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Risk Analysis for Water Resources
Under Climate Change, Population Growth, and Land Use Change

By

Michael Jason Kiparsky

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

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in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor William Michael Hanemann, Chair
Professor William A. Collins
Professor Richard B. Norgaard

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Risk Analysis for Water Resources Under Climate Change, Population Growth, and Land Use Change

Abstract

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By

Michael Jason Kiparsky

Doctor of Philosophy in Energy and Resources

University of California, Berkeley

Professor W. Michael Hanemann, Chair

My dissertation research poses two overarching questions. First, how do climate change, land use change, and population growth compare and interact as drivers of change to future water demands and supply in California's Central Valley? Second, how can risk be integrated into such assessments of climate impacts?

To address the first of these questions, I built and calibrated an integrated hydrology and water operations model to simulate the historical water system operations in the Stanislaus, Tuolumne, and Merced river basins in California's Central Valley. I then drove this model over the course of the century using simulations of climate change, population growth, land use change and water use efficiency to compare the effects on water demands and water supply reliability.

Model results indicate that in the rapidly urbanizing study area, with projected low-density growth displacing farmland, the impacts of population and urbanization on water demands are greater than that of climate change alone. The net effect throughout the study area is decreasing water demands, driven by removal of acreage from agricultural production. Although climate change considered alone results in decreasing water supply reliability, population growth and land use change mute the effect.

To address the second question with risk analysis, I developed a method for quantifying risk preferences of water managers, using the economic concepts of risk aversion (the desire to avoid and manage risks) and loss aversion (a tendency for people to strongly prefer avoiding losses to acquiring gains). I applied the method in interviews with managers responsible for water supply to irrigation districts in the study area. My interviews revealed high levels of both risk aversion and loss aversion when it comes to their duties in water provision for agricultural customers.

I then combined the risk preferences with output from the climate-driven hydrology modeling to estimate expected utility under climate change. Model results for water supply under climate change give lower expected utility for managers than when assuming historical conditions, indicating that impacts of climate change will be negative for the water sector in this region regardless of the degree of managers' risk aversion. However, the expected utility for decision

makers is strongly influenced by their risk preferences, and these risk preferences are stronger determinants of results for expected utility than are climate conditions.

The results highlight the importance of considering land use as a driver of water system change, especially when invoking population growth as a driver of change. They also show the limitations of climate impacts assessments that do not incorporate other major stressors, complementing previous path-breaking global-scale efforts and highlighting the importance of place-specific, spatially explicit analyses.

The analysis reported in this dissertation supports the notion that managers' risk preferences may be underutilized in impacts assessment, and in particular that ignoring them may understate estimates of climate change impacts. If results using this and other methods on water managers stand to scrutiny and repeated application, and particularly if variants produce congruent results in other sectors of resource management, they may also indicate that loss aversion on the local scale could drive the use of risk analysis in global scale integrated assessment.

For Bree and Chloe

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Acknowledgements

While this dissertation has a single author on its cover, it could not have come to fruition without a large cast of characters. The years of effort represented in these pages are in no small part a reminder of the importance of support from mentors, colleagues, friends, and family. I benefitted from inspiration and substantive help from all those listed below, but responsibility for any shortcomings in this document, including inadvertent omissions from this list, lies with me alone.

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1 Chapter 1 – Climate change, risk, and water resources

1.1 Motivation and context

There is a near consensus among scientists that the Earth’s climate is changing, and that under even the best-case scenarios of emissions and climate sensitivity, climate impacts are virtually certain (Oreskes 2004; IPCC 2007b). Climate change is a global environmental problem, but humans will be most concerned with the local and regional effects. Impacts on hydrology will cascade directly into human and ecological systems at all scales. In California, as in other snow dominated watersheds, climate change will result in reduced snowpack storage, reduced streamflow, and changing seasonal flow patterns that will challenge the resilience of coupled water, energy, agricultural, and ecological systems (Barnett et al. 2005; Barnett et al. 2008). The scientific community has shown a growing recognition of the importance of adaptation (adjustment of human systems to moderate harm from climatic stimuli) as a response to climate change (Parry et al. 2009). In turn, scientists and policymakers alike increasingly view adaptation as a complement to mitigation (reduction of greenhouse gas emissions), rather than a potential competitor for policy-makers’ attention (IPCC 2007a; Pielke et al. 2007), and as a critical component of responses to climate change at Federal, regional, and local levels (King 2004; California Department of Water Resources 2006; Dessler and Parson 2006; Luers and Moser 2006; IPCC 2007a; Pielke et al. 2007; United States Government Accountability Office 2009).

Adding urgency to the challenge posed for future planning for climate change, the impacts of population growth and land use change have not been adequately addressed, nor do they currently garner as much attention as climate change impacts. Work from the local (Seager et al. 2009) to the global (Vörösmarty et al. 2000) scale suggests that effects of population growth may present challenges that rival or exceed the importance of those of climate change. Hydrologists also suggest that impacts of land use change, which often occurs concomitant with population growth, represents an understudied but clearly important frontier in the understanding of hydrologic processes (DeFries and Eshleman 2004).

Thus, two observations form the central motivation for the work presented here. First, climate change will not take place on a static stage – other aspects of the global system will be changing, and impacts assessments that include those other changes will be more powerful decision-making tools for adaptation. Second, given the uncertainties inherent to (Roe and Baker 2007) projections of climate change and other future impacts, such forward-looking assessments are intrinsically about risk.

In spite of the abovementioned observations, research on climate adaptation has lagged far behind mitigation research, studies on impacts and adaptation to multiple stressors simultaneously have not been sufficiently investigated, and risk is not yet integrated into either local-scale climate responses or global scale assessments of climate impacts.

1.1.1 Overview of contributions

This dissertation addresses two lacunae in the literature on climate impacts and adaptation in water resources. First, to date, while most global analysis of the impacts of increasing atmospheric greenhouse gas (GHG) concentrations incorporate scenarios of socio-economic change as drivers of changes in GHG production, many regional studies focus on sector-specific sensitivity analysis of the resulting impacts, often assuming static conditions aside from those directly driven by changing climatic inputs. The first set of results in this dissertation brings together multiple stressors in addition to climate change, and supports the notion that if scientific results are to be useful to decision-making about adaptation, climate change cannot be considered in isolation from other drivers of change. It broadens impacts assessment from climate-specific analysis to also include comparisons and multi-stressor assessments that explicitly include regional projections of population growth, land use change, and water use efficiency in addition to downscaled climate change.

The second advance described in this dissertation is an integration of risk preferences (decision-makers' responses to risk) to a regional climate impacts analysis. As described below, economic theory points to risk preferences (risk aversion, risk neutrality, and risk seeking behavior) as important theoretical and empirically demonstrated components of human decision-making (Chavas 2004; Eeckhoudt et al. 2005). While risk aversion has begun to be discussed in global scale modeling of economic impacts of climate change (Stern 2007; Anthoff et al. 2009) it has not been integrated into climate impacts assessments at the level of local decision-making. A key goal of this dissertation is to integrate economic risk analysis, and in particular risk aversion, into an impacts assessment focused on local decision-maker risk preferences.

To address these two issues, I use Integrated Assessment (IA) modeling. IA can be broadly defined (Parson and Fisher-Vanden 1997) as the quantitative translation of climate change impacts from global scale, coarse grained coupled Ocean-Atmosphere General Circulation Models (GCMs) to representations of things we care more directly about, such as water supply. IA (Parson and Fisher-Vanden 1997) describes potential impacts and adaptation options quantitatively by integrating results from multiple models. This can be done using a cascade of modeling information, from large-scale, coarse-grained models, to finer resolution models that cover less spatial or conceptual area but represent specific processes of interest in more detail. Figure 2 gives an overview of the conceptual structure of the integrated assessment, and Figure 3 depicts the methodological structure used to address the questions posed. The following sections describe briefly the component parts of the modeling effort, which are detailed in the chapters that follow.

IA modeling can be applied descriptively, such as when used to clarify the projected impacts of climate change on a system of interest, or prescriptively, if it were to be used as part of decision-making about appropriate responses to projected changes. The dissertation attempts to contribute on both fronts, ultimately to inform adaptation responses.

