still so large such that most or all of the inflow introduced to the reservoir must be immediately passed through to satisfy it. Therefore, an incremental water savings does not allow as much inflow to be stored as in higher reservoir levels. This trend starts to taper off as reservoir levels become full, and passing through of inflow occurs to prevent overfilling the reservoir.

In this context, urban water conservation and thermal desalination with waste heat are unable to increase reservoir levels to any significant amount. The net reservoir fill change at 100% capacity for both measures is −54.72% and −57.98% respectively, up from −59.81%. Water reuse, which has a much larger potential capacity, is able to raise the net reservoir fill change to −36.36% if 100% of the capacity is utilized. This option

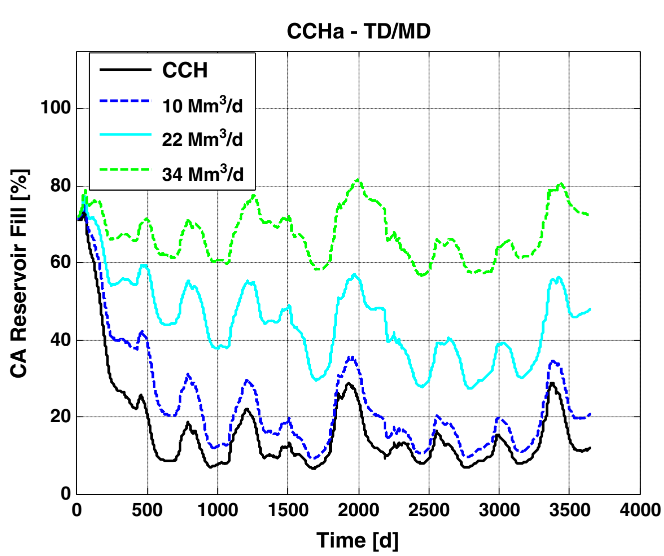

Fig. 9. Reservoir fill profiles for thermal/membrane desalination (TD/MD) under climate change augment (CCHa) conditions.

Table 2
Securing or maximum capacities for individual (orange) and hybrid (blue) option cases in Mm^3/d — baseline conditions.

Designation	UC	TDw	TD	MD	PR
No options	0.00	0.00	0.00	0.00	0.00
TDw	0.00	3.63 (100%)	0.00	0.00	0.00
TD	0.00	0.00	7.60	0.00	0.00
MD	0.00	0.00	0.00	7.60	0.00
MD (SC)	0.00	0.00	0.00	7.10	0.00
UC	6.83 (100%)	0.00	0.00	0.00	0.00
PR	0.00	0.00	0.00	0.00	7.00 (38%)
UC/PR	6.83 (100%)	0.00	0.00	0.00	0.55 (3%)
MD/UC	6.83 (100%)	0.00	0.00	0.65	0.00

is able to reach the point where proportionally more of the reservoir inflow is able to be stored.

Profiles of the statewide aggregate reservoir fill condition for wastewater purification/reuse and for thermal and membrane desalination are presented in Figs. 8 and 9, respectively.

In contrast to the profiles displayed for the baseline conditions, incremental increases in water stabilizing option capacity does not increase the reservoir fill levels to a significant extent when the reservoir fill levels are already low. The profiles for implementing water reuse only show small increases in overall reservoir levels, with the 25% and 50% potential curves showing almost no increase during certain time periods. This is consistent with the notion explained previously that when the demand is high and inflow is low, most if not all of the inflow that is introduced to the reservoir must immediately be passed through to meet the demand and very little to no inflow is actually stored to increase reservoir fill levels. This is also evident for the profiles using desalination, where 10 Mm^3/d barely increases reservoir levels, but 22 Mm^3/d noticeably increases reservoir levels.

