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Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir management

A.P. Georgakakos[a,*], H. Yao[a], M. Kistenmacher[a], K.P. Georgakakos[b,c], N.E. Graham[b,c], F.-Y. Cheng[b,d], C. Spencer[b], E. Shamir[b]

[a] Georgia Water Resources Institute and School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA
[b] Hydrologic Research Center, 12555 High Bluff Drive, Ste. 255, San Diego, CA 92130, USA
[c] Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093, USA
[d] Dept. of Atmospheric Sciences, National Central University, No. 300, Zhongda Road, Zhongli City, Taoyuan County 320, Taiwan

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SUMMARY

This article aims to assess the value of adaptive reservoir management versus traditional operation practices in the context of climatic change for Northern California. The assessment uses *adaptive* decision model being developed for planning and operational management of the Northern California (central valley) water resources system (HRC-GWRI, 2007), coupled with a dynamic downscaling and hydrologic modeling system described in Georgakakos et al. (this issue). The assessment process compares the water system response in four simulated scenarios, pertaining to two management policies (traditional and adaptive) and two hydrologic data sets (one for the historical and a second for a future scenario). The assessments show that the current policy, which is tuned to the historical hydrologic regime, is unable to cope effectively with the more variable future climate. As a result, the water supply, energy, and environmental water uses cannot be effectively satisfied during future droughts, exposing the system to higher vulnerabilities and risks. By contrast, the adaptive policy maintains similar performance under both hydrologic scenarios, suggesting that adaptive management constitutes an effective mitigation measure to climate change.

1. Introduction

Most reservoir and river systems are traditionally managed through heuristic regulation policies derived based on historical system response experience. In the US, this practice has become institutionalized in the form of operation plans (prescribed in regulation manuals) which are followed routinely by the US Army Corps of Engineers (USACE), the US Bureau of Reclamation (USBR), and other management agencies. Reservoir and river systems comprise a critical infrastructure of the regional US economy and, given their many users, benefits, risks, and liabilities, their operation plans and policies were historically established through tedious legal proceedings.

However, to protect against potential liabilities, legal proceedings seek to anticipate all potential critical and conflicting outcomes and set forth specific corrective actions to address them. Such outcomes are derived from historical conditions (of inputs and demands), and, as a result, traditional operation plans comprise policies that tend to micromanage the historical stresses they seek to restore. Commonly, they classify drought and wet conditions into a few discrete categories (using aggregate indicators) and determine reservoir releases and/or storage levels that in the past would have helped the system respond satisfactorily. Once these categories and policies are fixed, system operation is as simple as following the pages of a manual, eliminating legal liabilities but also the flexibility to alter the operation in response to unanticipated circumstances. Unfortunately, unanticipated circumstances arise often because reservoir and river systems evolve in complex ways (on account of supply as well as demand), and a few aggregate categories cannot capture the full range of best management policies.

A second unintended consequence of the way reservoir operation plans and policies have historically evolved is that it discourages the use of key science advances related to hydro-climatic forecasting, multi-reservoir optimization, uncertainty characterization, and integrated water resources management. True adaptive water resources management relies critically on such methods because they provide a formal and consistent framework to distill the value of newly acquired information and tune system operations to the variable and changing physical and socio-economic circumstances. However, the value of adaptive management cannot be realized if the operation policies are rigid, prescribing, as

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* Corresponding author. Address: School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA. Tel.: +1 404 894 2240; fax: +1 404 385 1131.
E-mail address: Aris.Georgakakos@ce.gatech.edu (A.P. Georgakakos).

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they often do, the quantities and timing of water stored and released regardless of new information.

In the past, an argument in support of traditional management policies was that they are low risk, because managers "know where they stand on." However, studies have shown that the risk of ignoring useful and decision-worthy information, including input and other uncertainties, leads to more frequent and costly failures (Georgakakos et al., 1998; Yao and Georgakakos, 2001). Presently, most water resources professionals appreciate the value of adaptive management but also acknowledge that management processes are legally and institutionally vested in traditional procedures and are change resistant.

Adaptive management is compatible with legal and institutional processes underlying the development of operation plans and guidelines, if only these processes concerned themselves with establishing the *framework, broad objectives, and criteria* for shared water management and not with laying down policy specifics. This would not only encourage the use of adaptive management and new science advances but also the meaningful participation of informed stakeholders, deliberating on shared and balanced operation policies relevant to current conditions.

This article aims to assess the value of adaptive management versus traditional practices in the context of climatic change and to demonstrate that the latter are ill-prepared to handle a more variable and potentially changing climate. It also advocates that adaptive management is an effective mitigation approach and should become the technical foundation of reliable, well informed, and science driven management processes and policies.

2. Climate change assessment studies for Northern California

Relevant previous studies assessing the sensitivity of Northern California water resources include VanRheenen et al. (2004), Tanaka et al. (2006), Medellin-Azuara et al. (2008), and Vicuna et al. (2009).

VanRheenen et al., 2004, employed three PCM (Parallel Climate Model) climate scenarios, a statistical downscaling procedure, the Variable Infiltration Capacity (VIC; Liang et al., 1996) hydrologic model, and a simulation model of the California Central Valley water resources system (CVmod). CVmod simulates the monthly response of the major federal and state storage projects including the Bay Delta, and determines reservoir releases based on perfect (deterministic) foresight of all future inflows and current or modified operating rules.

The study concludes that 21st century runoff is expected to decline relative to historical runoff, especially in the southern subbasin (San Joaquin River valley). Shifts in seasonal hydrology, though expected due to earlier snow melt, are not clearly discernible. Future hydrology is expected to be drier than historical hydrology, leading to increased percentage of critically dry water years from 18% in the control scenario to 40% in the last third of the 21st century; 5–13% lower reservoir storages; 4–11% hydropower generation reduction; and a 10% decrease in system reliability relative to fishery requirements. Assessments were also carried out with modified reservoir operation rules (as a potential mitigation measure), but these modifications were unable to offset the negative hydrologic alteration impacts. The general conclusion is that climate change would impair the system to an extent that changes in system operation (of the type considered) could not restore past performance levels.

Tanaka et al. (2006), continuing work initiated by Lund et al. (2003), consider two GCM warming scenarios, one dry (PCM) and a second very wet (Hadley Centre Climate Model 2—HADCM2), intending to bracket the extremes of climate change. The study does not include formal downscaling procedures, but uses GCM results and historical inflow permutations to generate future hydrologic inflows. CALVIN, a water resources economic model (Draper et al., 2003), is employed to simulate and optimize the response of the entire California water system to future hydrologic and demand scenarios. The simulation–optimization process uses a monthly resolution; assumes perfect knowledge of hydrologic inputs (surface and groundwater), projected population levels, and water demands (Landis and Reilly, 2002); and seeks to minimize system-wide water scarcity and operational costs. The integrated system representation is by necessity approximate, and some water uses are not explicitly modeled (e.g., the Delta environmental conditions, fisheries, recreation, flooding, operational facility constraints, adaptive management policy features, and possible interactions between population growth and climatic change). The study goal is to assess California's adaptation capacity to long term changes in climate, population, and land use change. Among the considered adaptation measures are surface reservoirs; groundwater recharge and banking; water conveyance infrastructure; wastewater reuse; desalination; water rights and pricing; and water conservation and efficiency improvements.

Compared to historical conditions, the dry climate scenario results in 37% lower water deliveries (in the central valley); more extensive use of groundwater; increased water conservation, wastewater reuse, and desalination; 30% hydropower reduction; significant water delivery shifts from agricultural to urban users (in southern California); and 15% reduction of irrigated land. The adaptation cost is 50% higher than the baseline, with conveyance infrastructure expansion measures having the highest adaptation value. Notwithstanding flooding consequences (not modeled), the wet climate scenario impacts are generally positive relative to the historical baseline. The study concludes that California can adapt to severe population growth and climatic change, albeit at a significant economic cost, more intense utilization of groundwater resources, and potentially serious impacts on agriculture and the environment. It also suggests that complex systems with highly interconnected physical and economic infrastructure can more effectively cope with concomitant climatic and population changes.

In a follow-up article, Medellin-Azuara et al. (2008), re-assess the California water resources and economic impacts using a dry-warm (A2 emissions) scenario from the Geophysical Fluid Dynamics Laboratory GCM and the same methods as Tanaka et al. (2006). For a 30-year period centered around 2085, this scenario leads to a 27% reduction in annual streamflow and a more discernible hydrologic shift of higher flows earlier in the spring. The assessment shows that total water scarcity is expected to reach 15%, with 9% due to demand and population growth and 6% to climate change. Agriculture is the most severely impacted sector with 22% average scarcity statewide, increasing from north to south. Significant adverse impacts are also reported for hydropower, environmental flows, and reservoir levels. The article includes an interesting analysis of heuristic reservoir operation policies suggesting that system performance improves when such policies (that depend on prespecified storage levels and specific water year classification categories) are properly modified for each climate scenario.

