A Proposal for Advancement to PhD Candidacy

Integration of reservoir management into a Global Climate Model for evaluation of impacts on climate feedbacks and flow regime in California

Kurt Solander
University of California, Irvine
Department of Earth System Science
Hydrology and Climate Research Group

PhD Advancement Committee Members:
Professor James Famiglietti (adviser)
Professor Keith Moore
Professor James Randerson
Professor Brett Sanders
Professor Charles Zender
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ABSTRACT

Global Climate Models (GCMs) are ideal for hydrologic evaluations because they include climate feedbacks, which provide a more complete picture of how water moves between the land and atmosphere than uncoupled models. To date, these models lack any mechanism to represent the impact that reservoir management has on the climate or affects streamflow. Achieving such a feat would not only improve the predictive capabilities of these models, but also enable simulations to be run that would enhance the understanding of water resources management impacts on the climate. This study will improve GCMs for climate and hydrologic investigations by integrating reservoir management into the framework of a GCM, while focusing on California as a test case. A simple method of representing reservoir management influences on streamflow will first be developed offline using in-situ data and this will then be incorporated into a land surface model linked to a river routing model. The combined models will be run with and without the representation of reservoirs to determine reservoir management impacts on the flow regime through comparison of ecologically relevant flow metrics for both simulations. Biological survey data including fish, macroinvertebrates, and riparian vegetation from locations upstream and downstream of reservoirs used in the model will be obtained to assess how certain species are impacted by the flow alterations, as time permits. The models will then be run in combination with an atmospheric model as a GCM to simulate climate feedbacks affecting the water cycle. This information will be useful for leading to better estimates of how much reservoir management alters the climate system and streamflow and what the cost of these alterations is to the ecosystem.

INTRODUCTION

Global climate models (GCMs) offer excellent tools for analyzing how water interacts vertically between the land and the atmosphere and moves horizontally across the land surface. These models have historically focused on evaluations of vertical water and energy exchanges between the land and atmosphere (Famiglietti and Wood, 1994). However, these models are also useful for simulating the horizontal transport of water across the landscape because many of these feedbacks have a direct influence on the amount of water available on the land. The integrated climate feedbacks thereby provide a more complete picture of gains and losses in water storage and fluxes (Liang et al., 1994; Oleson et al., 2010). As such, GCM applications have proven useful for providing estimates of water availability, water use, and water scarcity at either the global or regional scale (Lehner and Grill, 2013). Failing to include or accurately represent these feedbacks in GCMs thus detracts from their ability to realistically depict hydrologic behavior (Gornitz et al., 1997; Vorosmarty and Sahagian, 2000).

Omitting some sort of mechanism to represent how streamflow is managed in reservoirs may exclude key climate feedbacks from being represented in model simulations. Missing these feedbacks would reduce the value of GCMs as predictive tools or to test hypotheses. This is especially true for simulations in semi-arid regions where the management of water resources is already extreme and expected to intensify, such as in California (Gleick et al., 2010). The use of GCMs to provide beneficial information for improving water resource management thus hinges upon including a reservoir management component that would enable better representation of climate feedbacks. This study will work towards this end by developing a basic method to characterize releases from reservoirs for integration into a GCM. Once integrated, model simulations will be run to evaluate how reservoirs in the model affect climate feedbacks.
Secondarily, use of the GCM as a tool to evaluate ecosystem impacts will be explored by running model simulations to determine flow alterations downstream from reservoirs and evaluating what the implications are for aquatic flora and fauna.

GOALS AND OBJECTIVES

The main goals of this study are to:

- Properly describe the basic function of man-made reservoirs in California through development of a simple mathematical model
- Investigate the impacts of reservoir management in California on the regional terrestrial water cycle and ecosystem
- Determine the impact of reservoir management on the climate system using an earth system modeling approach

One major objective of this research is to improve the representation of discharge in the Community Land Model (CLM) by developing a method to represent reservoir management within the model framework. Currently, CLM is only capable of simulating natural flows, which leads to gross misrepresentations of the timing and magnitude of peak and low flows (Figure 1). In this study, a way to represent reservoir management will be developed using in situ data and integrated into CLM to reduce errors associated with the simulated flow magnitude and timing. The representation of reservoirs will necessarily be simple using minimal data inputs to facilitate integration into CLM, which will ultimately be run in combination with an atmospheric model as a global climate model (GCM). Maintaining model parsimony is essential so the basics of reservoir management can be captured while still allowing for the simulation of climate feedbacks within a GCM. Some research has already been conducted towards including basic reservoir operations in global hydrologic models (Hanasaki et al., 2006; Haddeland et al., 2006; Doll et al., 2009; Van Beek and Bierkens, 2009). However, reservoir management has yet to be integrated within the framework of a GCM. Successful completion of the proposed work in this study is thus crucial for providing a better outlook on the future of reservoir management impacts on the water cycle and climate system at both regional and global scales.