This result has potentially significant policy implications for statewide and regional water managers. All of these alternative water supply strategies are based at or near the site of consumer end-use, which is in contrast to the current paradigm of supplying a large portion of water from management of a centralized aqueduct system. The need for these alternative strategies implies that regional water managers will become more responsible for procuring adequate water supply for their corresponding region and relying less on allocations and imports from the aqueduct. Since different water utilities have more or less access to these options than others – for example, coastal utilities have access to desalination while inland utilities do not – policies and regulations must be in place to coordinate rights to allocations from these local measures to ensure satisfaction of demand in all regions.

Additionally, this result demonstrates the need for a portfolio approach toward securing water availability due to the scale of the water deficit under climate change conditions. Policies for securing water availability must be multifaceted and incentivize the eventual rollout of all of these options in the future, and optimization of technology rollout should be conducted to advise these policies.

4.3. Securing capacities — hybrid cases

Based on the behavior of individual options, a number of hybrid scenarios were constructed to secure water availability. These scenarios, as well as either the securing capacities for each individual option is presented in Table 2 for baseline conditions and in Table 3 for climate change augment conditions. If an individual option is unable to secure water availability by itself, its maximum capacity is listed. The MD (SC) case is an additional case using only membrane desalination, but instead of spatially distributing along the coast according to urban population, it is more heavily biased to have 80% of its capacity in the South Coast region (compared to 64.8% in the MD case).

Table 3
Securing or maximum capacities for individual (orange) and hybrid (blue) option cases in Mm^3/d — climate change augment conditions.

Designation	UC	TDw	TD	MD	PR
No options	0.00	0.00	0.00	0.00	0.00
TDw	0.00	3.63 (100%)	0.00	0.00	0.00
TD	0.00	0.00	34.00	0.00	0.00
MD	0.00	0.00	0.00	34.00	0.00
MD (SC)	0.00	0.00	0.00	30.50	0.00
UC	9.50 (100%)	0.00	0.00	0.00	0.00
PR	0.00	0.00	0.00	0.00	18.44 (100%)
UC/PR	9.50 (100%)	0.00	0.00	0.00	18.44 (100%)
MD/UC	9.50 (100%)	0.00	0.00	19.50	0.00
MD/PR	0.00	0.00	0.00	7.20	18.44 (100%)
P1	9.50 (100%)	0.00	0.00	7.40	18.44 (100%)
P2	9.50 (100%)	3.63 (100%)	0.00	5.00	18.44 (100%)

Table 4
Net reservoir fill level changes for statewide aggregate and regional reservoir groups under baseline conditions.

Designation	CA Total (%)	SC (%)	TL (%)	SJ (%)	SR (%)
No options	−33.000	−57.798	−5.461	−15.779	−23.403
TDw	−24.970	−52.809	1.623	−5.173	−13.928
TD	0.069	3.269	13.686	2.612	−6.545
MD	0.069	3.269	13.686	2.612	−6.545
MD (SC)	0.031	4.857	13.757	1.595	−7.562
UC	−1.712	−4.122	19.118	5.192	−6.588
PR	0.210	1.720	13.009	6.274	−6.924
UC/PR	0.184	−0.633	19.454	6.458	−5.645
MD/UC	0.092	−0.290	17.516	6.082	−5.739

For each individual and hybrid scenario, the effect on the California statewide fill condition, as well as on regional groups of reservoirs is presented in Table 4 for baseline conditions and in Table 5 for climate change augment conditions. The reservoirs that are included in the model are grouped according to their location by hydrologic region to give a sense of regional reservoir level changes and management capabilities. South Coast reservoirs include Pyramid Lake, Castaic Lake, and the CA Effective Lake Mead, Tulare Lake Reservoirs include Millerton Lake and Pine Flat, San Joaquin River reservoirs include San Luis, Don Pedro, New Melones, and Exchequer, while Sacramento River reservoirs include Folsom Lake, Lake Shasta, Trinity Lake, and Lake Oroville. The cases which are unable to secure water availability are highlighted in red, while those which are able to accomplish this goal are highlighted in green.