Vicuna et al. (2009), carry out an assessment for two high elevation hydropower systems located in sub-basins of the Upper American and San Joaquin Rivers. They use 12 GCM scenarios, six of the B1 type and six of the A2. The scenarios are downscaled using the Bias Correction and Spatial Downscaling (BCSD; Wood et al., 2004) approach and subsequently used as input to the VIC hydrologic model to develop reservoir inflows. The hydropower system is represented using a daily simulation and a sequential optimization model which determines hydro-generation (or turbine release) based on (a) an objective function that balances energy prices and system storage and (b) simulated inflow forecast information. The authors find that by the late 21st century, the American and San Joaquin subsystems respectively exhibit the following *average* changes relative to the historical climate (control run): seasonal shift of inflow hydrograph earlier in the year by 2 and 1 months; annual inflow reduction of 10% and 18%; wet season high inflow (90th percentile) increase of 24% and 71%; energy generation loss of 12% and 10%; revenue loss of 9% and 8%; and annual spills increase of 11% and 22%. The ranges for the above quantities are large, varying between 40% and 120% of the average values. These authors also conclude that reservoir operation rules must be modified to mitigate the impacts of the potential flow alterations.

The previous studies reach important and alarming conclusions regarding California's water future and collectively show that the system response to future climates exhibit large uncertainties. Most of the previous studies also agree that the current management policies may not serve the state in the future as well as they did in the past. This conclusion was derived indirectly by tuning the management policy parameters to a particular climate scenario and comparing the results with the baseline.

The study described herein takes a more direct and quantitative approach to assessing the value of adaptive management versus traditional practices under a variable and changing climate. The assessment entails the use of a formal *adaptive* decision model being developed for planning and operational management of the Northern California (central valley) water resources system (HRC-GWRI, 2007). This decision model is coupled with the dynamic downscaling and hydrologic modeling system described in Georgakakos et al. (this issue).

3. System description and decision support tools

3.1. The Northern California water and power system (NCWPS)

The reservoir and river network is schematically illustrated in Fig. 1 and consists of six subsystems:

- Trinity River system including Clair Engle Lake, Trinity Power Plant, Lewiston Lake, Lewiston Plant, JF Carr Plant, Whiskeytown, Clear Creek, and Spring Creek Plant.
- Shasta Lake system including Shasta Lake, Shasta Power Plant, Keswick Lake, Keswick Plant, and the river reach from Keswick to Wilkins.
- Feather River system including Oroville Lake, Oroville plants, Thermalito diversion pond, Yuba River, and Bear River. The inflows from Yuba and Bear are not modeled separately in the simulation model. The flow contributions to the Delta from both rivers are lumped into an aggregated quantity called Sacramento Accretion.
- American River system including Folsom Lake, Folsom Plant, Natoma Lake, Nimbus Plant, Natoma Plant, and Natoma diversions.
- San Joaquin system including the New Melones Lake, New Melones Power Plant, Tulloch Lake, Demands from Goodwin, and the inflows from the main San Joaquin River.
- Bay Delta which is a key integrating element receiving inflows from Sacramento, San Joaquin, and several local streams. In addition to being a very rich biodiversity area, the Delta also supplies fresh water to other California regions.

The Oroville–Thermalito complex comprises the State Water Project (SWP), while the rest of the system facilities are federal and comprise the Central Valley Project (CVP). The Northern California River and Reservoir system provides two-thirds of the state's drinking water, irrigates 7 million acres of the world's most productive farmland, and is home to hundreds of species of fish, birds, and plants. In addition, the system protects Sacramento and other major cities from flood disasters and contributes significantly to the production of hydroelectric energy. The Sacramento-San Joaquin Delta provides a unique environment and is California's most important fishery habitat. Water from the Delta is pumped and transported through canals and aqueducts south and west and supports a multitude of vital water uses.

An agreement between the US Department of the Interior, Bureau of Reclamation, and the California Department of Water Resources (1986) provides for the coordinated operation of the SWP and CVP facilities (Agreement of Coordinated Operation—COA). The agreement aims to ensure that each project obtains its share of water from the Delta and protects other beneficial uses in the Delta and the Sacramento Valley. The coordination is structured around the necessity to meet the in-basin use requirements in the Sacramento Valley and the Delta, including Delta outflow and water quality requirements. Under normal hydrological conditions, the inflows from the Sacramento River, San Joaquin River, and the local stream flows can meet the needs of Delta demands and the water export. However, during dry water years, extra water has to be released from the upper major reservoirs to meet the demands. The COA specifies the manner in which the required extra water is shared by the large reservoirs in the Sacramento River basin (Clair Engle Lake [Trinity], Shasta, Oroville, and Folsom).

3.2. Overview of decision support tools used for planning

Several decision support tools exist and used to varying degrees by federal and state management agencies. Such tools include simple spreadsheet models as well as detailed simulation and dynamic optimization models.

3.2.1. DWRPS model

The California Department of Water Resources (DWR) Planning Simulation (DWRPS) model (DWR, 1999) is the basis for several existing models.

The DWRPS model represents the six NCWPS sub-systems described above and simulates their operation in monthly time steps. The network is represented by eight major reservoirs, eight large hydropower plants housing 28 turbines, 14 river nodes with tributary inflows, 30 water supply nodes, and three river nodes with anadromous fish flow requirements. The simulation begins with the specification of a trace of upcoming inflows. The inflow forecast trace is used to specify the water year type, a key indicator for determining the water demand targets (also referred to as water deliveries). The specification of the water year type is described in the DWR website as well as in HRC-GWRI, 2010 (Appendix C). The water year type may fall into one of five categories: critical, dry, normal, above normal, and wet. Depending on the category, the actual demand targets are obtained by multiplying the base demand targets (model input) by an adjustment coefficient. The coefficients are 0.5, 0.8, 1, 1.2, and 1.5, respectively, for the critical, dry, normal, above normal, and wet water year categories. As in current practice, the water demand targets in the DWRPS model are updated twice a year, first in February and also in October.

The DWRPS model objectives are to (i) meet water delivery targets and minimum required flows at various river network locations, (ii) meet the environmental and ecological Delta requirements associated with the X2 location and Delta outflow, (iii) generate as much energy as possible, and (iv) maintain high reservoir levels and sufficient carry-over storage. The maximum X2 location target is 80 km from the Golden Gate Bridge.

Assuming that no extra release is required to meet the Delta demands and water deliveries to southern California, reservoir releases are determined to meet local requirements such as minimum flows (supporting environmental and water supply requirements) and target storage levels. If reservoir releases, along with the contributions of Delta local streams, can meet the Delta requirements, then the initial assumption is valid and no extra