Secondarily, integrating reservoir management into a GCM for simulations in California will be beneficial for evaluating appropriate minimum in-stream flow requirements. An assessment of flow regime changes due to reservoir operations for a number of managed river systems will be accomplished using a set of monthly flow alteration metrics. Although this type of analysis has been conducted using physical observations (Richter et al., 1997; 2003), analysis of these metrics within a GCM will be beneficial for future simulations of how reservoir management impacts on the flow regime might shift under a changing climate.

BACKGROUND

Existing global hydrologic models do not account for reservoir management

Water resources are most heavily managed in the global low and mid-latitudes (Revenga et al., 2005). Developing a mechanism to better represent the management of reservoirs (or major surface water diversions and groundwater pumping) in models is thus necessary to
improve hydrologic simulations particularly for these areas. Failing to include this essential component results in large under- or over-estimates of actual discharge depending on the temporal characteristics of the discharge being simulated (Figure 1). Incorporation of reservoir management into GCMs would reduce this issue with flow magnitude and timing in GCM simulations as well as improve our understanding of how water resource management impacts the climate feedbacks being represented in the model.

Although reservoir management has yet to be fully integrated into a GCM, several global-scale models linking reservoir management to land surface hydrology have been produced. Hanasaki et al. (2006) developed a reservoir operation scheme for a global river routing model. Reservoir storage capacity, main reservoir function, inflow, and downstream water demands were used to simulate reservoir releases on a monthly timescale (Hanasaki et al., 2006). Haddeland et al. (2006) incorporated a reservoir operation scheme into the Variable Infiltration Capacity (VIC) macroscale hydrologic model that includes full water and energy balances (Liang et al., 1994). Reservoir releases were based on storage, inflow, and evaporation within VIC for part of North America and Asia (Haddeland et al., 2006). Biemans et al. (2011) developed a reservoir operation scheme for use in a global-scale hydrology and vegetation model LPJmL. The operation scheme selected for LPJmL follows that of Hanasaki et al. (2006), but also includes water demands linked to dynamic crop types. Although these models proved to be successful for modeling the impacts of reservoir operations on the global water cycle, the proposed approach in this study is designed to be simpler to facilitate integration into a GCM with the purpose of evaluating associated climate feedbacks and impacts on the flow regime.

Figure 1: 1995-2012 mean monthly inflow (red) and corresponding outflow (blue) from the Shasta Reservoir to the Sacramento River in California. Data obtained from the California Department of Water Resources (www.water.ca.gov).
State of water resources management and modeling in California

California serves as an ideal test case for integrating reservoir management into GCMs due to the widespread availability of existing in-situ hydrologic observations and the intense system of water resource management being practiced in the region. Although the extensive management system has provided a significant boost to the economy by increasing agricultural productivity and hydroelectricity (Hanak et al., 2011), this has simultaneously led to a host of environmental problems associated with natural flow regime alterations and corresponding negative consequences for aquatic species populations (Poff et al., 1997). In-stream flow requirements exist for a number of streams to mitigate this ecological impact, but these flows are often inadequate at preserving the natural flow regime required to sustain all the biotic components of an ecosystem (Richter et al., 2003).

Further exacerbating these problems are the anticipated affects on water resources from climate change. Mean surface air temperatures are projected to increase from 2 to 6°C by 2100, which is expected to have a number of consequences for water supplies in California (Hayhoe et al., 2004). These effects include a reduction in snowpack, shift in peak runoff towards earlier in the season, decrease in reservoir storage later in the season, further deviations from the natural flow regime in rivers, and increase in evapotranspiration (vanRheenen et al., 2004; Mott, 2006; Cayan et al., 2008; Barnett et al., 2008). Simultaneously, the population is anticipated to increase by approximately 250% to 92 million by 2100 (Landis and Reilly, 2003; Viers and Rheinheimer, 2011). Agricultural water demand, which currently accounts for 75% of the total water demand in California (Stanton and Fitzgerald, 2011), is anticipated to stabilize or even decrease from conservation efforts, technological upgrades, and urbanization of agricultural land (Tanaka et al., 2006). Despite this projected stabilization in agricultural demand, the growth in population is expected to increase the overall water demand (Tanaka et al., 2006; Viers and Rheinheimer, 2011). These projected changes in water supplies and demand will likely result in further intensifying the management of these systems (Tanaka et al., 2006; Gleick, 2010; Willis et al., 2011).

Given the anticipated affects on water resources in California, several statewide planning models were developed to improve the management of water resources. Three of the more well-known of these models collective aim is to better optimize groundwater and surface water allocations in California based on economic, management, or climate change considerations (DWR, 2003; Jenkins et al., 2004; Yates et al., 2009). The mechanics of these models as well as their limitations for the proposed work in this study are described in the following paragraphs.