1.1.2 Climate, hydrology, and water resources

Hydrologic systems are among those most vulnerable to climate change (IPCC 2007a). Hydrology is directly influenced by climatic variables, and modeling studies consistently suggest that hydrology will be sensitive to changes in climate (Arnell and Liu 2001; Kundzewicz et al. 2007). Indeed, these changes are already upon us; observations have revealed climate-driven hydrologic changes at multiple spatial scales (Roos 1987; Barnett et al. 2005; Knowles et al. 2006; Zhang et al. 2007; Barnett et al. 2008). Two decades ago, Gleick (1987) demonstrated the sensitivity of California's snowmelt-dominated hydrology to climate warming scenarios. Since then, the fundamental conclusion that climate warming will lead to an earlier hydrograph peak in snowmelt-dominated basins has proven robust over dozens of studies globally (Barnett et al.

2005), in the Western U.S. (Stewart et al. 2004), and in California (Kiparsky and Gleick 2003; Vicuna and Dracup 2007). Such changes in hydrology may impact the ability of California's water system to deliver water supplies during peak demand in the dry summer months (Vanrheenen et al. 2004).

Thus, water resources present an important venue for examining potential climate impacts and adaptation. Recent studies disagree about the potential difficulty of adapting to climate change in water resources. For example, Tanaka et al. (2006) apply an economic optimization model to adaptation in California water, and conclude that the costs of adapting to climate change will be high for the water sector, but small relative to California's overall economy or budget. However, they acknowledge that their approach may produce optimistic results, partly because it assumes perfect foresight by water users in the face of hydrologic uncertainty and partly because it overlooks key geographical and institutional aspects of the system. VanRheenan et al. (2004) integrate hydrology modeling to their impacts analysis and conclude that "...achieving and maintaining status quo ... system performance in the future would be nearly impossible, given altered climate scenario hydrologies." The contrast between the above studies suggests that impacts need to be further studied, that efforts to quantify the risks to the system from these impacts may be useful to those who will need to manage those risks, and that choice of methods matters.

1.1.3 Risk-based frameworks for climate impacts assessment

Because of the inherent uncertainties, climate change assessment and adaptation strategies are fundamentally about risk. Although definitions of uncertainty and risk vary widely, for the purposes of this dissertation, uncertain events are those with unknown probabilities (Chavas 2004), because of error in measurement, natural variability or epistemic uncertainties (Morgan and Henrion 1990). In contrast, economists consider risky events to be those for which probabilities can be estimated (Chavas 2004), and risk generically is the product of these probabilities times the consequences of the events as defined for a given decision-maker. More concrete definitions of risk and risk preferences follow in the text along with a description of my approach to formalizing each.

Decision-making without estimates of uncertainty or risk amounts in effect to ignoring the uncertainty present in any model (Beven 2000; Oreskes 2003), which may hinder the effectiveness of decision-making by water managers. Risk assessment combines probabilistic estimates of impacts with the consequences to given agents, but the definition of 'risk' depends on the context.

While a large body of theoretical and empirical literature demonstrates that risk aversion is a critical component of human decision-making (Chavas 2004; Eeckhoudt et al. 2005), and thus important to the real-world implications of uncertainty for human behavior, this has scarcely been used in climate change assessments in spite of the inherently uncertain nature of climate change. In particular, climate impacts assessments have not explicitly taken the risk aversion of public and private decision-makers into account in analysis of vulnerability and adaptation on regional and local scales. Incorporating risk aversion into models of impacts and responses may be a critical next step in understanding human responses to a changing geophysical setting. Impacts assessments in water supply analysis in large-scale systems could benefit from more sophisticated risk analysis.

As methods advance for incorporating probabilistic information into climate models, it is becoming increasingly clear that climate change impacts assessments need to move from deterministic approaches towards incorporating uncertainty and risk (Jones 2000; Dessai et al. 2007). Recently, the Stern Review employed an integrated assessment model which explicitly incorporated risk aversion for the global-scale economic assessment of climate impacts (Stern 2007), fueling an active debate about the importance of risk aversion (the desire to manage events so as to reduce risk) (Nordhaus 2007; Stern and Taylor 2007; Anthoff et al. 2009).

The importance of risk aversion is only recently beginning to receive attention in the context of climate change. The central notion is that a risk averse decision maker will evaluate uncertain quantities not on the basis of their expected value but rather by adding a risk factor (a risk premium) that serves to discount expected gains (raise expected losses) associated with the uncertainty (Chavas 2004). The risk premium is greater the larger the degree of risk aversion and the greater the magnitude of the uncertainty. A related concept is that of loss aversion, a tendency for people to strongly prefer avoiding losses to acquiring gains, which has been described theoretically and empirically as different behavior above and below a defined threshold value (Fishburn 1977; Bawa 1978; Kahneman and Tversky 1979; Tversky and Kahneman 1992). Loss aversion, when combined with notions from expected utility theory, leads to the notion of downside risk: the potentially different treatment of risk above and below a threshold between perceived losses and perceived gains (Markowitz 1959; Fishburn 1977).

The focus of this study is water users in Central Valley of California. These include both agricultural and urban water users, users of hydropower, and environmental stakeholders, as well as the management of the water districts supplying these uses that face strong incentives to be responsive to the districts' customer base and regulations. The different water users have different potential responses to disruptions in water supply. They face different economic costs and have different tolerances for risk, and therefore different risk premiums. The districts' own risk preference will reflect some weighting of the interests of their various users.

1.1.4 Water management

Water planning and management in the U.S. is primarily a local affair for several reasons. First, there is tremendous fragmentation in retail water supply; broad regional supply organizations are the exception rather than the rule (Thompson Jr. 1993; Lund 2006). (Consider the following contrast: while about 80% of all electricity users in California are supplied by three large investor-owned retail electric utilities and two large municipal ones, water users in California are served by about 125 urban water agencies and 300 agricultural ones.) Second, water rights are governed by state law, not federal law (Sax et al. 2006), and this contributes to heterogeneity. Furthermore, a fundamental principle of state law for surface water in the Western U.S. is that water rights should be based on historical use – this is enshrined in the prior appropriation doctrine (Sax et al. 2006). This is a system that elevates history over rationality, equity or flexibility (Walker and Williams 1982; Worster 1985). The system is also poorly suited to climate non-stationarity (Milly et al. 2008) because, at least at present, there is no legal precedent in most western states for modifying existing water rights to accommodate different climatic conditions (Doremus and Hanemann 2008).

Against this backdrop of a legal system unlikely to be resilient in the face of climate change, a disconnect exists between institutional assumptions and scientific understandings of climate. The historical climate in which the institutional system evolved (Sax et al. 2006) does not capture extreme droughts in the paleoclimate record (Stine 1994; Meko and Woodhouse 2005; Woodhouse and Lukas 2006) or the increase in extreme events projected by climate modelers (IPCC 2007b; IPCC 2007a). Water users may thus be more vulnerable to climate risk than they realize.

Alongside the inflexibility of the legal structure of water rights, social scientists have observed that U.S. water organizations are conservative and risk averse (Haddad 1999; Lach et al. 2005). These organizations tend to make marginal and incremental change even in situations where more fundamental legal, technical, and behavioral innovation are warranted because of institutional conservatism (Rayner et al. 2005), although perceptions of acute risk can motivate action such as the use of weather forecasts (O'Connor et al. 2005).

The importance of legal and management institutions as drivers of local responses to a global phenomenon, combined with a tendency towards risk aversion, suggests that local-scale assessment of adaptation with estimates of risk aversion will improve projections of adaptive response to climate change, and that water resources is a logical arena for integrating risk aversion and climate impacts.

1.1.5 Parallel stressors: Regional climate change on a dynamic stage

Climate change has received increasing attention by scientists as a driver of future impacts on coupled human-natural systems, in particular on hydrology and water resources. However, climate change will not play out on a static stage. Scientists have long understood that other changes will co-occur with climate change. For example, on a global scale, the SRES scenarios that drive climate change modeling under different greenhouse gas emissions trajectories incorporate different scenarios of population growth, economic activity, resource use, and other factors, and thus imply that these and other associated factors will not remain static.

The magnitude of the associated responses, let alone their interplay, has not yet been sufficiently explored.

In water resources, researchers have long recognized the importance of other drivers of change on water systems. Vorosmarty et al. (2000) compared the projected effects of population growth and climate change, concluding that rising demands would outweigh climate-induced hydrologic changes as drivers of water stress by 2025. Similarly, Saeger et al. (2009) suggest (in a conclusion that was tangential to the focus of their paper, yet received much media attention) that recent drought impacts in the Southeastern US are likely attributable more to increasing demand than an anthropogenic climate change signature.

Land use change, whether directly or indirectly associated with population growth, will continue to be a primary anthropogenic change to the earth system, with its own set of associated impacts. There has been work done on land use and its impacts on watershed hydrology such as on the hydrologic impacts of forest management practices (Harr et al. 1982; Stednick 1996) and urbanization (DeWalle et al. 2000; Beighley and Moglen 2002; Claessens et al. 2006). However, in spite of the acknowledged likely importance, the consequences of land use change on hydrology, let alone on water resources management, remains an understudied topic (DeFries and Eshleman 2004).