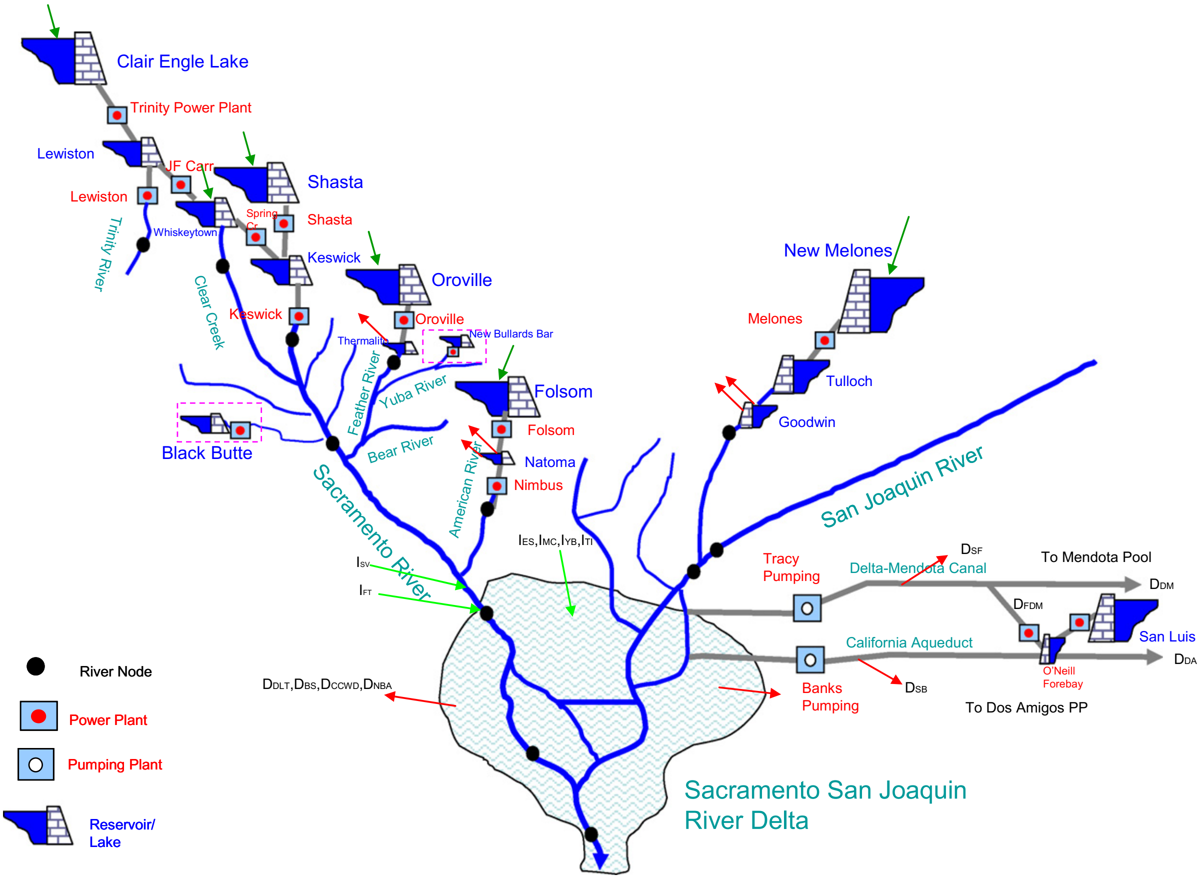

Fig. 1. Northern California reservoir system.

release is required. In this case, the model simulates the system response using the actual historical inflows for the current month, and the simulation process advances one month forward.

Otherwise, if the X2 requirement or the southern California water delivery targets are not met, extra water is released from the upstream reservoirs. The extra release is shared among the four major reservoirs based on the Coordinated Operations Agreement (COA) rule. With respect to intra-basin deficits, COA mandates that they be met 25% by Oroville (the state-owned reservoir also known as the State Water Project—SWP) and 75% by Trinity, Shasta, and Folsom (the federal reservoirs comprising the Central Valley Project—CVP). With respect to southern California exports and the storage of excess water, COA mandates that they be shared 45% and 55% respectively by SWP and CVP. In very dry years when storage is insufficient to meet all demand targets, the first priority is assigned to X2 (environmental and ecological requirements), and the remaining water is used to meet the water delivery targets as much as possible.

This process is repeated for every month until the end of the simulation horizon. For each month, the simulation model records reservoir storage levels, releases, water deliveries, target deficits, energy generation, and all other quantities of interest, 271 in all, of which 68 pertain to the Bay Delta. The complete mathematical formulation of the DWRPS model can be found in HRC-GWRI (2010) (Appendix E).

The DWRPS model is the basis for a simpler spreadsheet-type model used by the US Bureau of Reclamation (Washburn (USBR), personal communication, 2005), as well as a more detailed hybrid simulation–optimization model named CalSim (Draper et al., 2004), presently in its third version.

3.2.2. CALSIM and CalLite models

CALSIM (Draper et al., 2004) was developed jointly by DWR and USBR. The model operates on a monthly time step, simulates the operations of the SWP and CVP facilities with great spatial detail, and uses a long deterministic inflow time series spanning several decades. Though it is a simulation model, CALSIM is actually driven by a linear programming solver. Its objective function is a weighted sum of various objectives specified to mimic real-life water allocation priorities. Constraints are imposed to reflect physical capacity limits and also impose other requirements, such as water quality and minimum flow standards. Though primarily used in long term planning studies, short and mid-range operations can also be analyzed by performing short duration simulations that use the latest reservoir storages as initial conditions.

CalLite (Islam et al., 2011) is also a joint DWR and USBR product. It is a screening model designed to be accessible to policy makers without requiring extensive technical training and expertise in water resources modeling. CalLite uses the GoldSim (GoldSim, 2007) system dynamics software to solve a set of algebraic equations representing the system water balance, constraints, and objectives. The model covers the same geographic area as CALSIM and also uses a deterministic inflow time series with a monthly time step. CalLite models the SWP and CVP facilities at considerably less spatial detail than CALSIM, but it employs CALSIM-derived time series to represent smaller facilities, inflows, and withdrawals not explicitly modeled. It includes several pre-specified scenarios that represent baseline conditions, as well as scenarios that evaluate possible changes in the system infrastructure, water demands, and climate. Even though CalLite offers less flexibility in allowing the user to create new and customized scenarios, its user friendliness and computational efficiency make it attractive for interactive stakeholder deliberations.

3.2.3. CALVIN model

The California Value Integrated Network (CALVIN) model is a water resources economic optimization model whose overall objective is to minimize total water scarcity and operation costs in California's interconnected water system (Draper et al., 2003). The water system comprises of 51 reservoirs, 28 groundwater basins (corresponding to entire aquifers or parts of aquifers), and 54 economically represented urban and agricultural demand areas, along with over 1250 links representing the State's natural and built conveyance system.

CALVIN software is based on an optimization solver for water resources systems called HEC-PRM (Hydrologic Engineering Center-Prescriptive Reservoir Model), a network flow optimization computer code developed by the US Army Corps of Engineers.

CALVIN allocates water optimally among the different competing water uses on a monthly time step. Scarcity occurs whenever the user's target demand is not fulfilled and scarcity cost is estimated from the integral between target and delivery water amounts below a water value (demand) curve. The basic economic idea behind the model is to assign an economic cost to water scarcity for each agricultural or urban demand node in a region. Each demand node has a water delivery target, and the total cost is computed as the cumulative piece-wise linear costs for deliveries less than this target.

The model requires several datasets including, planted acres, factor usage (i.e., land, water, labor, and agricultural supplies), market price of products and production factors. Model input data include, among others, surface and groundwater hydrology, water facilities capacities and operational costs, urban water use, agricultural water use, and environmental flow constraints. Major model outputs include water allocations and delivery reliabilities; willingness to pay for water (i.e., the economic value of delivering the next additional unit of water); conjunctive water use operations; and overall economic benefits of efficient system operations.

CALVIN's strength lies in its ability to explicitly integrate operations of surface and groundwater supplies and water reuse with water use efficiency activities, including pricing and water markets (Medellin-Azuara et al., 2007). Model assessments go beyond traditional cost-benefit analysis by using the economic value of water for different users and supply costs to develop economically viable combinations of water management strategies from a broad array of options including system re-operation, conjunctive use, water reuse and desalination, water markets, and reductions in water use (Newlin et al., 2002).

As a deterministic optimization model, however, CALVIN's main inherent limitation is the assumption of perfect hydrological foresight (Howitt, 1999) and static management policies and demand targets. The model minimizes total water scarcity and operation costs based on perfect knowledge of the hydrology for the entire modeling period. This approach does not address hydrological and economic uncertainty which could have significant ramifications for sustainable water resources management and use. There is also need to incorporate more comprehensive valuation of water uses other than agricultural and urban, including hydropower generation, recreation, flood control, fisheries, and water for environmental and ecological sustainability.

3.2.4. INFORM DSS

The INFORM Decision Support System (DSS) modeling framework is illustrated in Fig. 2 (HRC-GWRI, 2007). The DSS includes multiple modeling layers designed to support decisions pertaining to various temporal scales and objectives. The three modeling layers shown in the figure include (1) turbine load dispatching (which models each turbine and hydraulic outlet and has hourly resolution and a horizon of one day), (2) short/mid range reservoir control (which has an hourly resolution and a horizon of one month), and (3) long range reservoir control (which has a monthly resolution and a horizon of one year). The INFORM DSS also includes an assessment model which replicates the system response under various inflow scenarios, system configurations, and policy options.

The INFORM DSS is designed to operate sequentially. In a typical application, the long range control model is activated first to consider long range issues such as whether water conservation strategies are appropriate for the upcoming year in the face of climate and hydrologic forecasts. As part of these considerations, the DSS quantifies several tradeoffs of possible interest to the management agencies and system stakeholders. These include, among others, relative water allocations to water users throughout the system (including ecosystem demands), reservoir coordination strategies and target levels, water quality constraints, and energy generation targets. This information is provided to the forum of management agencies to use it as part of their planning decision process together with other information. After completing these deliberations, key decisions are made on monthly releases, energy generation, and reservoir coordination strategies.

The short/mid range control model is activated next to consider system operation at finer time scales. The objectives addressed here are more operational (than planning) and include flood management, water supply, and power plant scheduling. This model uses hydrologic forecasts with a 6-h resolution and can also quantify the relative importance of, say, upstream versus downstream flooding risks, energy generation versus flood control, and other applicable tradeoffs. Such information is again provided to management agencies to support operational policy decisions. Such policies are revised as information on reservoir levels and flow forecasts is updated. The model is constrained by the long range decisions, unless current conditions indicate that a departure is warranted.