The Water Evaluation and Planning (WEAP) model (Yates et al., 2005) is capable of integrating surface water and groundwater, consumptive and non-consumptive uses of water, as well as water resource management infrastructure and controls into model simulations. It has been used to reproduce hydrologic behavior, evaluate sustainable water use, and provide guidance on appropriate water allocation at local or regional scales (Yates et al., 1995; Vogel et al., 2007; Yates et al., 2009; Sandoval-Solis et al., 2011). WEAP uses a two-bucket water balance approach that partitions water into evapotranspiration, surface runoff, interflow, percolation, and baseflow for any quantity of water simulated to enter a given catchment. Water storages and fluxes are calculated for every reservoir and conveyance within the system at the specified time interval. Model calibration is achieved using a system of linear equations designed to satisfy water demands based on water supply priorities, mass balances, and other constraints (Yates et al., 2005). As exemplified with its application in the Sacramento River Basin, WEAP produces generally good agreement between observed and simulated storage and managed releases (Yates et al., 2009). However, the modeling system is designed for more
detailed, smaller scale applications requiring a relatively high amount of user input. Furthermore, there is no built-in mechanism to simulate climate feedbacks, which are integral to more realistic representations of hydrologic behavior, especially when considering implications of how climate change might impact the water cycle in the future.

The California Value Integrated Network (CALVIN) model (Jenkins et al., 2001) was developed to optimize groundwater and surface water allocations by maximizing the economic benefit for agricultural and urban uses in California based on 2020 levels of human development. An economic optimization model is ideal for its ability to systematically express different management options that involve a variety of alternatives in its solution. The model has been used to derive economically-driven estimates of water scarcity, water transfers, and conjunctive use, as well as evaluate value for reservoirs, environmental flow conveyances, recharge, and recycling facility expansions (Jenkins et al., 2001; Tanaka et al., 2006). CALVIN simulates monthly water allocation decisions based on 1922-1993 hydrologic conditions to ensure a wide range of conditions are represented. Appropriate water allocation is achieved in the model by optimizing to an extensive statewide network of agricultural and urban demands that accounts for 92% of California’s population and 88% of the irrigated acreage (Draper et al., 2003). Water management infrastructure within the model framework includes 51 reservoirs, 28 groundwater basins, 18 urban economic demand areas, 113 surface and groundwater inflows, and numerous conveyance structures (Jenkins et al., 2001). Similar to WEAP, CALVIN lacks the benefits from having climate feedbacks that are found in a GCM. CALVIN is also economically based and highly parameterized so its use is thus confined to more detailed, regional applications in California (Jenkins et al., 2001), while a GCM is physically-based and can be applied at either a regional or global scale and requires minimal user input (Subin et al., 2011; Lo and Famiglietti, 2013).

The California Water Resources Simulation Model (CALSIM) 2000 (DWR, 2003) was designed to aid in water resource allocation decisions for management of the State Water Project (SWP) and Central Valley Project (CVP). CALSIM uses a system of linear equations and constraints that describe physical or operational limitations to route water through these management networks at a monthly timescale (DWR, 2003; Draper et al., 2003). Approximately 24 surface reservoirs, as well as a number of channels, pumping plants, and operational rules are included within the management system component of the model (Parker, 2006). The model uses optimization techniques and user-defined priority weights, to appropriately allocate water through different networks. Regulatory constraints are included in the model, but must be updated every year due to their dynamic nature (CALSIM, 2000). Similar to WEAP and CALVIN, CALSIM lacks climate feedbacks so associated impacts on the water cycle are missed in model simulations. Furthermore, minimal documentation is available to describe the intricacies of model operations and the overall accuracy of model results is largely unknown by its users (Close et al., 2003).

**Reservoir management impacts on surface water resources**

The construction of dams on rivers has had a profound impact on discharge at a global scale. Over the past six decades, the number of large dams taller than 15m has risen to over 40,000 with a cumulative maximum storage capacity of 7,000 to 8,300 km³. Dams have provided many benefits such as boosting global food production by 12-16% and accounting for 19% of the world’s energy (Lehner et al., 2011). Simultaneously, however, the resulting flow restrictions have impacted the flow regime (Vorosmarty and Sahagian, 2000). Deviations from
the natural flow regime are most severe in semi-arid regions such as California where natural flows are already highly variable (Dudgeon et al., 2006). The only free-flowing rivers in the world were found to exist in the sparsely populated regions of North America and Russia, as well as smaller coastal basins in Africa and Latin America (Revenga et al., 2005).

Water storage behind large dams accounts for 20% of the global runoff and 75% of runoff in the United States (Biems et al., 2011). Dams retain 10,000 km³ annually, which represents approximately five-times the volume of the world’s rivers (Dudgeon et al., 2006). In a global assessment of 227 large river systems, 60% were determined to be moderately fragmented, affecting 90% of the total water volume in 227 systems (Revenga et al., 2005). Furthermore, global discharge from impoundments was found to decrease by 0.8%, resulting in a greater than 10% decrease in 17% of the global long-term average river discharge and 25% of global Q90 low flow (monthly discharge exceeded by nine out of ten months) (Doll et al., 2009). In some higher latitude systems, the reduction in peak flows and dam blockage of ice has severely reduced channel and floodplain scouring (Cowell and Stoudt, 2002). Such observations and statistics provide insight into how streamflow variability has decreased from dam construction. Flow modifications will likely become more extreme in the future due to climate change and population growth, leading to more water engineering projects for water supply security (Dudgeon et al., 2006; Arthington et al., 2006).