What emerges from these examples is not only the importance of scale and unit of analysis, but also the difficulties of generalizing from global hydrology to local cases. If land use change and population growth are indeed generalizably significant in their relative impacts on water systems, it argues for their inclusion in all climate impacts studies. Indeed, if such impacts are projected to be widespread, then climate change studies, if climate is the only variable altered, will be useful as sensitivity analyses, but may be of limited value for decision-making in adaptation if they are not contexualized among other stressors.

The importance of legal and management institutions as drivers of local responses to a global phenomenon, combined with a tendency towards risk aversion, suggests that local-scale assessment of adaptation with estimates of risk aversion will improve projections of adaptive response to climate change, and that water resources is a logical arena for integrating risk aversion and climate impacts. This dissertation builds on the theoretical work cited above by quantifying the implications of this risk aversion.

1.2 **Case study: San Joaquin River Basin, California**

The Stanislaus, Tuolumne, and Merced River Basins (STM) in California's Central Valley (Figure 1) together form an ideal case for integrating risk assessment into a study of climate adaptation. The three basins are on the western slope of the Sierra Nevada Mountains, where hydrology will be sensitive to climate change (e.g. Gleick 1987; Knowles and Cayan 2002; Dettinger et al. 2004; Stewart et al. 2004). Constraints below (water quality regulations at Vernalis) and above (diversions at Friant Dam deplete flows above the Merced River) the three basins allow for modeling local dynamics within a large and complex system using some reasonable assumptions. Thus, using this case study allows me to ask meso-scale questions, including comparative ones, on a dissertation time scale.

The three basins also have physical and management characteristics that allow me to investigate the geographical determination of climate-induced water supply risk, as well as geographical diversification as a risk reduction strategy. These geophysical characteristics, plus sufficient institutional diversity from which to draw case studies, combine to make the STM basins a rich arena for analysis relevant to climate change impacts and adaptation.

More broadly, California has traditionally been a national leader in the development of innovative environmental policies (Getches 2003), and climate change is no exception (Kiparsky and Gleick 2005; Schwarzenegger 2005; 2006c; 2006b; 2006a; Hanemann 2007; Stern and Taylor 2007; Franco et al. 2008; Kiparsky 2009). Pre-existing attention to these issues may also help the ideas gain support and traction in policy arenas (Franco et al. 2008; Kiparsky 2009).

1.3 **Overview of methods**

The dissertation research uses an integrated assessment model to translate climate change impacts from global-scale models to a regional and watershed scale water model, with the added innovations of 1) incorporating and comparing multiple stressors alongside climate change on local scales, and 2) using economic utility theory to integrate risk preferences of decision-makers and more accurately gage the impacts of increased risk to water supply.

The analysis proceeds in five steps. First, I implement an integrated hydrology and water operations simulation model of the STM Basins using the Water Evaluation and Planning

(WEAP, Yates et al. 2005) modeling framework. Second, driving this model over the period from 2000 through 2099 with an ensemble of downscaled GCM data, and aggregating model results over time slices at mid-century (2035-2064) and end of century (2065-2099) enable me to generate estimates of water supply reliability and associated metrics within the case study basins. Third, this analysis is repeated with comparisons to the model run incorporating projections of urbanization, population growth, and water use efficiency, to evaluate the sensitivity of the model to each of these inputs. Fourth, risk preferences for water organizations in the study basins are described using an empirical application of economic techniques for utility function elicitation. Combined with output from the hydrology model, these utility functions allow estimation of expected utility for water managers under scenarios of future conditions. Finally, scenarios of management options for adapting to projected changes are run under different assumptions of emissions trajectories, allowing for comparison of the expected utility to water organizations under each modeled scenario.

The overall goal is to 1) evaluate the sensitivity of water supply reliability in the three case study basins to climate change, population growth, urbanization, and water use efficiency, and 2) evaluate the utility to each water organization of each climate and adaptation scenario to generate both positive and normative evaluations of decision-making.

1.4 **Contributions and significance**

The dissertation research contributes to the interdisciplinary fields of climate impacts assessment for adaptation, and to water resources research, and includes advances in risk analysis and water resources modeling.

The hydrology and water operations modeling takes up theoretical challenges to the widespread assumption of climate stationarity in water resources planning models (Milly et al. 2008). By using an ensemble of climate models to drive an integrated hydrology and water operations model, it joins a relatively new, but fast growing thread of research that seeks to incorporate long-range climate projections into planning models, especially those studies that move away from perturbed time series of historical hydrology towards endogenizing climate-driven hydrologic variability into impacts assessment.

Further, it anticipates the need for more comprehensive assessments by simultaneously incorporating a range of scenarios of future land use and population growth, both of which have been recognized as important factors in future hydrology and water resources but are often not explicitly addressed in modeling of this sort.

In addition, this case study addresses issues of scale (Gibson et al. 2000) by demonstrating how regional physical geography can influence both the severity of climate impacts and the management landscape on which a larger global environmental change will play out (Gibson et al. 2000).

Finally, and most importantly, this dissertation challenges an implicit assumption of risk neutrality in the water resources and climate change literatures by demonstrating the importance of risk aversion in decision-making in these contexts, pointing the way to future integration of these methods into local decision making as well as global-scale impacts analysis.

1.5 Figures

Figure 1: The Stanislaus, Tuolumne, and Merced Rivers flow from the Sierra Nevada Mountains to the San Joaquin River, and thence north towards the Sacramento-San Joaquin Delta. Figure from (San Joaquin River Group Authority 2001).

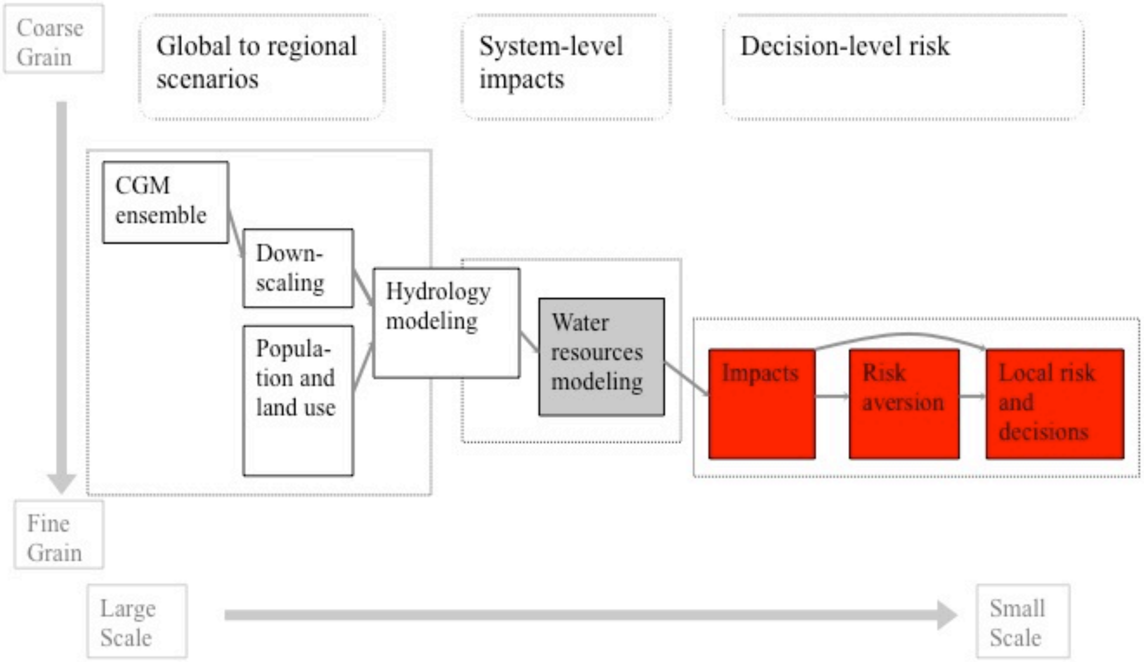

Figure 2: Conceptual model of the Integrated Assessment modeling, showing the integration of modeling techniques from global scale GCM ensembles (Dettinger 2005; Dettinger 2006; IPCC 2007b), downscaling (Kim 2001; Snyder et al. 2002; Wood et al. 2004; Kim 2005), hydrology and operations modeling (Gleick 1987; Knowles 2002; Kiparsky and Gleick 2003; Hayhoe et al. 2004; Vicuna and Dracup 2007), and risk analysis, with the emphasized areas in red. Figure 47 gives a more detailed conceptual model of the methods used to address the ideas depicted here, and Figure 56 and Figure 57 extend the description of the risk analysis concept.