For standard conditions, the hybrid cases which secured water availability did not include a combined PR/MD case. This was unnecessary since water reuse secures water availability alone. The regional effects of both hybrid cases are only slightly different, but show the same trend of being able to stabilize all regions except the northernmost part of California. It is important to note that since historical management practices are embedded in these results, this implies that changes in water management in addition to the freeing up of water allocations assumed in this model are required to stabilize the northernmost region of California.

For climate change augment conditions, many more hybrid cases were constructed since only desalination was able to scale up to the degree required to secure water availability. Desalination, however, can have significant energy implications as will be explained in part 2, and other measures may be implemented to reduce the required capacity of desalination needed. This informed the construction of the other hybrid cases.

The UC/PR case is unable to secure water availability, despite using 100% of the urban water conservation capacity and wastewater purification/reuse capacity considered in this study. This occurs due to the fact that these two measures can be parasitic to each other to some extent. Urban water conservation reduces the wastewater effluent available from wastewater treatment plants, which reduces the amount of water available for reuse, since it is tied to the water demand. Therefore, not all of the purification/reuse potential capacity can be effectively utilized under aggressive urban water conservation. The conserved water compensates for this reduced purification/reuse capacity, however, but the total effect on reservoir fill levels is no better than the case where 100% of the purification/reuse capacity is effectively utilized (PR). On a regional level, the PR and UC/PR cases differ due to the spatial distribution of each measure.

All of the other hybrid cases, therefore, include some amount of desalination. This highlights the role of desalination in securing the water supply for this region under worst case climate change augment conditions. The P1 and P2 cases make extensive use of conservation and purification/reuse, complemented between 7.4 and 8.6 Mm^3/d of desalination, depending on the desalination type. Regionally, most of these cases stabilize or nearly stabilize all of California with the exception of the northernmost Sacramento River region, which is drastically hit by reductions in inflow due to climate change.

A final important aspect to note is the sensitivity to the spatial distribution of installing a given capacity of an option. In both baseline and climate change augment conditions, the MD (SC) case is able to secure water availability with a lower installed desalination capacity compared to the MD case. This further demonstrates the importance of installing technologies in points of leverage on a water system for maximum effectiveness. In this case, southern California is the major point of leverage since changes in its demand can affect every reservoir in the state.

4.4. Implications for reducing groundwater demand

In this model, water allocations are freed up for recharging groundwater when the demand on a given reservoir is reduced below its minimum demand due to the implementation of water supply stabilizing options. It is important to remember, however, that the priority of freeing up water allocations goes to stabilizing surface reservoir levels in this study. In practice, freed allocations may be shared between replenishing groundwater and stabilizing surface reservoir levels. The total water allocation available for societal use, however, would not change. The changes in groundwater demands due to these allocations for each case are presented in Fig. 10 for baseline conditions and in Fig. 11 for climate change augment conditions.

All of the cases that have allocations freed up for groundwater recharge or reducing groundwater demand include some form of desalination. Given the operating behavior for each measure used in this study, this occurs since the steady-state nature of desalination plants allows the production of water during periods when the water demand is low. This allows more water allocations to be freed up for groundwater recharge, and is in contrast to the other measures which follow the temporal trends of the water demand and do not further reduce reservoir demand when it is already small. This occurs in both standard and climate change augment conditions.

Under baseline conditions, the cases are able to reduce the statewide groundwater demand by up to 6.3% with the pure desalination cases. The case where desalination plants are biased toward southern California reduces groundwater demand by 5.1%, since a lower total capacity is installed. Thermal desalination with waste heat reduces the groundwater demand by 1.95%, mostly concentrated in northern California.

Under climate change augment conditions, a similar pattern emerges but at a larger scale. Due to the significantly larger capacities of steady-state desalination required to secure water availability, significant amounts of water are produced during low demand periods. This allows a large amount of water allocations to be freed up for

Table 5
Net reservoir fill level changes for statewide aggregate and regional reservoir groups under climate change augment conditions.