Currently, over 170 indicator statistics have been developed to characterize the degree of flow alteration on different river systems (Gao et al., 2009). Many of these statistics are inter-correlated, leading to some redundancies in the interpretation of results and subsequent ineffective decisions made by policy makers. Ideally, only a few metrics could serve to accurately and sufficiently describe the characteristics of flow regimes that are relevant to aquatic ecosystems. The most ecologically relevant ecosystem characteristics include the magnitude of monthly streamflows; magnitude, duration, and timing of annual extreme flows; frequency and duration of high and low flow pulses, and rate and frequency of flow changes (Gao et al., 2009). The edecificit and ecosurplus metrics, which are based on the loss or gain in streamflow due to regulation (Vogel et al., 2007), were found to describe these overall flow alterations quite well and are recommended for use in studies involving flow alteration investigations (Gao et al., 2009).

Reservoir Management Implications for Ecology

Alterations to the flow regime have correspondingly large impacts on global river ecosystems. Ecosystems have quality, quantity, and seasonality water requirements that allow for a certain level of fluctuation within the natural range of variability. Variations too far outside this range can result in dire consequences for aquatic species. For example, many species adapt to specific river flow patterns, such as spring peak floods or summer low flows. Not only do such flow patterns subject the adapted species to non-threatening strength in flow, they also result in the appropriate amount of sediment and organic matter inputs, thermal and light intensities, chemistry and nutrient supplies, and relevant biotic assemblages (Baron et al., 2002). Furthermore, seasonal flow patterns often serve as cues for species to disperse, migrate, feed, or avoid predators. In addition, dam impoundments have tripled the mean travel time of rivers to the oceans to greater than one-month, thereby reducing the ability of rivers to flush away contaminants, transport sediment effectively, and maintain adequate oxygen levels to sustain aquatic life (Vorosmarty et al., 1997). Failure to maintain flow patterns within the natural range of variability could thus lead to declines in species populations (Lehner et al., 2011).
Major losses in global riparian biodiversity and species richness have already been observed and some of these losses can be attributed to human-induced shifts in flow patterns. Losses of 19 mammals, 92 birds, 72 reptiles, and 44 species were noted in aquatic ecosystems globally (Dudgeon et al., 2006). The number of freshwater species decreased by 50% between 1970 and 2000, compared to reductions of only 30% and 20% for marine and terrestrial species, respectively, over the same period (Doll et al., 2009). Management of the Colorado River system is so severe that the river has failed to reach its natural terminus in the Sea of Cortez in all but six years since the year the Glen Canyon Dam was completed in 1963. The severity of flow manipulation in this system has led to widespread declines in native fisheries and the failure of cottonwood species to regenerate (Baron et al., 2002). In California, the population of many native fish species is decreasing, partially as a result of dam construction for hydropower and flood control (Hanak et al., 2011).

Based on these detrimental impacts that flow alterations from dam impoundments have on aquatic habitats and associated species, it is critical that environmental flow requirements better mimic the natural variability and range of historic flows. More complex flow requirements should take precedence over simple minimum flow requirements to ensure greater rates of survival for freshwater flora and fauna. Based on the aforementioned considerations, appropriate guidelines for creating adequate flow requirements include recognizing the interconnectivity of aquatic to terrestrial ecosystems, maintaining dynamic flow requirements within the historic range of variability (HRV), and inclusion of sediment, thermal/light, chemical/nutrient, and sustainability of associated biologic populations within the dynamics of the HRVs (Baron et al., 2002). Moreover, flow requirements should provide for the protection of the entire riverine ecosystem and not just focus on single organisms such as trout or salmon species (Dudgeon et al., 2006). Assessments of reservoir management impacts on natural intra- and interannual variability of flow regimes are thus a necessary part of the solution to ensure the biodiversity and ecosystem integrity of affected river systems are upheld (Doll et al., 2009).

### Impact of water resources management in California on climate

The Central Valley of California accounts for one-sixth of the irrigated lands in the United States. This region provides 8 percent of the nation’s agricultural output by value, making it the most productive agricultural region in the country (Faunt, 2009). With much of this irrigation occurring during the hot and dry summers that are typical for the region, the excess water being brought to the surface has been shown to drive evapotranspiration rates past precipitation by 60% on an annual basis. The elevated evapotranspiration has been shown to impact relative humidity (Sorooshian et al., 2011), temperatures (Lobell et al.; 2009; Sorooshian et al., 2011), and horizontal water vapor transport and precipitation patterns on both local and regional scales (Lo and Famiglietti, 2009). These hydrologic changes were simulated to drive up summer runoff in the Colorado River Basin by 56%, resulting in an additional 5-km³ of water transport from the Colorado River to Southern California annually via the All-American Canal (Lo and Famiglietti, 2009). With greater than 60% of this irrigation coming from surface water reserves scattered throughout the state (Hanak et al., 2011), it is critical to better understand the managed reservoir influence on the regional climate.