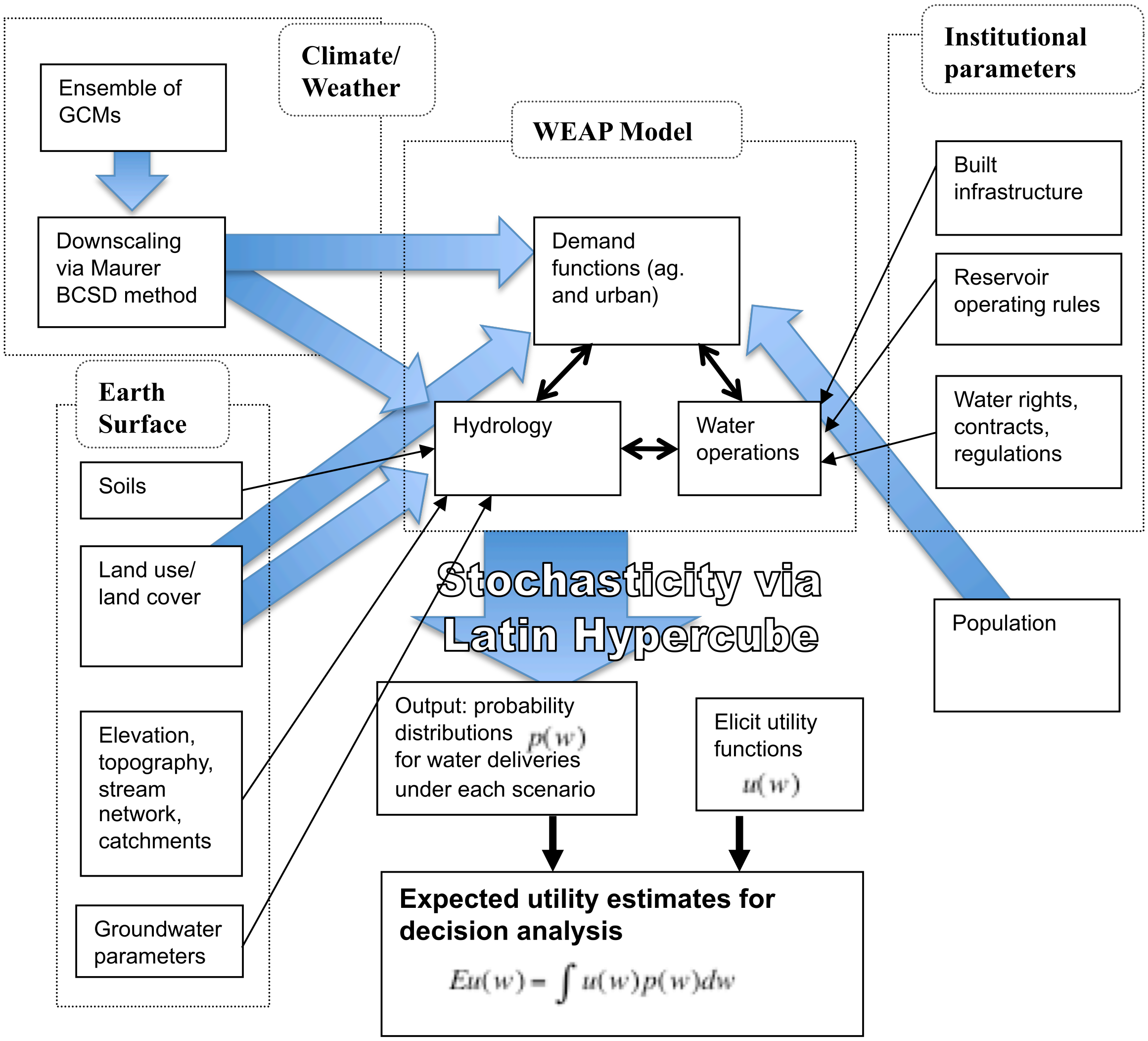

Figure 3: Methodological structure of the Integrated Assessment with risk and decision analysis. Thin dark arrows indicate parameters that are treated deterministically in this analysis. Fat blue arrows indicate parameters for which I will develop estimates of variability in future projections, using Latin Hypercube simulations in the case of large parameter ensembles, or in the case of this dissertation through a full factorial analysis using the computational methods described in the text. The blue arrows are the focus of the work presented in the Chapter 3.

1.6 References

(2006a). Air pollution: greenhouse gases. California Health and Safety Code. **Division 25.5**.

(2006b). Electricity: emissions of greenhouse gases. Public Utilities Code.

(2006c). Vehicular emissions: greenhouse gases. California Health and Safety Code.

Anthoff, D., R. S. J. Tol and G. W. Yohe (2009). "Risk aversion, time preference, and the social cost of carbon." Environmental Research Letters(2): 024002.

Arnell, N. and C. Liu (2001). Hydrology and Water Resources. Chapter 4 in Climate Change 2001: Impacts, Adaptation & Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White. Cambridge, Cambridge University Press**:** 195-233.

Barnett, T. P., J. C. Adam and D. P. Lettenmaier (2005). "Potential impacts of a warming climate on water availability in snow-dominated regions." Nature **438**(7066): 303-309.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan and M. D. Dettinger (2008). "Human-Induced Changes in the Hydrology of the Western United States." Science **319**(5866): 1080-1083.

Bawa, V. S. (1978). "Safety-first, stochastic dominance, and optimal portfolio choice." Journal of Financial and Quantitative Analysis: 255-271.

Beighley, R. E. and G. E. Moglen (2002). "Trend Assessment in Rainfall-Runoff Behavior in Urbanizing Watersheds." Journal of Hydrologic Engineering **7**(1): 27-34.

Beven, K. (2000). "On model uncertainty, risk and decision making." Hydrological Processes **14**(14): 2605-2606.

California Department of Water Resources (2006). Progress on Incorporating Climate Change into Planning and Management of California's Water Resources. Sacramento, CA, California Department of Water Resources Technical Memorandum Report.

Chavas, J.-P. (2004). Risk Analysis in Theory and Practice. San Diego and London, Elsevier Academic Press.

Claessens, L., C. Hopkinson, E. Rastetter and J. Vallino (2006). "Effect of historical changes in land use and climate on the water budget of an urbanizing watershed." Water Resources Research **42**(3): W03426.

DeFries, R. and K. N. Eshleman (2004). "Land-use change and hydrologic processes: a major focus for the future." Hydrological processes **18**(11): 2183-2186.

Dessai, S., K. O'Brien and M. Hulme (2007). "Editorial: On uncertainty and climate change." Global Environmental Change **17**(1): 1-3.

Dessler, A. E. and E. A. Parson (2006). The Science and Politics of Global Climate Change: A Guide to the Debate. Cambridge, Cambridge University Press.

Dettinger, M. D. (2005). "From Climate-Change Spaghetti to Climate-Change Distributions for 21st Century California." San Francisco Estuary and Watershed Science **3**(1): Article 4, http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4.

Dettinger, M. D. (2006). "A component-resampling approach for estimating probability distributions from small forecast ensembles." Climatic Change **76**(1-2): 149-168.

Dettinger, M. D., D. R. Cayan, M. Meyer and A. E. Jeton (2004). "Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099." Climatic Change **62**(1-3): 283-317.

DeWalle, D. R., B. R. Swistock, T. E. Johnson and K. J. McGuire (2000). "Potential Effects of Climate Change and Urbanization on Mean Annual Streamflow in the United States." Water Resources Research **36**.

Doremus, H. and M. Hanemann (2008). "The Challenges of Dynamic Water Management in the American West." UCLA J. Envtl. L. & Pol'y **26**: 55.

Eeckhoudt, L., C. Gollier and H. Schlesinger (2005). Economic and Financial Decisions under Risk. Princeton, Princeton University Press.

Fishburn, P. C. (1977). "Mean-Risk Analysis with Risk Associated with Below-Target Returns." The American Economic Review **67**(2): 116-126.

Franco, G., D. Cayan, A. Luers, M. Hanemann and B. Croes (2008). "Linking climate change science with policy in California." Climatic Change **87**: 7-20.

Getches, D. H. (2003). Constraints of Law and Policy on the Management of Western Water. Water and Climate in the Western United States. William M. Lewis Jr. Boulder, University Press of Colorado**:** 183-234.

Gibson, C. C., E. Ostrom and T. K. Ahn (2000). "The concept of scale and the human dimensions of global change: a survey." Ecological Economics **32**(2): 217-239.