Lastly, the turbine load dispatching model is activated to determine the turbine and spillway operation that will realize the hourly release decisions made by the short/mid range decision process. The results of this model can be used for near real time operations.

In developing the INFORM DSS, particular attention has been placed on ensuring consistency across modeling layers, both with respect to physical system approximations as well as with respect to the flow of decisions. For example, the short/mid range control model utilizes aggregate power plant functions that determine power generation based on reservoir level and total plant discharge. These functions are derived by the lower level model (turbine load dispatching) which determines the optimal turbine loads for each plant corresponding to the particular reservoir level and total discharge. Thus, the short/mid range model "knows" how much power generation will actually result from a particular hourly plant release decision. Furthermore, the short/mid range model generates similar energy functions to be used by the long range control model. In this manner, each model has a consistent representation of the benefits and implications of its decisions.

The three modeling layers discussed earlier address planning and management decisions. The scenario/policy assessment model addresses longer term planning issues such as the implications of increasing demands, inflow changes, storage re-allocation, basin development options, and mitigation measures. Altogether, the purpose of the INFORM DSS is to provide a modeling framework responsive to the information needs of the decision making process at all relevant time scales and water uses.

Notable features of the INFORM DSS include:

(a) Reservoir releases are determined by dynamic rules that consider current and anticipated water availability and demands system-wide. Namely, the release of a particular

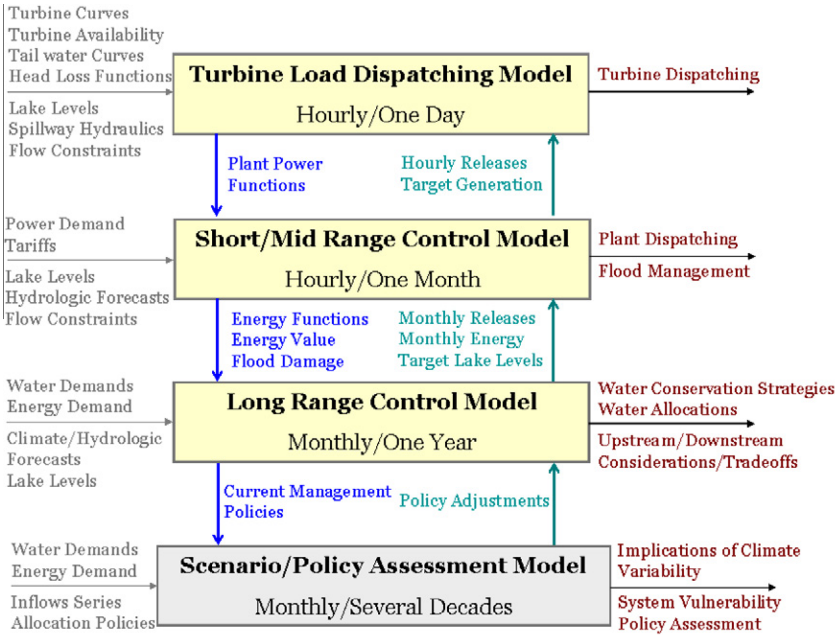

Fig. 2. INFORM DSS modeling framework (HRC-GWRI, 2007).

reservoir depends on all system storages as well as inflow forecasts and water use targets. These decisions are adaptive and are updated every month. This aspect of the decision models allows for exploring the benefit of adaptive management under changing climate and water demands.

(b) System-wide storage and release optimization explicitly considers inflow uncertainties through ensemble based forecasts. The goal is to identify release sequences that optimize the reliability of meeting the stated demand targets (pertaining to environmental and water supply requirements) and power generation, while keeping reservoir storage (including carry-over) as high as possible at pre-specified spillage (and flooding) risk. Multi-objective tradeoffs are generated by varying the acceptable reliability levels.

(c) The impacts of monthly decisions on flood protection, hydropower, water supply, and other water uses are determined by high resolution models that optimize daily and hourly releases, not by aggregate functions. This is possible because the INFORM DSS includes a hierarchy of simulation and decision models pertaining to multiple time resolutions, from monthly to hourly (see discussion associated with Fig. 2 above and further discussion in HRC-GWRI (2007)). This feature is expected to provide more refined and reliable assessments.

4. Assessment process

The assessment process consists of running the DWRPS and INFORM DSS planning models sequentially for each month of the assessment horizon (50 years). The assessment is carried out for four cases, two for each management model (DWRPS or INFORM DSS) and two for each hydrologic data set (historical and future). To avoid hydrologic data spin-up transients, all runs start from the 5th year of the hydrologic period with an assessment horizon of 46 years. For presentation purposes, the calendar dates of the future dataset are converted to the same calendar dates as the historical dataset. (Thus, the historical and future dataset results are plotted on the same chart.)

In this assessment, the management policy generated by the DWRPS model is referred to as "Current Policy" while that of the INFORM DSS is referred to as "Adaptive Policy". There is no doubt that the policy making process is far too complex to model exactly, and the designation "current" is only used to indicate that the DWRPS model policies incorporate many qualitative features characterizing the actual policies.

The model simulations start with the generation of forecasts for the upcoming inflows. An imbedded Historical Analog inflow forecasting model (Yao and Georgakakos, 2001) is used to simulate the forecasts utilized by the California Department of Water Resources (DWR). The HA model generates a 10-member inflow trace ensemble for the upcoming 9 months, using the inflows of the most recent three months as reference for selecting similar traces from each dataset, excluding the current year. The HA model forecasts are used to drive both management models.

The simulation process (see earlier discussion under the DWRPS model, Section 3.2.1) is sequential for both models and is intended to replicate the system response under the historical and future hydrologic scenarios, water demand targets, and the current and adaptive management policies. The comparison criteria include reservoir storage levels, releases, water deliveries, target deficits, energy generation, Delta outflow, X2 location, and other quantities of interest for each month of the simulation horizon.

The main differences between the DWRPS and the INFORM DSS planning models are as follows:

- Both models utilize forecasts generated by a Historical Analog inflow model. However, DWRPS uses the median forecast trace while the INFORM DSS uses the full forecast ensemble.
- The DWRPS model determines reservoir releases based on system conditions and targets for the current month; this determination is based on the COA which has been based on historical simulations and system performance. The INFORM DSS release policy consists of dynamically generated 9-month release policies, the first month of which is only implemented and simulated, while the rest are used to ensure that current decisions anticipate future constraints and requirements. The INFORM DSS releases are based on a formal stochastic optimization scheme that optimizes the likelihood that Delta requirements will be satisfied, water demand targets will be met, hydropower will be optimized, and reservoirs will not be depleted or forced to spill.

- The DWRPS model determines water demand targets twice a year, in February and October; the INFORM DSS determines water demand targets at the beginning of every month.
- The DWRPS model follows the COA to allocate extra required releases between SWP and CVP; the INFORM DSS optimizes the allocation of the extra required water based on current conditions and future forecasts and targets.

These differences are summarized in Table 1.

5. Assessment results

The assessment results pertain to monthly sequences of reservoir elevations, releases, energy generation, water deliveries, deficits, X2 locations, and other important system variables (HRC-GWRI, 2010). A comparative discussion of these sequences is provided in the following five sub-sections: (1) inflow comparison, (2) current policy assessments under historical and future scenarios, (3) adaptive policy assessments under historical and future scenarios, (4) current versus adaptive policy comparison, and (5) assessment summary.

5.1. Inflow comparison

Monthly inflow mean sequences of the four major reservoirs Trinity, Shasta, Oroville, and Folsom are shown in Fig. 3 for two periods: a historical period from 1970 to 2019, and a future period from 2050 to 2099. The figure shows that mean inflows of the two periods are very close during the dry months, but exhibit a shift during the wet season. The overall monthly average values in the future period are slightly smaller for Trinity, Shasta, and Oroville as listed in Table 2.

Future inflows portend more severe droughts. This is shown on Fig. 4 depicting the annual frequency curves of the total reservoir inflow for the historical and future periods. The minimum annual future inflow is 11,987 thousand acre-feet (TAF) compared to the minimum annual historical inflow of 13,708 TAF, corresponding to a 12.5% inflow decrease.

Thus, future inflows differ from historical inflows in three important aspects. They exhibit slightly lower annual averages, higher variability leading to more severe droughts, and a seasonal shift of the wet season earlier in the year. All of these aspects are bound to influence the ability of the Northern California reservoir system to meet its stated objectives. However, performance differences are expected to vary across objectives depending on the sensitivity to different aspects of inflow changes. For example, average water supply and average energy generation are expected to be sensitive to *average* inflow changes; while spillage, drought water deliveries, firm energy generation, and X2 location management are expected to be sensitive to *extreme* inflow changes. The following subsections quantify the degree to which these objectives are met under the two management policies.