The management of reservoirs has already been shown to have several important influences on the local and regional climate. Evaluation of data from the North American Regional Reanalysis database has shown reservoirs impounded from large dams to affect nearby available potential energy, specific humidity, and surface evaporation (Degu et al., 2011).
respective influence of reservoirs on these meteorological variables was strongest for regions dominated by semi-arid and Mediterranean climates (Degu et al., 2011), which represent the dominant climate regimes affecting much of California. These impacts were even shown to likely have an influence on local precipitation patterns (Degu et al., 2011). This finding was corroborated by Hossain (2010), who observed increases in extreme precipitation to be related to the locations of large dams and reservoirs. The relationship was particularly robust for the semi-arid regions including the western United States. No causal mechanisms were explored to provide a physical basis for this observation (Hossain, 2010).

METHODS

The methods for this study are divided into three parts with each section designed to take approximately one-year of research. The three sections are described in more detail below.

Development of method to represent reservoir management in a GCM

The goal of this section is to develop a simple method to represent reservoir management using observed records of reservoir inflow, outflow, and storage in California for eventual integration into a GCM. 25 reservoirs will be targeted for model development, which make up the largest in-stream reservoirs by volume in California and account for 78% of the total storage capacity of the 107 major reservoirs (Figure 2). Reservoirs receiving a significant proportion of storage from federal, state, or local water projects will be excluded from the analysis, as the impacts from such linkages on the flow regime are outside the scope of this study.

The model will be developed offline based on the continuity of mass equation where reservoir releases are determined from the sum of change in reservoir storage and inflow (Karamouz and Houck, 1987). Model development will proceed following the general guidelines for reservoir dynamics in California, where reservoirs are drawn down from early summer into early fall to meet peak water demands, and allowed to fill during the recharge season from late fall to late spring. Adequate space is maintained during the winter and early spring to capture potentially large flows and lessen the risk of downstream flooding (Yates et al., 2009). The system of equations

Figure 2: Initial study reservoir and dam locations
developed to represent reservoir management that follow this dual-season storage behavior is included in Figure 3.

Reservoir releases during the summer months will be determined by a parameterized fraction of the storage (Figure 3). This follows the linear reservoir concept (Dingman, 1994; Buytaert et al., 2004), which is commonly used to explain the catchment response to reservoir management (Equations 1-2).

\[
\begin{align*}
Q_{out}(t) &= k*S(t) \\
\frac{dS}{dt} &= -Q_{out}(t)
\end{align*}
\]

\[
Q_{out}(t) = \begin{cases} 
\frac{\beta}{\Delta t} S(t - \Delta t) & 6 \leq \text{month} \leq 10 \\
\alpha Q_{in}(t) & \text{month} < 6 \text{ or month} > 10 \\
Q_{in}(t) + \frac{S(t) - S_{max}}{\Delta t} & S_t \geq S_{max}
\end{cases}
\]

\[
S_t = S(t - \Delta t) + (Q_{in}(t) - Q_{out}(t))\Delta t \quad \text{all months}
\]

Figure 3: Equations used to represent reservoir management. **Input Variables:** $Q_{in}$ = Reservoir inflow (m$^3$/s); **Modeled Variables:** $Q_{out}$ = Reservoir outflow (m$^3$/s); $S$ = Storage (m$^3$); **Model Parameters:** $\alpha$ = Winter inflow fraction; $\beta$ = Summer storage fraction; **Constants:** $\Delta t$ = Change in time (month); $S_{max}$ = Maximum storage capacity (m$^3$).

where $Q_{out}$ is the reservoir outflow (m$^3$/s), $k$ is the rate constant (1/T), $S(t)$ is the reservoir storage (m$^3$) as a function of time, and $dS/dt$ is the change in reservoir storage over time. Given that $k = 1/T$, Equations 1-2 can be combined and re-written as Equations 3-4.

\[
\begin{align*}
Q_{out}(t) &= Q_0 \exp(t/T) \\
\ln(Q_{out}) &= \ln(Q_0) - t/T
\end{align*}
\]

where $Q_0$ is the initial reservoir outflow. The reservoir rate constant determines the time it takes the reservoir to drain until reservoir outflow falls to 37% of the initial outflow (Buytaert et al., 2004). During the non-summer months, reservoir releases will be determined by a parameterized fraction of the inflow (Figure 3). This change in method used to determine reservoir releases was necessary, as inflow typically exceeds monthly reservoir releases during the non-summer months in California. The relationship between inflow and outflow during these months stays largely linear, as shown for November to May in Figure 1.

Reservoir releases will be simulated using only inflow and the maximum storage capacity of the reservoir being modeled as user input. This serves to facilitate eventual integration into the GCM, as inflow can be easily derived from one of the GCM output variables when routed through a river routing model. Optimization will be achieved by changing parameter values to find the minimum error between observed and modeled reservoir storage and outflow using nonlinear optimization via the Nelder-Mead simplex algorithm (Nelder and Mead, 1965). Both the root-mean-squared-error (RMSE) and normalized RMSE (nRMSE) (Equations 5 and 6) will be used as objective functions, with the latter serving to lessen the emphasis on minimizing error for higher magnitudes of storage and outflow (David et al., 2011a).

\[
\begin{align*}
\text{RMSE} &= \sqrt{(1/n)\sum(y_o - y_i)^2} \\
\text{nRMSE} &= \sqrt{(1/n)\sum((y_o - y_i)/y_o)^2}
\end{align*}
\]
where \( n \) is the number of observations, \( y_0 \) is the observed time series, and \( y_i \) is the simulated time series. The final selection of appropriate objective function for use in the model will depend on a comparison of model performance statistics, including correlation coefficient, RMSE and Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Krause et al., 2005). Necessary improvements to the model will be made based on the results of these statistics and how well modeled discharge and storage capture the seasonal and interannual variability of observed records.