Gleick, P. H. (1987). "Regional Hydrologic Consequences of Increases in Atmospheric Carbon Dioxide and Other Trace Gases." Climatic Change **10**(2): 137-161.

Haddad, B. M. (1999). Rivers of Gold: Designing Markets to Allocate Water in California. Washington, D.C., Island Press.

Hanemann, W. M. (2007). How California Came to Pass AB 32, the Global Warming Solutions Act of 2006. CUDARE Working Paper 1040, Department of Agricultural & Resource Economics, U.C. Berkeley**:** 30.

Harr, R. D., A. Levno and R. Mersereau (1982). "Streamflow changes after logging 130-year-old Douglas fir in two small watersheds." Water Resources Research **18**(3).

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan and J. H. Verville (2004). "Emissions pathways, climate change, and impacts on California." PNAS: 0404500101.

IPCC (2007a). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2007b). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Jones, R. N. (2000). "Managing uncertainty in climate change projections - Issues for impact assessment - An editorial comment." Climatic Change **45**(3-4): 403-419.

Kahneman, D. and A. Tversky (1979). "Prospect Theory - Analysis of Decision under Risk." Econometrica **47**(2): 263-291.

Kim, J. (2001). "A nested modeling study of elevation-dependent climate change signals in California induced by increased atmospheric CO2." Geophysical Research Letters **28**(15): 2951-2954.

Kim, J. (2005). "A projection of the effects of the climate change induced by increased CO2 on extreme hydrologic events in the western US." Climatic Change **68**(1-2): 153-168.

King, D. A. (2004). "Environment - Climate change science: Adapt, mitigate, or ignore?" Science **303**(5655): 176-177.

Kiparsky, M. (2009). "Sedimentation-upwelling: a model for the science-policy interface in the case of climate change and California water." Water Policy **11**(1): 107-124.

Kiparsky, M. and P. H. Gleick (2003). Climate Change and California Water Resources: A Survey and Summary of the Literature, California Energy Commission**:** 35 pp.

Kiparsky, M. and P. H. Gleick (2005). Climate Change and California Water Resources. The World's Water 2004-2005. P. H. Gleick. Washington, D.C., Island Press.

Knowles, N. (2002). "Natural and human influences on freshwater inflows and salinity in the San Francisco Estuary at monthly to interannual scales." Water Resources Research **38**: 1289.

Knowles, N. and D. R. Cayan (2002). "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." Geophysical Research Letters **29**(18): 1891.

Knowles, N., M. D. Dettinger and D. R. Cayan (2006). "Trends in snowfall versus rainfall in the Western United States." Journal of Climate **19**(18): 4545-4559.

Kundzewicz, Z. W., L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, K. A. Miller, T. Oki, Z. Sen and I. A. Shiklomanov (2007). Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry, O. F. Canziani, J. P. Palutikofet al. Cambridge, UK, Cambridge University Press**:** 173-210.

Lach, D., H. Ingram and S. Rayner (2005). "Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations " Texas Law Review **83**: 2027-2053.

Luers, A. L. and S. C. Moser (2006). Preparing for the impacts of climate change in California: opportunities and constraints for adaptation. Berkeley, CA, California Climate Change Center.

Lund, J. R. (2006). Most Excellent Integrated Water Management from California. Operations Management 2006: Operating Reservoirs in Changing Conditions, Sacramento, California, USA, ASCE.

Markowitz, H. (1959). Portfolio selection: efficient diversification of investments. New York, Wiley.

Meko, D. M. and C. A. Woodhouse (2005). "Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado river basins, western USA." Journal of Hydrology **308**(1-4): 196-213.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier and R. J. Stouffer (2008). "CLIMATE CHANGE: Stationarity Is Dead: Whither Water Management?" Science **319**(5863): 573-574.

Morgan, M. G. and M. Henrion (1990). Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge, Cambridge University Press.

Nordhaus, W. (2007). "Critical Assumptions in the Stern Review on Climate Change." Science **317**(5835): 201.

O'Connor, R. E., B. Yarnal, K. Dow, C. L. Jocoy and G. J. Carbone (2005). "Feeling at risk matters: Water managers and the decision to use forecasts." Risk Analysis **25**(5): 1265-1275.

Oreskes, N. (2003). The role of quantitative models in science. Models in Ecosystem Science. C. D. Canham, J. J. Cole and W. K. Lauenroth. Princeton, Princeton University Press**:** 13-31.

Oreskes, N. (2004). "Beyond the Ivory Tower: The Scientific Consensus on Climate Change." Science **306**(5702): 1686-.

Parry, M., J. Lowe and C. Hanson (2009). "Overshoot, adapt and recover." Nature **458**(7242): 1102-1103.

Parson, E. A. and K. Fisher-Vanden (1997). "Integrated Assessment Models of Global Climate Change." Annual Review of Energy and the Environment **22**(1): 589-628.

Pielke, R., G. Prins, S. Rayner and D. Sarewitz (2007). "Climate change 2007: Lifting the taboo on adaptation." Nature **445**(7128): 597-598.

Rayner, S., D. Lach and H. Ingram (2005). "Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts." Climatic Change **69**(2 - 3): 197-227.

Roe, G. H. and M. B. Baker (2007). "Why Is Climate Sensitivity So Unpredictable?" Science **318**(5850): 629-632.

Roos, M. (1987). Possible Changes in California Snowmelt Runoff Patterns. Fourth Annual Pacific Climate (PACLIM) Workshop, Pacific Grove, CA.

San Joaquin River Group Authority. (2001, Accessed 29 August, 2007). "Additional Water for the San Joaquin River Agreement, 2001-2010 Supplemental EIS/EIR." from http://www.sjrg.org/EIR/supplemental/sup_contents.htm.

Sax, J. L., B. H. Thompson Jr., J. D. Leshy and R. H. Abrams (2006). Legal Control of Water Resources: Cases and Materials, Fourth Edition. St. Paul, MN, Thomson West.

Schwarzenegger, A. (2005). Executive Order S-3-05, State of California.

Seager, R., A. Tzanova and J. Nakamura (2009). "Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change&#42." Journal of Climate **22**(19): 5021-5045.

Snyder, M. A., J. L. Bell, L. C. Sloan, P. B. Duffy and B. Govindasamy (2002). "Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region." Geophysical Research Letters **29**(11): 10.1029/2001GL014431.

Stednick, J. D. (1996). "Monitoring the effects of timber harvest on annual water yield." Journal of Hydrology **176**(1-4): 79-95.

Stern, N. (2007). The Economics of Climate Change: The Stern Review, Cambridge University Press.

Stern, N. and C. Taylor (2007). "ECONOMICS: Climate Change: Risk, Ethics, and the Stern Review." Science **317**(5835): 203-204.

Stewart, I. T., D. R. Cayan and M. D. Dettinger (2004). "Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario." Climatic Change **62**(1-3): 217-232.

Stine, S. (1994). "Extreme and Persistent Drought in California and Patagonia During Medieval Time." Nature **369**(6481): 546-549.

Tanaka, S. K., T. J. Zhu, J. R. Lund, R. E. Howitt, M. W. Jenkins, M. A. Pulido, M. Tauber, R. S. Ritzema and I. C. Ferreira (2006). "Climate warming and water management adaptation for California." Climatic Change **76**(3-4): 361-387.

Thompson Jr., B. H. (1993). "Institutional Perspectives on Water Policy and Markets." California Law Review **81**: 671-764.

Tversky, A. and D. Kahneman (1992). "Advances in Prospect-Theory - Cumulative Representation of Uncertainty." Journal of Risk and Uncertainty **5**(4): 297-323.

United States Government Accountability Office (2009). Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions. Report to the Chairman, Select Committee on Energy Independence and Global Warming, House of Representatives Washington, D.C. , United States Government Accountability Office (GAO).

Vanrheenen, N. T., A. W. Wood, R. N. Palmer and D. P. Lettenmaier (2004). "Potential implications of PCM climate change scenarios for Sacramento-San Joaquin River Basin hydrology and water resources." Climatic Change **62**(1-3): 257-281.

Vicuna, S. and J. Dracup (2007). "The evolution of climate change impact studies on hydrology and water resources in California." Climatic Change **82**(3): 327-350.

Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers (2000). "Global water resources: Vulnerability from climate change acid population growth." Science **289**(5477): 284-288.

Walker, R. A. and M. J. Williams (1982). "Water from Power - Water Supply and Regional Growth in the Santa-Clara Valley." Economic Geography **58**(2): 95-119.

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

Woodhouse, C. A. and J. J. Lukas (2006). "Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning." Climatic Change **78**(2-4): 293-315.