5.2. Current policy assessment under historical and future scenarios

The simulation sequences of reservoir elevation, reservoir release, water deliveries to southern California, energy generation, X2 location, and Delta outflow support the following observations.

5.2.1. Reservoir levels and spillage

Reservoir levels exhibit more pronounced fluctuations under the future scenario compared to the historical scenario, both inter-annually and seasonally. The increased inter-annual fluctuations are a consequence of the wider future inflow variability, while the increased seasonal fluctuations are a consequence of the increased phase shift between inflows and demand targets. Spillage, defined as reservoir outflow in excess of turbine capacity, increases to 1358 TAF under the future scenario from 1035 TAF under the historical scenario.

5.2.2. Water supply deliveries

On average, the system delivers almost the same amount of water per year in both periods (10,366 TAF under the future scenario vs. 10,304 TAF under the historical inflow scenario). However, deliveries during droughts are reduced significantly in the future scenario. During the most severe drought, the system can only support 5955 TAF per year under the future scenario versus 7963 TAF under the historical scenario, corresponding to a 25% reduction. Thus, compared to the annual average over the entire period, water deliveries during the most severe drought year are reduced by 42% for the future scenario versus only 22% for the historical scenario. This performance degradation is a consequence of (a) more severe future droughts and (b) the heuristic character of the current policy tuned to the historical inflow regime. (Fig. 5,

Table 1
Current vs. adaptive release policy comparison.

Current policy	Adaptive, risk- based Policy
• Generate inflow forecasts—median trace (HA).	• Generate inflow forecasts—full ensemble (HA).
• Determine water year type (DWR: C/D/N/AN/W).	
• Adjust base demands based on year type.	
• Determine next month reservoir releases to – meet water delivery targets and minimum required flows at various river nodes, assuming no extra releases are required to meet Delta demands (X2) and pumping to South CA.	• Determine reservoir releases for the next 9 months to – meet water delivery targets and minimum required flows at various river nodes, – meet environmental and ecological Delta requirements associated with the X2 location and Delta outflow, – generate as much energy as possible, and – maintain high reservoir levels and sufficient carry-over storage.
• If X2 requirements and south CA delivery targets are not met, increase releases according to COA (roughly 25/75 rule).	(*System-wide, stochastic optimization; Not according to the COA.*)
• If deficits persist, allocate water to meet X2 first, then south CA water deliveries.	
• Apply release and repeat at the next month.	• Apply first month release and repeat.

Main policy differences

Current policy	Adaptive policy
• Focuses on current month.	• Optimizes over the next 9 months.
• Deterministic.	• Risk based.
• Adjusts demand targets twice a year.	• Re-optimizes every month.
• Follows COA in extra water allocation.	• Finds optimal allocation strategy each time.

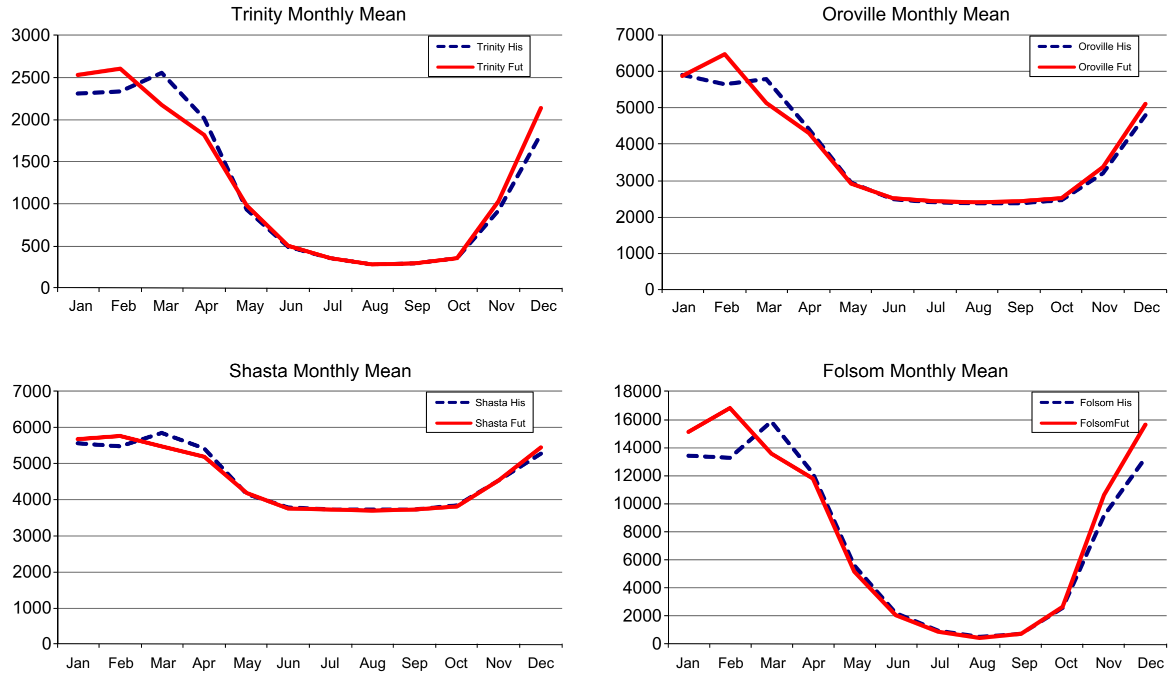

Fig. 3. Comparison of monthly reservoir inflows (thousand acre-feet per month) for the historical (blue/dashed) and future (red/solid) climate.

Table 2
Average annual inflows (thousand acre-feet—TAF).

	Trinity	Shasta	Oroville	Folsom	Total
Historical	1623.04	7512.82	5586.63	3040.67	17763.17
Future	1594.78	7387.36	5479.26	3049.02	17510.42
Difference (%)	−1.74	−1.67	−1.92	0.27	−1.42

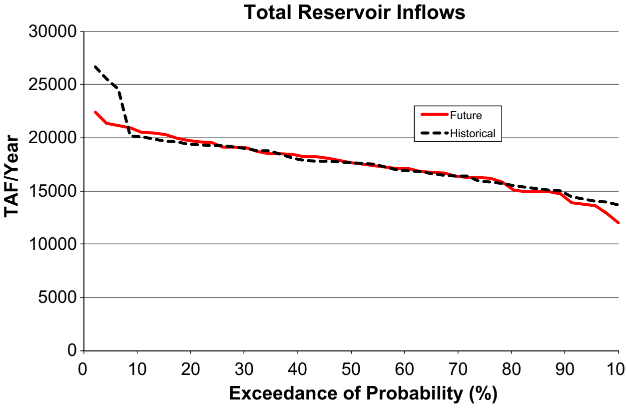

Fig. 4. Total reservoir inflow frequency curve comparison.

compares the annual water deliveries across the entire frequency range.)

5.2.3. Energy generation

Energy generation follows a similar to the water deliveries pattern. On average, the future scenario produces to 7176 GWH per year compared to 7384 GWH of the historical scenario, a 2.8% reduction. However, the annual energy generation during the most severe drought (firm energy) under the future scenario is again drastically lower than the historical scenario. Specifically, 3697 GWH of firm energy are generated under the future scenario compared to 5095 GWH of the historical scenario, a 27% decrease. Firm energy generation under the future scenario corresponds to 48% of annual energy generation while under the historical scenario it corresponds to 31%. Fig. 6 compares the system energy generation under the two scenarios across the entire frequency range.

5.2.4. X2 location

The X2 location constraint (i.e., not to exceed 80 km from the Golden Gate Bridge) begins to experience violations for the future scenario, reaching a maximum of 108.5 km (1% probability of violation).

5.2.5. Delta water outflow

The Delta water outflow is the excessive flow which discharges into the sea after meeting all water demands. The Delta outflow has a minimum constraint because of ecological requirements. The assessment shows that during drought years in the future cli-

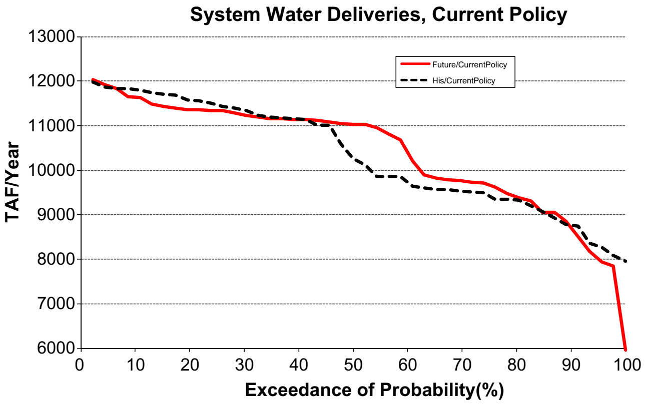

Fig. 5. Total water deliveries comparison; current policy.