Optimization of parameter values will proceed for each individual reservoir initially. A uniform set of initial parameter values will be used for all reservoirs during optimization, as determined by best model performance from experimenting with different combinations of initial parameter values for all the reservoirs. Averages of the optimized parameter values will then be used to run the model for all the reservoirs and the resulting performance of the model will be evaluated.

The use of dynamic parameter values will be assessed by attempting to generalize the parameters to different characteristics of the local climate or reservoir. This will be achieved by regressing final best-fit parameter values from the individual reservoir optimization experiments against the reservoir storage capacities and annual inflow. Linking the best-fit parameter values to storage capacities and annual inflow will be useful for developing dynamic parameter values that could be used to easily generate reservoirs within the GCM upon integration. Secondly, the parameters will be linked to apparent water-year type based on the previous October to May wet season inflow. This will be achieved by dividing the October to May inflow for each reservoir into below-normal, normal, and above-normal inflow. Parameter values will then be adjusted within each of these apparent water year types for the different reservoirs in an alternative attempt to develop dynamic parameter values and improve model performance. The use of dynamic model seasons to improve model performance will also be explored by expanding and contracting the modeling season based on apparent water-year type.

Observed records for model development will be obtained from the California Data Exchange Center (http://cdec.water.ca.gov/), which includes reservoir and flow data from the USBR, DWR, the US Army Corps of Engineers (USACE), and the US Geological Survey (USGS). These records include storage, inflow, and outflow from major dam locations. The reported outflow is based on a calculation involving hydropower generation and excess volume topping the spillway or other outlet works, if present. Inflow is derived from the change in storage over the previous month, outflow, and measured losses from evaporation. Storage is derived from measurements of reservoir elevation and the change observed over the previous month (Personal Correspondence: Stacey Smith, USBR). Storage losses from seepage and sedimentation at the base of the dam are not included in the observed records. Annual mean seepage loss rates from reservoirs have been estimated at 5% of total volume at a global scale (Gleick, 1992).

Analysis of available data reveals a number of the major California reservoirs to be inadequate for integration into the study and many others to contain major gaps in hydrologic records (Table 1). Several methods will be utilized in an attempt to address data gaps in inflow, outflow, or storage observations. Missing inflow or outflow data will be derived from the Drainage Area Ratio (DAR) method (Equation 7).

\[
\frac{Q_1}{A_1} = \frac{Q_2}{A_2}
\]  

(7)
where $Q_1$ (m$^3$/s) and $A_1$ (m$^2$) are monthly streamflow and upstream watershed area from one watershed and $Q_2$ (m$^3$/s) and $A_2$ (m$^2$) are monthly streamflow and upstream watershed area from an adjacent watershed, or one with similar climate conditions. This method will be used in cases where portions of the streamflow record from one watershed are unknown, while the record from an adjacent watershed over the same period is known. The climate conditions between the two watersheds must be similar for this method to produce reasonably accurate results (Farmer and Vogel, 2013). Alternatively, storage-outflow ratios during months when this information is known could be used to derive estimates of one of these variables for a month when its value is unknown. As long as two of the three variables are known in the conservation of mass equation (Equation 8), either method could be used in conjunction with this equation to derive one of the other missing variables.

$$\Delta S = Q_{in} - Q_{out}$$  \hspace{1cm} (8)

where $\Delta S$ (m$^3$) is the monthly change in reservoir storage, $Q_{in}$ (m$^3$/s) is monthly reservoir inflow and $Q_{out}$ (m$^3$/s) is monthly reservoir outflow (m$^3$/s).

**Integration of reservoir management in CLM to evaluate flow regime changes and implications for ecology**
The goal of this task is to integrate the reservoir management equations (Figure 3) into the land surface model to evaluate flow alterations and implications for downstream ecosystems. The reservoir equations will be integrated into the land modeling component of the Community Earth System Model (CESM) known as the Community Land Model (CLM) (Oleson et al., 2010). The use of land surface models such as CLM are ideal for this application because they represent one of the few tools capable of simulating all the components of the terrestrial hydrologic cycle with climate feedbacks when run in conjunction with the atmosphere component of CESM as a GCM (Gornitz et al., 1997; Goteti et al., 2008; Lo and Famiglietti, 2013). Therefore, these models provide a more realistic physical representation of water storages and fluxes than other large-scale models. Furthermore, despite its proposed application in a regional setting such as California, the use of global models is preferred over regional models for eliminating the problem with having to derive boundary conditions in a regional-scale analysis (Lo and Famiglietti, 2013).