Worster, D. (1985). Rivers of Empire: Water, Aridity, and the Growth of the American West. New York, Pantheon Books.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee (2005). "WEAP21 - A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics." Water International **30**(4): 487-500.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott and T. Nozawa (2007). "Detection of human influence on twentieth-century precipitation trends." Nature **448**(7152): 461-465.

2 Chapter 2 – Integrated hydrology and water operations modeling of the Stanislaus, Tuolumne, and Merced River Basins, California: model characterization

2.1 The need for new tools to study impacts and adaptation

While projected hydrologic impacts of climate change have been described in ever-increasing detail, quantitative descriptions of the potential impacts on water rights holders and water users who might be affected by such impacts are rare.

To the extent that scenarios of future water supply reliability in California (and in water resources in general) model water deliveries, these probabilities tend to be derived from historical climate (e.g. Draper et al. 2004) that may neither accurately represent past (Stine 1994) nor future (Kiparsky and Gleick 2003; Vicuna and Dracup 2007, and refs therein) climatic conditions. This disconnect has motivated integration of climate into water planning, and the uncertainties inherent in both water systems modeling and climate modeling suggest that formally incorporating climate impacts on hydrology and water resources could help define potential anticipatory responses.

In sum, new tools could be useful to complement and expand on existing approaches to planning under climate variability and change.

2.2 Research goal: Development of an Integrated Assessment modeling tool

This chapter describes an effort to develop an integrated assessment modeling tool that will enable investigation of climate impacts and adaptation in the case study of the Merced, Tuolumne, and Stanislaus River Basins in California's Central Valley. This study focuses on the methods and development of an integrated hydrology/water operations model using the Water Evaluation and Planning (WEAP) platform. This work builds on previous work for the 2006 governor's report to investigate the Sacramento River Basin (Joyce et al. 2006) and will enable future connections and synergies between that previous modeling effort and the current study.

Integrated assessment models (Parson and Fisher-Vanden 1997) describe potential impacts and adaptation options quantitatively by integrating results from multiple models. This can be done using a cascade of modeling information, from large-scale, coarse-grained models, to finer resolution models that cover less spatial or conceptual area but represent specific processes of interest in more detail. Figure 1 gives an overview of the structure of the proposed integrated assessment. This study focuses on describing the highlighted boxes in the figure, namely on the hydrology and water operations modeling.

2.3 Model application: Merced, Tuolumne, and Stanislaus River basins

California provides an interesting laboratory for impacts and adaptation studies for a number of reasons. As elsewhere, water is important in California economically, politically, and socially. California has been well-studied with respect to climate impacts on water resources (Vicuna and Dracup 2007). Hydrology in California, as in many mountainous regions, is dominated by the dynamics of snow accumulation and melting. Gleick (1987) demonstrated the sensitivity of this hydrology to climate warming, projecting earlier and higher hydrograph peaks under climate warming scenarios. This general conclusion has proven robust after two decades and over 60 peer-reviewed studies (Vicuna and Dracup 2007), and exemplifies a hydrologic response of the type that threatens snowmelt-dominated hydrologic systems providing water supply to one-sixth of the world's population (Barnett et al. 2005). In general, the state is under water stress, even without the additional perturbation of climate change.

In addition, California has traditionally been a national leader in the development of innovative environmental policies (Getches 2003), and climate change is no exception (Kiparsky and Gleick 2005; Hanemann 2007). Recently, legal motivation to consider climate change in planning decisions has increased in the state, primarily on mitigation but increasingly on adaptation (Schwarzenegger 2005), resulting in path-breaking studies and efforts to apply cutting-edge science.

The Stanislaus, Tuolumne, and Merced River Basins (STM) in California's Central Valley (Figure 2) together form a potentially interesting case for a study of climate adaptation. The three basins are on the western slope of the Sierra Nevada Mountains, where hydrology will be sensitive to climate change (e.g. Gleick 1987; Knowles and Cayan 2002; Dettinger et al. 2004; Stewart et al. 2004). Water allocation in these basins is run through a variety of institutions, much of which revolves around legal and regulatory constraints (e.g., water rights and water quality regulations) and decisions made by water organizations such as federal and state agencies, and local Irrigation Districts.

Close proximity, varied institutional settings, and differing elevational characteristics that may drive differential hydrologic responses (Knowles and Cayan 2004) combine to make the STM basins a potentially rich arena for integrating several critical elements of analysis relevant to climate change impacts and adaptation: hydrology, water operations, and sensitivity to climate change that will together influence the management of water supply. In addition, with some bounding assumptions, the three basins can be modeled as a distinct hydrologic unit.

2.4 **Overview of research approach**

To address these water modeling needs, I have built a modeling tool to enable blending of hydrology and water operations modeling with climatic inputs based on results from coupled Atmosphere-Ocean General Circulation Models (GCMs). I used the Water Evaluation and Planning (WEAP, Yates et al. 2005 , www.weap21.org) modeling framework to model hydrology and water operations in the three case study basins.

The entire model is dynamically interconnected, and the entire model integrates physical hydrology and infrastructure and operations logic. However, there are conceptual and operational differences between the modeled representations of the upper watersheds (areas above the large dam on each river) and the valley floor (agriculturally dominated areas below these dams) that reflect the differences between the two areas. In the upper watersheds, land use is predominantly native vegetation, while in the valley floor agriculture dominates and urban centers are larger. In the upper watersheds, terrain is complex, with individual watersheds spanning large elevation ranges, while the lower watersheds are relatively homogenous.

These differences result in different emphasis in the modeling of the upper and lower watersheds within a single integrated model. The upper watersheds are modeled primarily with the goal of representing inflows to the major reservoirs in the system, and the sensitivity of those inflows to changes in temperature and precipitation patterns in downscaled GGM outputs. The lower watersheds are modeled primarily to represent agricultural and urban demands, the storage and conveyance facilities that deliver water to satisfy those demands, and the sensitivity of both demands and deliveries to changes in climate and other variables in future projections.

I describe below the component parts of these overlapping and integrated analyses.

2.5 **WEAP model structure**

The WEAP model consists of interlinked modules for both physical hydrology and operations to calculate demands and allocate water at each time step. Figure 5 shows a screenshot of the model schematic, which includes both. I describe them separately for conceptual simplicity.

2.5.1 Hydrology

The physical hydrology module consists of several conceptually simple components that are designed to represent variability in the key hydrologic components relevant to a study at this temporal and spatial resolution. A one-dimensional soil water accounting scheme routes moisture through two soil layers, with empirical functions describing evapotranspiration, surface runoff, sub-surface runoff, and deep percolation (Yates et al. 2005).

WEAP's quasi-physical lumped parameter hydrology routine has been detailed elsewhere (Yates et al. 2005; Young et al. 2009). I briefly summarize the WEAP model algorithms below, and refer the interested reader to these publications for more details.

The study area was first divided geographically at nested scales based on topography. *Watersheds* were defined hydrologically by the major dam on each of the three rivers that drain the Sierra mountains. Each watershed was further divided into *sub-watersheds* based on pour points at which streamflow is simulated (e.g. locations of gages with historical data). Each sub-watershed is further divided into 500 m elevation bands (*catchments*).

Sub-watersheds and catchments were also defined in the area below the upper watersheds and bounded by the San Joaquin River, in this case by institutional boundaries rather than topography.

Each catchment contains *N* unique combinations of soil and land cover, as determined in the GIS described above. The area in each such land class is expressed as a fraction of the total sub-watershed area, and a water balance is computed for each fractional area *j* of *N* using a continuous mass balance equation (Yates et al. 2005; Young et al. 2009).

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{\frac{LAI_j}{2}} - f_j k_j z_{1,j}^2 - (1 - f_j)k_j z_{1,j}^2$$

Equation 1

Here, soil water storage $z_{1,j}$ is expressed as a fraction of the soil water holding capacity (Sw_j, mm) for each fractional area.

A snowmelt model computes effective precipitation P_e in each time step as the sum of rain plus snow melt. To get the latter term, snow water equivalent and snow melt are computed using a temperature index snow accumulation model. Assigned melting and freezing thresholds are used to determine a melting coefficient, m_c. If 0, m_c specifies accumulation of additional snowpack. If positive, m_c specifies snow melt based on available melting energy and available snow pack during each time step. Available melting energy is a function of net solar radiation and a lumped term comprising other available forms of energy that is adjusted during calibration.

Evapotranspiration from each fractional area *j* is computed using the Penman-Montieth reference crop potential evapotranspiration equation (*PET(t)* in Equation 1), using crop/plant coefficients assigned to each land cover type.