Designation	CA Total (%)	SC	TL	SJ	SR
No options	-59.819	-64.787	-34.556	-58.360	-59.203
TDw	-57.982	-64.343	-33.159	-56.150	-56.176
TD	0.570	10.862	12.008	-4.162	-8.009
MD	0.570	10.862	12.008	-4.162	-8.009
MD (SC)	0.119	13.809	19.656	-8.363	-10.434
UC	-54.725	-62.662	-28.345	-53.494	-51.179
PR	-36.364	-52.950	-20.949	-13.829	-36.738
UC/PR	-36.535	-59.233	7.695	-14.733	-34.201
MD/UC	0.390	5.965	21.750	-1.624	-6.617
MD/PR	0.062	5.404	19.713	2.294	-9.258
P1	0.059	2.188	25.301	2.313	-6.843
P2	0.046	-2.104	24.930	4.971	-4.330

groundwater recharge. The pure desalination cases reduce up to 37% of current groundwater demand, with the hybrid cases exhibiting reductions between 6.3% and 19% depending on technology mix.

These results have positive implications for potentially reducing groundwater overdraft in this region, which has become a concern over recent years. To achieve these benefits in the practical setting, however, strong coordination of water management between centralized and local water authorities must be present.

5. Discussion

When evaluating options to secure water availability and the water supply as a whole, the advantages and disadvantages of each option on a wide range of criteria must be evaluated. This is important for understanding the role that different options are best suited to fulfill as part of a portfolio for securing the water supply. Some of these characteristics have been quantitatively evaluated in this study for this system: water saving potential, spatial distribution, and potential for groundwater recharge. Other quantitative criteria such as energy consumption, greenhouse gases, and implications for the renewable portfolio standards will be evaluated in part 2 of the study.

There are many other characteristics of each option, however, that shape its potential role as part of the water supply stabilizing option portfolio. Many of these options may be difficult to quantify because they are based in a more practical nature such as implementation advantages or challenges and handling of reject products such as brine. These considerations are discussed for each option here. In California, wastewater treatment plants must apply for a permit and be approved to discharge effluent into the local environment. The implementation of water reuse can alleviate this burden by reducing discharge levels and redirecting effluent for additional treatment. Full scale implementation of reuse could potentially exempt wastewater treatment plants from the requirement of obtaining a discharge permit and from paying the associated costs. Additionally, in 1980, the EPA identified drinking water treatment plants impacted by upstream wastewater treatment plant discharges, and found the top 25 most impacted plants contained between 2% and 16% wastewater discharges from upstream locations under average stream flow conditions. Any increase in planned water reuse implementation potentially decreases the volume of treated wastewater discharge into water bodies and consequently abates the aforementioned negative impacts. Finally, reductions in the energy needed to transport water from other areas can be realized since water reuse is implemented in the local context. This is described in more detail in part 2.

Water reuse projects, however, face serious challenges regarding the public perception and concern for the trace hormones, pharmaceuticals, and human viruses in treated wastewater, the elimination of these contaminants from reused water, and the removal efficiency of the remaining contaminants by conventional and advanced drinking water treatment processes (Snyder, 2008). Additionally, N-nitrosodimethylamine (NDMA), which has been classified as a human carcinogen by the US Environmental Protection Agency (N-Nitrosodimethylamine (CASRN 62-75-9) Integrated Risk Information System (IRIS), 1993) is another emerging concern in water reuse implementation, specifically with potable purposes. This compound is detected in the secondary wastewater treatment and throughout the advanced purification treatments (e.g. MF and RO) and necessitates employing an expensive advanced oxidation process (e.g. UV irradiation) in combination with RO treatment to reliably maintain the residual NDMA below the acceptable level in reused water production (Plumlee et al., 2008).