The reservoir equations will be incorporated directly into CLM using Fortran. CLM will be run for California using ¼-degree spatially and temporally resolved North American Land Data Assimilation System (NLDAS) meteorological forcing data (Mitchell et al., 2004). The discharge portion of the output will be routed to river channels using RAPID (David et al., 2013). The model will be run from 1979 to the current period with approximately 10-15 years of spin-up depending on when the land reaches equilibrium with the simulated climate (Oleson et al., 2010). The regional analysis will then proceed by running the model at 1-km spatial and monthly temporal resolution and routing the runoff to river channels using RAPID (David et al., 2011b). The representation of reservoirs developed offline will be integrated by using the generated monthly runoff as inflow and the parameters to simulate downstream releases during the different model seasons. This will generate a new storage variable that will increase or decrease through time depending on the season and dominant meteorological conditions. Storage losses from evaporation will be derived using a simple temperature-based equation and will also be simulated within CLM.

Reservoir management impacts on the flow regime will be determined by analysis of changes to different flow metrics deemed important to stream ecosystems when running the model with and without reservoir management. Specific flow metrics to be analyzed will include those that can be calculated using monthly flow data such as the long-term average flows (LTA), statistical low flows (LF), seasonal amplitude (SA), seasonal regime (SR), seasonal flow shifts (TS), and interannual variability of monthly flows (IV) (Richter et al., 1997; Richter et al., 2003; Doll et al., 2009). Evaluations of these metrics will also focus on how the magnitude of flow alterations might be influenced by different reservoir functions (water supply, hydropower, flood control, recreation), maximum storage capacity, reservoir residence times (storage capacity: inflow or storage capacity: outflow ratios), and magnitude of flow regulation (reservoir storage capacity / mean annual inflow or outflow). The implications these respective flow alterations have on aquatic ecosystems including fish, macroinvertebrates, and vegetation will be described.

Finally, time permitting, biological data will be obtained from locations immediately upstream and downstream of reservoirs in the model to derive ecosystem impacts from reservoir flow alterations, as determined in model simulations. Data sources may include time series of point observations, models, or satellite-derived biological survey datasets of fish, macroinvertebrates, and riparian vegetation from locations just upstream and downstream of reservoirs. Satellite-derived biological datasets would focus on deriving changes in vegetation coverage from upstream and downstream locations. Historic LANDSAT satellite images with spatial resolutions as fine as 15-m that cover the modeling period would be used for this purpose.
Because the biological data will come from locations just upstream and downstream from the reservoirs, the influence that changes in factors unrelated to reservoir management (such as water quality) might have on the biological populations will be controlled.

Integration of reservoir management in a GCM for evaluation of climate feedbacks

The goal of this task is to evaluate reservoir management impacts on the regional climate system in California by integrating the reservoir management equations into a GCM. Using an approach similar to Lo and Famiglietti (2013), the evaluation of climate feedbacks will proceed by simulating CLM coupled with the atmospheric modeling component of CESM. The generated runoff will be routed through RAPID. The GCM will be run at 1-degree resolution globally and the resulting atmospheric and hydrologic conditions for the cells bordering California will be used as boundary conditions for the regional analysis. Approximately 10-15 years will be used as model spin-up, depending on when the land reaches equilibrium with the simulated climate (Oleson et al., 2010). The GCM will be run with and without the reservoir component to determine the influence of reservoirs on the climate feedbacks affecting the water cycle. Specific variables to be analyzed include water vapor, evapotranspiration, and precipitation (Lo and Famiglietti, 2013).

PRELIMINARY MODEL DEVELOPMENT AND RESULTS

The equations used to represent reservoir management and comparison of modeled and observed reservoir discharge and storage for the three largest reservoirs in California were presented at the 2012 AGU fall meeting (Solander et al., 2012). Since this time, the reservoir management equations have been further revised and applied to five additional major California reservoirs resulting in a total of eight reservoirs being utilized in model development (see shaded reservoirs in Table 1). These eight reservoirs represent approximately 41% of the total storage capacity from the 107 major reservoirs. Additional reservoirs will be added to the model development phase depending on data availability and ability to adequately fill-in data gaps.

Model parameters were optimized for each reservoir on an individual basis. Both the RMSE and normalized RMSE (see Equations 3 and 4) were used in model development. Because the model improved only marginally with the use of the nRMSE cost function, the RMSE cost function was selected for final parameter optimization at each reservoir.