Surface runoff is calculated using a term scaled by a runoff resistance factor (LAI in the third term of Equation 1) that represents surface characteristics such as roughness, Leaf and Stem Area Index, average slope, porosity, etc.

In the two-layer soil moisture scheme (Figure 6), interflow ($f_j k_j z_{1,j}^2$) and deep percolation ($(1 - f_j) k_j z_{1,j}^2$) are adjusted using the conductivity parameter k_j, which represents an estimate of upper storage conductivity, and f_j, a tuning parameter that partitions flow between horizontal (f_j) and vertical ($1-f_j$).

For each subcatchment, runoff from the upper layer in each time step is the sum of the runoff contributions from each land class type weighted by its area A_j (Yates et al. 2005)

$$Ro(t) = \sum_{i=1}^{N} A_j \left(P_e(t) z_{1,j}^{\frac{LAI_j}{2}} + f_j k_j z_{1,j}^2 \right) \qquad \text{Equation 2}$$

A mass balance for the deep water layer is the deep percolation term from Equation 1 and term including the conductivity rate k_2 of the lower storage in the catchment

$$Dw \frac{dz_{2,j}}{dt} = (1 - f_j) k_j z_{1,j}^2 - k_2 \, z_{2,j}^2 \, .$$

Equation 3

Alluvial aquifers are represented in the valley portion of the model, and in these catchments the deep water storage layer is removed and deep percolation term replaced by percolation from the upper layer directly to the aquifer (Yates et al. 2005)

$$P = \sum_{i=1}^{N} A_j (f_j k_j z_{1,j}^2) \cdot \qquad \text{Equation 4}$$

2.5.2 Irrigation demands

Catchments can be designated as containing irrigated agriculture, at which point the upper soil water store serves the additional function as a trigger for irrigation demands. Upper and lower thresholds U_j and L_j are assigned for each crop *j*. When evapotranspiration and percolation cause upper layer storage $z_{1,j}$ to decrease below L_j,, an irrigation demand is triggered for enough water to fill the upper layer storage to the upper threshold. Crop coefficients are described below.

2.5.3 Water allocation

The WEAP Model uses a preference- and priority-driven logic to determine allocation of water within each time step. Each demand node in the model is assigned a priority (e.g., 1 for the most senior water rights holder in a basin, with decreasing priority assigned to more junior rights holders). Within each time step in the model, a linear program satisfies demands first to nodes with highest priority, then sequentially allocates water to lower priority users until either demands are satisfied or supply constraints preclude further allocation of water.

Each demand node may be supplied by multiple water sources. Demand node "preferences" are assigned to simulate user behavior when multiple sources are available. For example, water users within an irrigation district may have access to both groundwater and surface water. In such cases, preferences are assigned to reflect historical allocations. For example, most irrigation districts, even those with senior surface water rights and water users with a strong preference for surface water, also use groundwater, in the form of pumping by the district itself for distribution and/or in the form of pumping by individual water users.

2.6 **Defining watershed characteristics**

In order to develop initial parameters for the spatially explicit WEAP model, I developed a Geographic Information System (GIS) of the physical and institutional aspects of the study basins (Figure 7). This enabled development of a set of spatially explicit estimates of watershed characteristics relevant to WEAP's hydrology and operations components. The GIS was developed using ArcGIS (ESRI 2007a) software. All data were projected to California Teale Albers projection for GIS analysis, and to North American Datum (NAD) 1983 for use within WEAP.

2.6.1 Physical characteristics

I first describe my process for developing parameters for WEAP's physical hydrology, which involves developing a model of the land surface and subsurface characteristics in order to model hydrologic interactions.

United States Geological Survey (USGS) digital elevation models (USGS 2007a) at 10 meters (m) (upper watersheds) and 30 m (valley floor) resolutions form the backbone for the physical description of the watershed. First, the ArcHydro toolkit (ESRI 2007b) was used to delineate a stream network consistent with the digital elevation model. This stream network is used to describe the position of the major streams and rivers in the system within WEAP.

Second, the elevation network is used to define sub-watersheds within each basin. Important points within each basin (e.g., gages or dams) are defined as described below. These points represent places where historical hydrological data are available, or points of significance to watershed management. Each defined *pour point* in turn defines a *sub-watershed*, the entire area from which water flows to each pour point. Thus, sub-watersheds define hydrologically distinct units that enable calibration through comparison of known hydrologic response of smaller model sections to modeled response, as well as describing areas meaningful to managers.

Third, *catchments* were defined based on 500 m elevation bands within each sub-watershed. These bands enable the WEAP model to describe elevation-dependent climate inputs and hydrologic responses. Given the relatively uniform topography and weather, and small total elevation range below each major dam, I defined each sub-watershed in the valley floor as a single elevation catchment.

Within each of the catchments, I then defined classifications of land use, land cover, and soil type, each with different parameters for hydrologic response. For each catchment, fractional land area for each parameter was determined via the intersection of these data in ArcGIS.

Vegetation and landcover for the upper, mostly non-agricultural watersheds were based on the National Land Cover Dataset (NLCD) (Multi-Resolution Land Characteristics Consortium 2001) for the upper watersheds (Table 1). On the agriculturally intensive valley floor, estimates of land use were based on the more detailed, agriculturally focused California Land and Water Use survey (CADWR 2007). Cropping patterns were also taken from this dataset. I mapped the detailed land use classifications onto simplified typologies of those used by DWR's Division of Planning and Local Assistance in their annual land use surveys. I grouped the detailed categories into 15 categories with comparable hydrologic characteristics, irrigation schedules, and economic values (Table 2).

Soils were classified to simulate their runoff characteristics based on the SSURGO dataset (USDA 2006). In a few areas, these data did not have complete coverage, and the less-detailed State Soil Geographic (STATSGO) (Natural Resources Conservation Service 2006) data was used (Table 2). For each, soils were classified as deep (>50 centimeters, cm) or shallow (USDA 2006). Where exact depth was not specified in either dataset, the presence of rocky outcrops was used to define shallow soil depth.

2.6.2 Water infrastructure

Dams (National Atlas of the United States 2006), canals and other conveyances (USBR 2003a) streamflow gage data, and locations (USGS 2007b) were also incorporated into the GIS model and the WEAP model.

For computational efficiency, reservoirs were combined into single objects in WEAP where appropriate, as described starting on page 45. Reservoir physical characteristics were taken from published sources (Table 3).

2.6.3 Model boundaries

The Sierra crest forms the upper boundary of the three main watersheds in the model. All three rivers flow into the San Joaquin River (SJR), which in turn flows north to the Sacramento-San Joaquin Delta. Because of upstream diversions, these three basins form a somewhat isolated hydrologic unit: the "section of the SJR between Gravelly Ford and Mendota Pool, a reach of approximately 17 miles, is generally dry except when releases are made from Friant Dam for flood control" (URS 2008). Thus, I assume for the purposes of this model calibration that

Gravelly Ford constitutes an upper boundary of the model, while leaving the option to connect the model with the upper San Joaquin River system in future work.[1]

The lower boundaries of the model are currently at the confluences of each river with the San Joaquin. To fully represent operational parameters, future versions of this model will need to be connected with a representation of the Sacramento-San Joaquin Delta, as well as with inflows from west side tributaries to the San Joaquin River.

2.6.4 Groundwater basins

Within the domain of this model, groundwater basins are located in the alluvial material below the Sierra Foothills. Eastern San Joaquin Subbasin underlies the area north of the Stanislaus River, Modesto Subbasin underlies the area between the Stanislaus and Tuolumne Rivers, Turlock Subbasin underlies the area between the Tuolumne and Merced Rivers, and the Merced Subbasin underlies the area south of the Merced River.

I defined groundwater basins and sub-basins as characterized by California DWR in Bulletin 118 (DWR 2003) and in associated updated basin information. Modeled groundwater objects are described in Table 4.[2] Note that it is beyond the scope of this research to model groundwater in detail in these basins, and thus the use of these coarse and estimated data are justified to estimate capacity and location of the subbasins in the model, without detailing hydrogeological characteristics. Future work could incorporate more detailed groundwater modeling.

2.6.5 Institutional characteristics

To enable a spatially oriented analysis, I incorporated institutional and infrastructure characteristics into the GIS, and used this information in constructing the WEAP model. Irrigation district locations (USBR 2003c; USBR 2003b; USBR 2006) were overlaid on the cropping patterns, and intersecting these data allowed me to determine the percentages of each land cover and crop type at the time of each detailed agricultural survey.