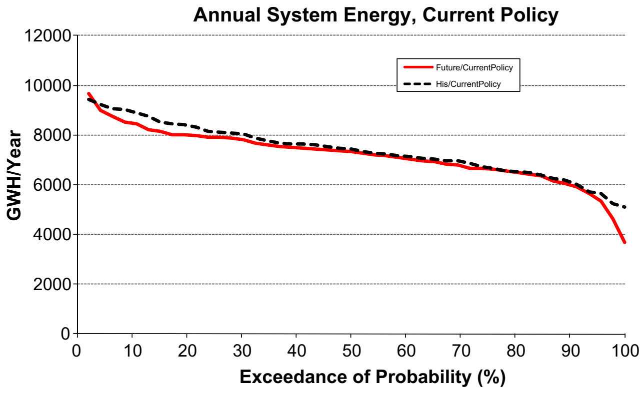

Fig. 6. System energy generation comparison; current policy.

mate, the system cannot meet the Delta outflow constraint and registers violations.

5.3. Adaptive policy assessment under historical and future scenarios

Corresponding sequences of reservoir elevation, reservoir release, energy generation, water deliveries to the south, X2 location, and Delta outflow were also generated by the INFORM DSS (adaptive policy) assessments. These results (fully presented in HRC-GWRI (2010)) support the following comments.

5.3.1. Reservoir levels and spillage

The higher variability of the future inflows causes higher reservoir level fluctuations, both inter-annually and seasonally. To manage the increased inflow variability, the DSS policies utilize all of the reservoir live storage. Spillage slightly increases to 1095 TAF under the future scenario from 1087 TAF under the historical scenario.

5.3.2. Water deliveries

Under the future scenario, the DSS policy delivers an average of 10,432 TAF of water per year compared to 10,536 TAF per year under the historical scenario (less than 1% decrease). However, the higher future inflow variability reduces the system ability to provide water during dry years. Specifically, the minimum annual delivery for the future scenario is 9398 TAF, representing a 10% reduction from its mean value. By contrast, the minimum annual delivery for the historical period is 9725 TAF, corresponding to an 8% reduction from its mean value. The frequency curves of the annual system water deliveries under the DSS management policy are shown in Fig. 7.

5.3.3. Energy generation

Energy generation follows a pattern similar to that of the water deliveries. On average, the future period produces 7119 GWH per year compared to 7238 GWH of the historical period (a 1.6% decrease). However, the energy output during the most severe drought (firm energy) is lower in the future scenario. Specifically, the minimum annual generation of the future scenario is 4802 GWH compared to 5049 GWH of the historical scenario, a 5% decrease. Firm energy generation under the future scenario corresponds to 67% of the annual energy generation, while under the historical scenario it corresponds to 70%. Fig. 8 depicts and compares the entire frequency range of the system energy generation.

5.3.4. X2 location

The X2 requirement is always met throughout the historical and future periods. However, although no violations are reported, the 80 km constraint stays binding for a longer time in the future period as a consequence of the seasonal inflow shift.

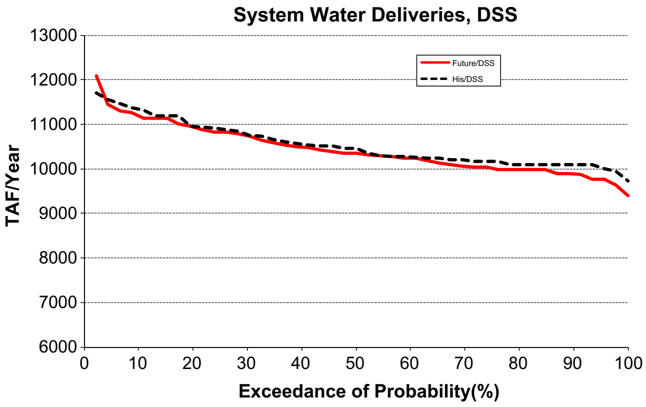

Fig. 7. Water deliveries comparison; adaptive policy.

5.3.5. Delta outflow

The Delta water outflow requirements are always met throughout the historical and future periods.

5.4. Current versus adaptive policy comparison

5.4.1. Reservoir levels and spillage

The performance with respect to reservoir levels essentially conditions the performance with respect to all other criteria. Failures occur when the reservoirs experience excessive spillage or are forced to deplete their storage causing water supply and other deficits. In this regard, the adaptive policy outperforms the current policy resulting in better storage management during droughts and less spillage during both hydrologic scenarios (HRC-GWRI, 2010, Figs. 6–28 and 6–29). Moreover, the current policy becomes notably worse in the future scenario where inflows are more variable and drought severity increases.

5.4.2. Water deliveries

The performance with respect to water deliveries depends on the model ability to manage reservoir storage and exemplifies the differences between the two policies. Under the current policy, the frequency distribution of the actual water deliveries is wider, providing higher amounts during wet years and lower during dry years. By contrast, the water delivery distribution of the adaptive policy is more concentrated, striking a better balance between wet and dry years. Specifically, under the historical period, the minimum adaptive policy water delivery is 9725 TAF per year which is 22% more than the 7963 TAF of the current policy (Fig. 9

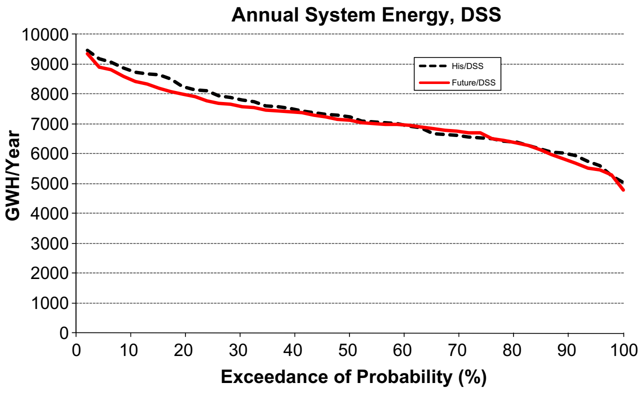

Fig. 8. Energy generation comparison; adaptive policy.

left graph). Under the future scenario, the minimum adaptive policy water delivery is 9398 TAF which amounts to 58% more water than the 5955 TAF of the current policy (Fig. 9 right graph). Thus, with respect to drought management, the performance of the current policy degrades markedly under climate change. The same trend is also observed in the mean deliveries where the adaptive policy reverses the historical performance and slightly exceeds the current policy in the future scenario.

5.4.3. Energy generation

The performance with respect to energy generation parallels that of the water deliveries. Firm energy generation under the adaptive policy is higher than under the current policy for the future period (4802 GWH versus 3697 GWH). The mean energy generation is almost the same for both policies (7118 versus 7176 GWH per year for the historical period). The system energy generation frequency curves for each hydrologic period and both management policies are shown in Fig. 10.

5.4.4. X2 location

Finally, the adaptive policy manages the X2 location better than the current policy. Specifically, in the future scenario, the current policy violates the 80 km target by 28 km, while the adaptive policy always meets this target in both hydrologic periods. Model performance with respect to the X2 is directly connected with the performance with respect to water deliveries during droughts. Thus, if the current policy were to meet the X2 target it would have to limit its drought water deliveries (and firm power generation) even more so that additional water is allocated to the Delta. In all, these assessments clearly support the view that the adaptive policy of the INFORM DSS outperforms the current policy in the face of a changing climate.

5.4.5. Delta water outflow

The adaptive policy always meets the minimum Delta outflow requirement in both hydrologic periods. The current policy violates this constraint in the future scenario.

5.5. Assessment summary

The assessment findings are summarized in Figs. 11 and 12 which illustrate the percent differences of basin response by hydrologic scenario and management policy. More specifically, Fig. 11 summarizes the percent performance difference in the future versus the historical scenario for each management policy. The comparison criteria include:

- Annual Average Spillage (“Avg. Spillage”);
- Annual Average Water Supply Deliveries (“Avg. WS”);
- Minimum Annual Water Supply Deliveries (“Min. WS”);
- Annual Average Energy Generation (“Avg. Energy”);
- Firm Energy Generation (“Firm Energy”); and
- Maximum X2 Violation (“X2 Violation”).

The percent difference is computed as the criterion value in the future scenario less its value in the historical scenario divided by the historical value. For each criterion, the black bar corresponds to the percent difference realized under the current policy, and the red bar to the percent difference under the adaptive policy.