Table 2: Results summary for offline model simulation using 8 major California reservoirs with continuous time series of reservoir storage, inflow, and outflow. Results include initial and final parameter values, $Q_{\text{out}}$ (outflow) and $S$ (storage) normalized RMSE and $R^2$, and $Q_{\text{out}}$ (outflow) Nash-Sutcliffe Efficiency (NSE) values.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>$\alpha$ (Initial)</th>
<th>$\beta$ (Initial)</th>
<th>$\alpha$ Final</th>
<th>$\beta$ Final</th>
<th>nRMSE $Q_{\text{out}}$</th>
<th>nRMSE $S$</th>
<th>$R^2$ $Q_{\text{out}}$</th>
<th>NSE $Q_{\text{out}}$</th>
<th>$R^2$ S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shasta</td>
<td>0.75</td>
<td>0.2</td>
<td>0.57</td>
<td>0.17</td>
<td>3.37</td>
<td>0.46</td>
<td>0.75</td>
<td>0.52</td>
<td>0.84</td>
</tr>
<tr>
<td>Oroville</td>
<td>0.75</td>
<td>0.2</td>
<td>0.61</td>
<td>0.15</td>
<td>3.58</td>
<td>0.40</td>
<td>0.84</td>
<td>0.64</td>
<td>0.90</td>
</tr>
<tr>
<td>Trinity</td>
<td>0.75</td>
<td>0.2</td>
<td>0.44</td>
<td>0.08</td>
<td>14.52</td>
<td>0.91</td>
<td>0.60</td>
<td>0.13</td>
<td>0.88</td>
</tr>
<tr>
<td>New Melones</td>
<td>0.75</td>
<td>0.2</td>
<td>0.24</td>
<td>0.10</td>
<td>5.95</td>
<td>0.12</td>
<td>0.57</td>
<td>-0.40</td>
<td>0.91</td>
</tr>
<tr>
<td>Pine Flat</td>
<td>0.75</td>
<td>0.2</td>
<td>0.41</td>
<td>0.34</td>
<td>21.00</td>
<td>0.71</td>
<td>0.76</td>
<td>0.46</td>
<td>0.83</td>
</tr>
<tr>
<td>Folsom</td>
<td>0.75</td>
<td>0.2</td>
<td>0.71</td>
<td>0.30</td>
<td>1.07</td>
<td>0.57</td>
<td>0.87</td>
<td>0.72</td>
<td>0.71</td>
</tr>
<tr>
<td>Millerton</td>
<td>0.75</td>
<td>0.2</td>
<td>0.60</td>
<td>0.47</td>
<td>4.60</td>
<td>1.10</td>
<td>0.79</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>New Hogan</td>
<td>0.75</td>
<td>0.2</td>
<td>0.45</td>
<td>0.11</td>
<td>12.81</td>
<td>0.12</td>
<td>0.78</td>
<td>0.61</td>
<td>0.83</td>
</tr>
<tr>
<td>Average</td>
<td>0.75</td>
<td>0.20</td>
<td>0.50</td>
<td>0.22</td>
<td>8.36</td>
<td>0.55</td>
<td>0.75</td>
<td>0.38</td>
<td>0.78</td>
</tr>
</tbody>
</table>
presents a summary of results for the eight reservoirs, including initial and final parameter values and model performance metrics. Modeled and observed discharge and storage for the Shasta Reservoir, which is the largest reservoir in California, are shown in Figures 4 and 5.

![Graph of Shasta Reservoir Monthly Outflow (1995-2012)](image)

**Figure 4**: 1995 to 2012 Shasta Reservoir observed and monthly outflow.

![Graph of Shasta Reservoir Monthly Storage (1995-2012)](image)

**Figure 5**: 1995 to 2012 Shasta Reservoir observed and monthly storage.
Initial results indicate the model shows promise for providing more realistic estimates of water storage and fluxes. Outflow $R^2$ values range from a minimum of 0.57 at New Melones to a maximum of 0.87 at Folsom with an average of 0.75 among all the reservoirs. Storage $R^2$ values fared better, ranging from a minimum of 0.36 at Millerton to a maximum of 0.91 at New Melones with an average of 0.78 among all the reservoirs. Nash-Sutcliffe Efficiency values ranged from a minimum of -0.40 at New Melones to a maximum of 0.72 at Folsom with an average of 0.38 among all the reservoirs.

The less robust results at Millerton and New Melones indicate that additional model development must be conducted prior to commencing integration into CLM. Moreover, the modeled storage and outflow at Millerton was negative for many months. Closer inspection of these results indicates the negative modeled storage and outflow is associated with elevated observed monthly inflows and outflows in conjunction with late spring to early summer peak runoff and the commencement of reservoir drawdown season. Further evaluation and model development is required to address these errors in model results.

**EXPECTED OUTCOMES AND SIGNIFICANCE**

This study will directly result in the following:

- Developing a simple method to represent reservoir behavior for use in a GCM
- Exploring the use of GCMs as tools to evaluate flow alteration implications for associated aquatic ecosystems
- Improving the representations of hydrologic fluxes and storages and climate feedbacks within a GCM
- Provide insight into how well balanced the system of water resources management in California is between humans and the environment
- Setting the stage for GCM applications with integrated reservoir management at a global scale

The use of a coupled land-atmosphere model that includes climatic, hydrologic, and ecosystem impacts in the analysis of results offers a more holistic approach to water resources modeling and management than what is typically achieved in hydrologic model applications. By offering different methods to explore how reservoir management impacts hydrology and the climate system, this research will result in a better understanding of sustainable water use between humans and environment. Furthermore, integrating reservoir management in a GCM at a regional scale will help lay the foundation for simulations that could be used to derive the same information at a global scale. This research will thus be beneficial for a more comprehensive understanding of sustainable water resources management not only at a regional, but global scale.

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