Desalination of seawater extracts freshwater from seawater and leaves a stream of highly concentrated reject brine. Seawater typically has a salinity of about 36 ppt, causing reject brine TDS (total dissolved solids) levels to be about 60–85 ppt. Plants that use chemicals such as coagulants, anti-scalants, polymers, or disinfectants for desalination pretreatment could see these chemicals in the effluent brine (Voutchkov, 2011). Currently, the predominant method for disposing seawater desalination plant reject brine is to discharge the effluent back into the ocean. This practice can affect ecosystems by stratifying the water body, creating a briny bottom layer that can impact benthic communities (Riera et al., 2012). Additionally, chemical products found in desalination brine have the potential to cause adverse impacts

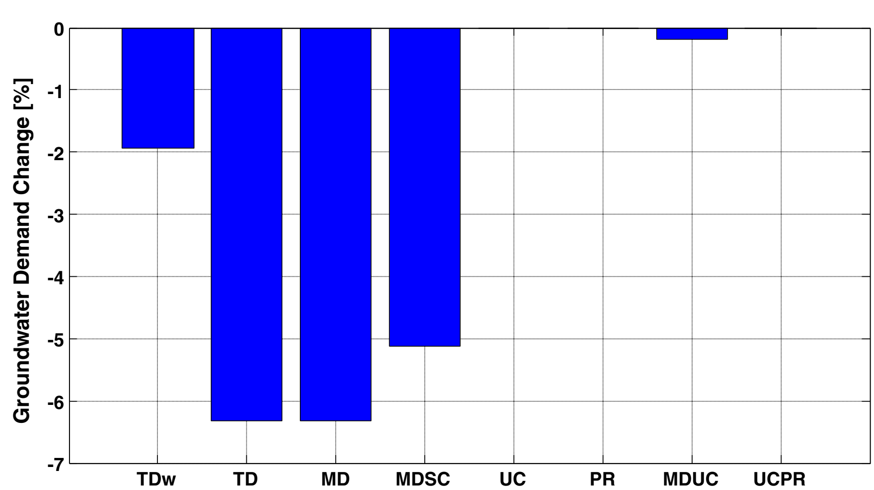

Fig. 10. Change in groundwater demand for baseline condition cases.

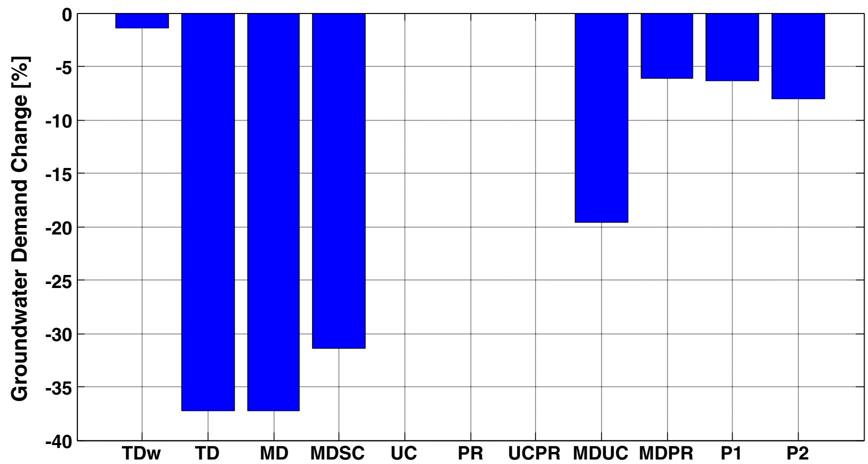

Fig. 11. Change in groundwater demand for climate change augment condition cases.

on local communities. Recent ecological monitoring has found variable effects ranging from no impact to widespread sea grass, coral reef and other ecosystem alterations (Roberts et al., 2010). These effects are particularly noticeable in poorly mixed areas.