This bar chart shows that the performance of the current policy worsens in the future scenario, registering substantial spillage increase (~31.2%), reductions in the minimum water deliveries and firm energy (25.2% and 27.4% respectively), slight reduction in energy generation (2.89%), and significant X2 violations (35.6%). Modest increases of average water deliveries are also noted (0.6%) as a result of the wetter average flows.

The statistics of the adaptive policy are more favorable, with modest differences between the future and the historical period. Spillage increases by 0.8%, average water deliveries decreases by 1.%, water deliveries during the most severe drought by 3.4% (as opposed to the current policy’s 25.2% *reduction*), and average energy by 1.7%. Firm energy decreases by 4.9% and X2 registers no violation in either scenario.

The performance differences between the two management policies against the same criteria are contrasted in Fig. 12 for both the historical and future periods. These differences are computed as the criteria values realized under the adaptive policy less their values under the current policy divided by the latter. Two bars are again shown, one pertaining to the historical scenario (black) and a second to the future scenario (red).

This figure shows that in the historical scenario the policy differences are fairly minor across all criteria. However, the situation in the future scenario is drastically different (red bars), with the adaptive policy visibly outperforming the current policy, and achieving consistently effective performance in both hydrologic scenarios. The performance differences are particularly striking with respect to providing water deliveries during droughts, maintaining firm energy generation, and sustaining favorable environmental conditions in the Bay Delta.

These performance differences are a direct result of the forecast-management differences outlined in Table 1. More specifically, the current operational policy makes decisions based on average deterministic forecasts updated twice a year, and follows the existing regulation agreements (COA). By contrast, the adaptive policy makes decisions (a) considering the full forecast uncertainty updated every month, including the risks of extreme events and (b) using a system-wide water utilization perspective optimal with

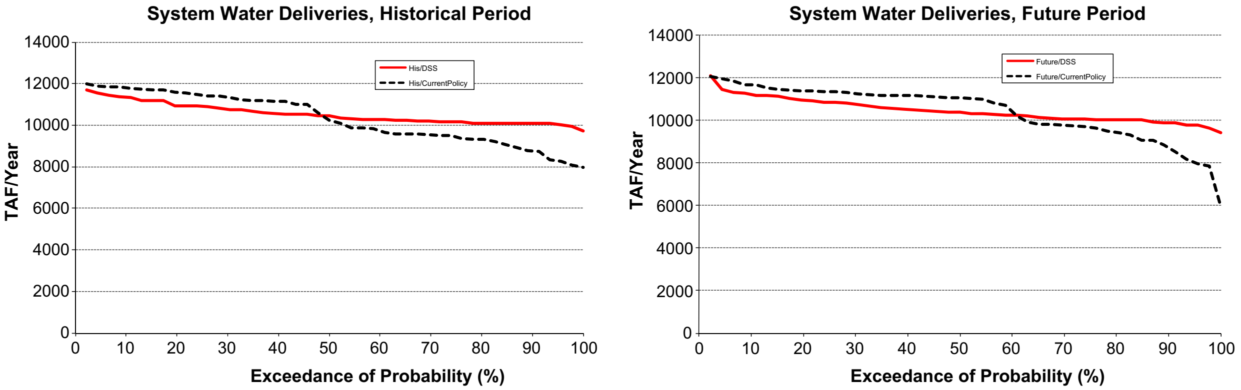

Fig. 9. Total water delivery sequences; historical (left) and future (right) periods for the current (black/dashed) and adaptive (red/solid) policies.

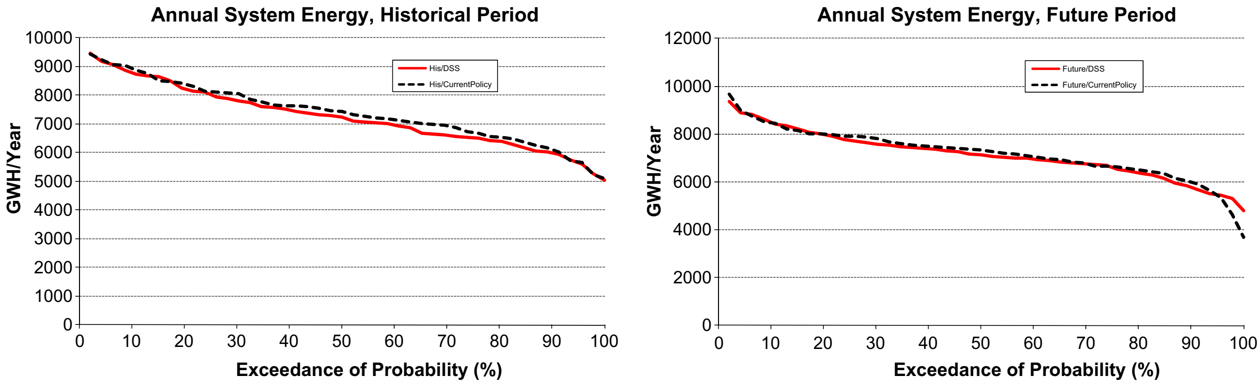

Fig. 10. System energy generation; historical (left) and future (right) periods for the current (black/dashed) and adaptive (red/solid) policies.

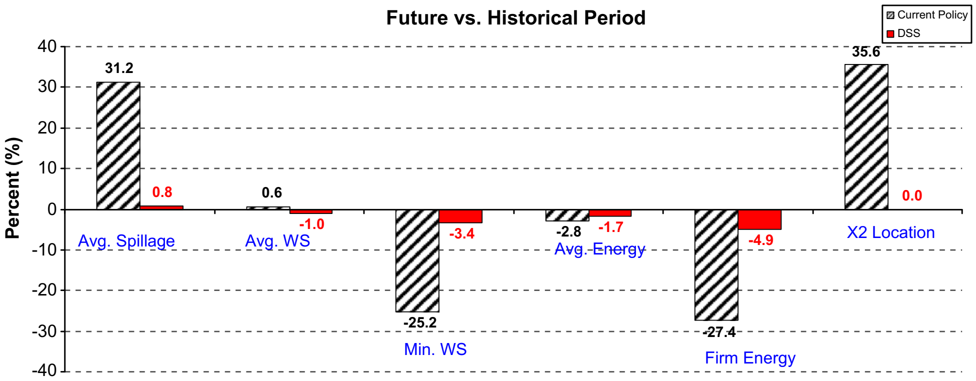

Fig. 11. Percent performance differences in the future versus the historical scenario (black/hatched bars correspond to the current policy and red/solid bars to the adaptive policy).

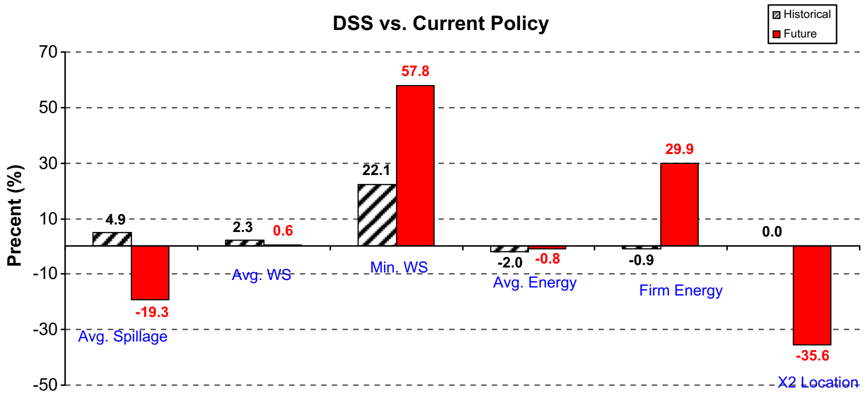

Fig. 12. Percent performance differences of the adaptive versus the current policy (black/hatched bars correspond to the historical period and red/solid bars to the future period).

respect to the current forecasts. These differences in the forecast-management schemes are exacerbated during droughts because of the hard Bay Delta X2 requirement.

These results demonstrate that adaptive management, in the comprehensive form implemented herein, can effectively counteract the adverse impacts of climatic change and maintain historical system performance. By contrast, the continued use of current management approaches (developed based on historical climate responses) leads to impaired performance under a changing climate. The first part of this conclusion differs from those of previous studies (e.g., Vanrheenen et al., 2004) which only analyzed current management approaches and related parametric extensions. The present study advocates that adaptive management, with due uncertainty consideration, provides an effective and inexpensive first mitigation line of defense against a changing and variable climate.

6. Conclusions and further research opportunities

6.1. Conclusions

This assessment compares the response of the Northern California reservoir system under two reservoir management policies and two hydrologic scenarios. The reservoir management policies include the current policy, simulated through the DWRPS model (DWR, 1999), and an adaptive policy, generated by the INFORM DSS (HRC-GWRI, 2007). The hydrologic scenarios comprise two 50-year inflow sequences, one reflective of historical and a second of future atmospheric emissions and hydrology.

The assessments show that the current policy, which is tuned to historical hydrologic regimes, is unable to cope effectively with the more variable future climate. As a result, the water supply, energy, and environmental water uses (Delta X2) cannot be effectively satisfied during future droughts, exposing the system to higher vulnerabilities and risks. By contrast, the adaptive management policy maintains similar performance under both hydrologic scenarios, suggesting that adaptive management constitutes an effective mitigation measure to climate change.

The simulation results support the following conclusions:

- Future A1B scenario portents intensifying water stresses (due to seasonal inflow shifts and higher inflow variability) and higher vulnerability to extreme droughts.
- Adaptive, risk based, reservoir regulation strategies are self tuning to the changing climate, deliver more robust performance than current management practices, and can considerably mitigate the negative impacts of increased water stresses.

Effective implementation of adaptive, risk based, reservoir regulation strategies require:

- More flexible laws and policy statutes (COA, heuristic rules, etc.);
- A new level of institutional cooperation for water resources management; and
- The adoption of adaptive decision support tools and concomitant training of agency personnel in their effective use.

6.2. Further research opportunities

In addition to the recommendations provided in the companion article (Georgakakos et al., this issue), the present research effort would benefit from several extensions.

6.2.1. Incorporate the impacts of sea-level rise

This aspect is very important as sea level rise affects the Bay Delta environmental conditions, the water supply to the south, and all other water uses. Under higher sea levels, the current environmental conditions in the Bay Delta can only be maintained if fresh water inflow from the upstream watersheds increases. However, this would imply that all consumptive water uses be reduced. The purpose of this assessment would be to quantify this tradeoff.

6.2.2. Assessments of other GCM scenarios (A2, A1B, etc.)

The scenario A1B is but one scenario of potential climate change. Additional scenarios should be investigated to explore the full range of potential water resources impacts under different emissions strategies.

6.2.3. Assessments with daily and sub-daily temporal resolution

The assessment presented herein utilized a monthly time resolution and, thus, focused on long term water resources impacts such as drought management. Other climate change impacts (flooding, energy economics, fisheries, etc.) pertain to finer temporal resolutions (daily and sub-daily response) and should also be assessed. The INFORM assessment system includes tools of pertinent resolution that can carry out such assessments.

6.2.4. Conjunctive, statewide surface water – groundwater assessments

On average, California's water demands (with a population of more than 35 million) exceed its natural supplies by approximately 6–8 million acre-feet (MAF). More specifically, annual average water supply is 78 MAF, of which 80% comes from surface water resources and the remainder from groundwater (California Department of Water Resources Bulletins). Average annual water use is estimated at 80 MAF, of which 11% accrues to urban water supply, 44% to agriculture, and 45% to environmental and ecological uses. However, during droughts, water supply declines by 25% or more, creating severe water shortages and the need for risk based and adaptive planning and management. The purpose of this extension would be to carry out an integrated assessment of all water sources to quantify the impacts on each and all water use types. The findings of such an assessment would provide information the state needs for sustainable water supply planning.

6.2.5. Integrated economic assessments

The socio-economic implications of climate change under various climate, demand, and management scenarios can be assessed by combining the strengths of the existing assessment tools. This would require that (1) CALVIN's economic valuation modules be expanded to include all pertinent water uses and (2) INFORM DSS, CALSIM, and CALVIN be linked to provide a more reliable representation of the management alternatives, the physical system response, and the accrued economic benefits, costs, and risks. This integrated approach would rely on (1) INFORM DSS to generate adaptive storage, release, and power generation strategies that meet environmental and water supply requirements at acceptable risk levels, (2) CALSIM to translate the implications of the adaptive policies for each stakeholder, and (3) CALVIN to assess the associated economic benefits and costs.

Acknowledgements

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References

Draper, A.J., Jenkins, M.W., Kirby, K.W., Lund, J.R., Howitt, R.E., 2003. Economic-engineering optimization for California water management. J. Water Res. Plann. Manage. 129 (3).

Draper, A.J., Munevar, A., Arora, S.K., Reyes, E., Parker, N.L., Chung, F.I., Peterson, L.E., 2004. CalSim: generalized model for reservoir system analysis. J. Water Res. Plann. Manage. 130 (6), 480–489.

Department of Water Resources (DWR), 1999. Operations Criteria Applied in DWR Planning Simulation Model. Draft Technical Report (for internal use), 96p., personal communication.

Georgakakos, A.P., Yao, H., Mullusky, M.G., Georgakakos, K.P., 1998. Impacts of climate variability on the operational forecast and management of the Des Moines River basin. Water Resources Res. 34 (4), 799–821.

Georgakakos, K.P., Graham, N.H., Cheng, F.-Y., Spencer, C., Shamir, E., Georgakakos, A.P, Yao, H., Kistenmacher, M., this issue. Value of adaptive water resources management in northern California under climatic variability and change: dynamic hydroclimatology. J. Hydrol.

GoldSim, 2007. GoldSim: Engineering and Environmental Simulation Software for Water Resources Applications. GoldSim Technology Group, Issaquah, Wash.

Howitt, R.E., 1999. Integrated Economic-Engineering Analysis of California's Future Water Supply. Project Completion Rep. Dept. of Civil and Environmental Engineering, Univ. of California, Davis, California.

HRC-GWRI, 2007. Integrated Forecast and Reservoir Management (INFORM) for Northern California: System Development and Initial Demonstration. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-109, 244 pp. + 9 Appendices. <http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-109.html>.

HRC-GWRI, 2010. Implications of Climatic Changes for Northern California Water Resources Management for the Later Part of the 21st Century. California Energy Commission. PIER Energy-Related Environmental Research, Final Report, Award No. 500-07-013, 114pp. <http://www.hrc-lab.org/climate_change/HRC_GWRI_FR_ClimateChangeNorthernCalifornia_2010.pdf>.

Islam, N., Arora, S., Chung, F., Reyes, E., Field, R., Munévar, A., Sumer, D., Parker, N., Chen, Z.Q.R., 2011. CalLite: California central valley water management screening model. J. Water Res. Plann. Manage. 137 (1).

Landis, J.S., Reilly, M., 2002. How We Will Grow: Baseline Projections of California's Urban Footprint through the Year 2100. Project Completion Report. Department of City and Regional Planning, Institute of Urban and Regional Development, University of California, Berkeley.

Liang, X., Wood, E.F., Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: evaluation and modifications. J. Global Planet. Change 13, 195–206.

Lund, R.J., Howitt, R.E., Jenkins, M.W., Zhu, T., Tanaka, S.K., Pulido, M., Tauber, M., Ritzema, R., Ferriera, I., 2003. Climate Warming and California's Water Future. Report 03-1. Center for Environmental and Water Resource Engineering, University of California, Davis, 85p.

Medellin-Azuara, J., Lund, J.R., Howitt, R.E., 2007. Water supply analysis for restoring the Colorado River Delta, Mexico. J. Water Res. Plann. Manage. 133.

Medellin-Azuara, J., Harou, J.J., Olivares, M.A., Madani, K., Lund, J.R., Howitt, R.E., Tanaka, S.K., Jenkins, M.W., Zhu, T., 2008. Adaptability and adaptations of California's water supply system to dry climate warming. Climatic Change 87, S75–S90.

Newlin, B.D., Jenkins, M.W., Lund, J.R., Howitt, R.E., 2002. Southern California water markets: potential and limitations. J. Water Res. Plann. Manage. 128 (1).

Tanaka, S.K., Tingju, Z., Lund, J.R., Howitt, R.E., Jenkins, M.W., Pulido, M.A., Tauber, M., Ritzema, R.S., Ferreira, I.C., 2006. Climate warming and water management adaptation for California. Climatic Change 76, 361–387.

VanRheenen, N.T., Wood, A.W., Palmer, R.N., Lettenmaier, D.P., 2004. Potential implications of PCM climate change scenarios for Sacramento-Jan Joaquin River basin hydrology and water resources. Climatic Change 62, 257–281.

Vicuna, S., Dracup, J.A., Dale, L., 2009. Climate change impacts on the operation of two high elevation hydropower systems in California. California Climate Change Center, CEC-500-2009-019-D. <http://www.energy.ca.gov/2009publications/CEC-500-2009-019/CEC-500–2009-019-D.PDF>.

Washburn, T. (USBR), 2005. USBR planning model (based on EXCEL spreadsheets), personal communication.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climatic Change 62 (1–3), 189–216.

Yao, H., Georgakakos, A.P., 2001. Assessment of Folsom lake response to historical and potential future climate scenarios: 2. Reservoir management. J. Hydrol. 249, 176–196.