To prevent the negative ecological impact to the environment, California requires implementation of safe practices, such as appropriate discharge site selection, blending with another source of low salinity water (i.e. sewage effluent) and installation of efficient diffusors at the end of discharge pipes to improve the mixing rate. New diffuser technologies are being further explored for reducing the impact of saline brine on coastal areas. Many novel methods have also been developed to aid in extracting the valuable salts and metals from desalination reject brine. For example, Ma et al. (2012) reports application of solid inorganic adsorbents to extract lithium chlorides. Membrane distillation–crystallization technology was utilized to recover sodium chloride crystals from reverse osmosis reject brine (Ji et al., 2010; Melián-Martel et al., 2011). Desalination brine was also proposed in the application of CO_2 sequestration by conversion of calcium and magnesium ions into dolomite and magnesium biocarbonate while reducing TDS from discharging water (El-Naas et al., 2010; Wang et al., 2011). With a well-managed system, options are available to minimize the negative impact of desalination brine discharge to the coastal region.

While water conservation practices are beneficial, innovations to conserve water face many implementation challenges. For example, demand-side approaches may burden economically-disadvantaged groups by ignoring their ability to pay for water, or forcing them to install high-cost, lower-water using appliances. Residential metering may generate opposition due to fear that meters will not be accurately read and that residents will be charged for excess water usage (Post, 2009). Moreover, different jurisdictions may have conflicting goals toward metering — California experience is exemplary. Since 2004, state law mandates that new dwellings have meters and that utilities bill at metered rates. Before the law's passage, discretion for reading meters was left to local communities that, in some regions, opposed meters (Hanak et al., 2009, 2011).

Increasing bloc rate (IBR) pricing, an economic mechanism to encourage conservation, where customers are charged more per unit of water used once their volume of use exceeds an average-derived use level (i.e., a "conservation base"), also faces challenges. IBR may not account for ability to pay, especially for those on fixed incomes who, for health reasons, use more water. Equity issues have arisen where IBR rates have been adopted or under consideration — recently in communities in Orange and Los Angeles counties. Customer concerns include: how individual household budgets eligible for "conservation" rates are calculated; skepticism regarding whether increased rates are revenue neutral; whether customers are rewarded for efforts to conserve; the failure of water boards to communicate details of their proposed rate structures — including charges they must pay to the MWD because of losses of imported water from the Delta and elsewhere; and, elected officials' frustration over the cost of enforcing conservation efforts and the lack of funds for appliance retrofits given tight budgets (Brennan, 2009; Webb, 2011). Additionally, as income grows, so do *outdoor and indoor* demands. This tends to be true in regions that do not employ IBR but use uniform rates that charge the same amount per unit of water (Hanak et al., 2009; Brennan, 2009). Finally, some communities forbid measures that conserve water through, for example, removing lawns and replacing them with water-saving landscaping due to aesthetic reasons.

Innovations to better manage freshwater resources and respond to shortages — including use of reclaimed wastewater, stormwater reclamation and desalination face numerous public acceptance challenges. Public support for water reuse, for example, is higher for uses such as landscape irrigation or car washing that minimizes human contact (Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater, 2012). Public acceptance is also a challenge for utilities contemplating water reuse and for firms to incorporate it in their production processes. In certain areas such as Toowoomba, Queensland in Australia, and in Los Angeles, California in the United States, anti-wastewater reuse campaigns which have exploited public apprehension over application of recycled wastewater for potable needs have posed difficulties for public acceptance. These campaigns can be overcome, however, if early, effective interventions are taken. For example, in Orange County, California in the United States, awareness of the anti-wastewater reuse campaigns prompted the development of dedicated public outreach efforts. First, district officials tailored public talks to the needs, interests, and concerns of various community groups. They emphasized the details of system operations, safety, and benefits. Secondly, there were numerous publications disseminated, including a brochure and website produced, and a public television documentary that reinforced positive images of the project, and the district worked closely with producers of these projects to ensure a consistent message was articulated and disseminated. Third, the project attracted federal, state, local grants — which permitted it to open on-time, and within budget (a related selling point was that the project was less expensive that other alternatives considered, including desalination). The result was the acceptance of the installation of the large wastewater reuse system in the district. Decision-makers must demonstrate why these innovations are to avert water shortages and that these water-saving schemes are safe. In addition, concerted efforts must focus on properly maintaining water infrastructure, especially when it pertains to water reuse; on allowing stakeholders to monitor the uses and operations of wastewater recycling; and on vigilantly ensuring the protection of public and environmental health (Dolnicar and Hurlimann, 2009). Finally, open and transparent decision-making processes in which individuals and groups affected by water decisions can equally participate, and where no important constituency (including "victims" of water crises such as women and the frail) is excluded, are required (Shonkoff et al., 2009) to gain public support for alternative water supply stabilization options.

The authors acknowledge that climate models are subject to uncertainties due to model physics, initial and boundary conditions, and model parameters (Wehner, 2013; Brekke and Barsugli, 2013; Feddema et al., 2005; Mehran et al., 2014; Sillmann et al., 2013; Pascale et al., 2014; Cayan et al., 2008; Brekke et al., 2008). Particularly, uncertainties of simulated climatic extremes are substantial (AghaKouchak et al., 2013; Zengchao et al., 2013). Uncertainties in climate models can affect simulation results. For this reason, the focus of this paper is on a modeling framework for assessing water–electricity nexus as opposed to providing future management solutions based on climate model simulations. Today's individual climate models cannot be used for projection of daily or annual conditions in specific times in the future. Instead, they should be used to assess system's behavior/response under prescribed climate scenarios.

6. Conclusions

This study evaluated the effectiveness of different water supply options for securing water availability in California, under historical and climate-change augmented inflow and demand conditions. The primary conclusions of the study are as follows.

1. Under baseline conditions, many of the available options are able to secure or nearly secure water availability in isolation. The only exception is thermal desalination with waste heat, which is limited due to the finite amount of waste heat present in coastal power plants in the state.
2. Under climate change augment conditions, including changes in inflow and increases in demand, a portfolio approach of measures will be required to secure water availability. The only option which could theoretically scale up to secure water availability is thermal desalination with natural gas and membrane desalination. Relying on these measures alone, however, requires extreme installed capacities which can have significant energy implications as well as brine management issues and ecological effects. Therefore, other measures may be implemented to reduce the amount of desalination required. Energy issues will be explored in part 2 of the study.
3. Deploying both water reuse along with conservation is not additive in terms of securing availability, since conservation may reduce the potential capacity for water reuse. Under worst-case scenario climate change augment conditions, urban water conservation and water purification/reuse are insufficient to secure water availability. Conservation, as will be described in part 2, is a very important option for energy considerations, however.
4. The steady-state nature of desalination plants allows a large potential for reducing groundwater demand. By producing water even during low demand periods combined with coordinated and adaptive management of water allocations, allows a large amount of water to be freed up for groundwater recharge or reducing groundwater demand. This is exacerbated with larger desalination capacities.
5. Coordinated management practices and policies are required to most effectively stabilize the water supply. Coordination between central and local water authorities are required to both regionally secure water availability and take advantage of groundwater demand reduction potential. Changes in water management practices may be required as a part of these policies.
6. Finding points of leverage in the system are important for maximizing the reservoir fill benefit of deploying a given option. The impact of deploying a water supply stabilization option does not just depend on the capacity of that option, but where in the reservoir network system it is deployed. In this study for example, biasing the distribution of membrane desalination toward the southern coastal regions more so than that dictated by the urban population distribution required less total desalination capacity to secure water availability. This occurred since the South Coast and Colorado River regions are at the ends of the reservoir chain, therefore direct supply into these regions increased reservoir fill levels not only for reservoirs in the immediate area, but all of the reservoirs ahead in the chain that supply those reservoirs. These types of points must be identified in every system to maximize the increase in water availability for deploying a given capacity of a water supply measure.

This study focused on the examining the details of different options for contributing to secure water availability. The main outcome of this part of the study, however, is to achieve a sense of scale for the capacities of available technologies needed to secure water availability, such that a more accurate sense of energy implications can be examined. This is the focus of part 2 of the study, which will be presented in a following paper.

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