The California Department of Water Resources' (DWR's) Division of Planning and Local Assistance (DPLA) currently uses geographical divisions of fine-scale Detailed Analysis Units (DAUs) and coarser Planning Areas (PAs) that in these basins equate to the area between each of the three major rivers modeled here. A spatial resolution between the two is appropriate for the current model. Thus, I described agricultural catchment nodes and demand sites, informed by irrigation district boundaries and supply infrastructure, while maintaining consistency with the DAUs.

The modeling effort described here focuses on the major Irrigation Districts and urban areas within the STM basins. Surrounding these, there are large areas of land which get minimal or no supplies from surface water, and thus do not materially affect the surface water system modeled here. I lumped these districts into areas referred to as 'non-district' lands, but there are certainly

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[1] Note that the San Joaquin River Basin Settlement, in negotiation at the time of writing, may change this situation through provision for instream flows for salmon habitat. Future scenarios could incorporate such inflows.

[2] http://www.groundwater.water.ca.gov/bulletin118/basin_desc/basins_t-y.cfm, accessed May 31, 2009.

Wright Act districts within them with the responsibilities and powers of the larger districts. Future modeling could disaggregate these entities.

Some of these districts contract for surface water deliveries from a larger district, and those contracts are generally represented as lower priority transmission links to the lumped district areas.

Water is supplied from the Stanislaus River to Oakdale Irrigation District and South San Joaquin Irrigation District. Stockton East Water District also receives some Stanislaus River water, but because it is only partially supplied by the Stanislaus I don't model this district in details.

Don Pedro Reservoir on the Tuolumne River supplies water to Turlock Irrigation District and Modesto Irrigation District.

Surface water from the Merced River supplies water to the Merced Irrigation District and other entities within its Sphere of Influence. These entities include, Stevenson Water District, El Nido Irrigation District, El Nido Irrigation District, and others. The lumped 'non-district' catchment is supplied with surface water through a transmission link from the Merced Main Canal at the lowest priority in the basin, per contracts with Stevenson and El Nido, after all other needs have been met. These Irrigation Districts are represented in the WEAP model as part of the 'non-district' lands surrounding Merced ID, and their demands are mostly met through groundwater. The Merced National Wildlife Refuge also receives surface water through the Merced Main Canal, but its priority is higher than Merced ID supplies.

2.6.6 Urban centers

Population centers were also incorporated into the GIS model and the WEAP model. Urban populations were aggregated based on agricultural district boundaries. Spatially explicit population projection grids (Sanstad et al. 2009) were clipped to catchment node areas in the valley floor (Table 5).

2.7 **Historical climate inputs**

Model calibration was performed using a 1/8 degree gridded observed meteorological historical climate dataset (Maurer et al. 2002b). For each catchment defined in the model, I used ArcGIS to select the gridpoint with the closest linear distance to the catchment centroid to define climate inputs. Coordinates for each of these points was used to choose time series for temperature, precipitation, and wind speed, which were then translated to the model's monthly time step.

One limitation of the climate input dataset is that its 1/8 degree spatial resolution does not allow for resolving fine-scale temperature and precipitation differences that exist in complex mountainous terrain, potentially introducing bias in the upper watersheds through underestimation in high-elevation climate zones. As this could in effect result in an overestimate of temperatures in high-elevation areas, I corrected for this using the average lapse rate. Average lapse rate is an empirical relationship between elevation and temperature, generally 6.5°C per 1000 m elevation change (3.6 °F/1000 ft). I adjusted each catchment's temperature input by the difference between the midpoint elevation of each catchment and the elevation of the corresponding climate input grid point, multiplied by lapse rate. Overall, these adjustments resulted in a slight decrease in modeled temperature inputs.

As making fine-scale adjustments to precipitation estimates would introduce additional uncertainty onto modeled and/or downscaled projections, I left precipitation inputs unmodified. However, the negative bias in modeled runoff in these and other hydrology models suggests there may be error in precipitation inputs. Similar effects from bias in input climate data have been observed previously (Knowles 2000; Koczot et al. 2005; Young et al. 2009). In this, as in other mountainous areas, daily precipitation totals can vary greatly between measurement instruments located within a basin (Lundquist et al. 2009). This can be reflected in hydrologic analysis where isolated, but significant, precipitation events are not captured by an existing precipitation measurement network. For example, detailed studies found stream responses that could not be explained by precipitation measurements alone (Lundquist et al. 2009). Since methods used for generating modeled historical climate data are based on precipitation gages, it follows they may not reflect all precipitation events. Also, since higher elevation areas do not have as dense networks of gages, there may be bias in total precipitation when extrapolated from existing gages. This is a subject for future investigation.

2.8 Unimpaired hydrology of the upper watersheds

For the upper watersheds, hydrology was calibrated using data from the GIS analysis (described above) and published work for initial parameterization. Reservoirs were added after this initial parameterization, as described below.

An initial calibration has been described in more detail in Young et al. (Young et al. 2009). In brief, physical parameters were initially chosen based on published values in the literature, and adjusted based on match between simulated and observed streamflow data. The model was calibrated based on 19 water years (WY, October – September) of historical data from WY 1981-2000.

For the present model, the model described in Young et al. (Young et al. 2009) has been refined for computational efficiency. Elevation bands have been collapsed to 500 m intervals (from 250 m intervals previously), reducing computational intensity while enabling representation of elevation dependant hydrologic response. Sub-watersheds were also combined to reflect a simplified representation of the operational system in the upper watersheds. The total number of catchments in the upper watersheds was condensed from 248 to 80, and parameters adjusted to retain seasonal and annual hydrologic variability.

Snow accumulation and melt parameters (melt and freeze thresholds, new and old snow albedo values, and an additional radiation factor) were adjusted such that snow pack evolution follows seasonal patterns based on comparison with snow observation stations. Modeled hydrology, in particular the timing of spring runoff, is particularly sensitive to melting point (Stanislaus, 11 degrees C; Tuolumne, 11 degrees C; Merced, 9 degrees C) and freezing point (Stanislaus, -3 degrees C; Tuolumne, -1 degrees C; Merced, -1 degrees C).

Relative humidity is not directly available in the climate data, but was estimated from values modeled by DAYMET, a model that generates estimates of historical weather parameters in complex terrain (Thornton et al. 1997). Monthly averaged values from DAYMET over the calibration period in the upper watershed catchments were used as inputs to the WEAP model by interpolating between an average high humidity of 60% in January and an average low humidity of 23% in September.

2.9 **Agricultural demands**

Agricultural demands are modeled as a function of climate and crop type using the Penman-Monteith equation and empirically derived crop coefficients. The WEAP calibration was carried out sequentially, from climatic inputs through demands and deliveries:

- Reference Potential Evapotranspiration was calibrated to measured historical values (California Irrigation Management Information System, CIMIS).[3]
- Crop coefficients were added based on empirically measured values, and adjusted based on differences in WEAP's representation.
- Demands were compared to a metric of Total Applied Water Demand, based on estimates for representative irrigation districts in the region (CH2M Hill 2001).

2.9.1 Reference Potential Evapotranspiration

In the agriculturally intensive valley floor, hydrology calibration began with tuning of Reference Potential Evapotranspiration (PET), the potential evapotranspiration of a reference grass crop.

Reference PET is modeled in WEAP using the Penman-Monteith equation. Climate inputs affecting evapotranspiration include temperature, relative humidity, wind speed, and insolation (a function in WEAP of latitude, Julian day, and cloud cover). Figure 8 shows simulated evapotranspiration, as compared to the measured average monthly evapotranspiration at the Merced CIMIS station (2000–2007) and a regional average value that overlaps the historical calibration period. Estimates of ETo calculated using the Modified Blaney Criddle Method are also shown for comparison (DWR 1975).

Climate inputs are a key driver of evapotranspiration, and thus were adjusted to approximate observations at CIMIS weather stations. Seasonal wind speed patterns were based roughly on monthly averages for two years of data at the Merced CIMIS station that overlapped with the calibration period. Available historical records from CIMIS suggest a typical pattern in the valley of average relative humidity peaking at 90% in January, decreasing to 45% in July. I interpolated between these two values to simulate annual patterns of humidity in each monthly time step. Modeled annual average ETo approximates the regional annual average (4.49 versus 4.44 feet). Modeled wintertime ETo is higher than measured ETo. This likely has a minimal effect on overall modeled water demands.

2.9.2 Applied water demands

Demand for irrigation water is modeled as a function of ETo and crop coefficients (Kc) for a given crop.

Crop coefficients (Kc) were estimated for each crop. These were based initially on data for the region found in Bulletin 113-3 (DWR 1975), and calibrated to observed values. Since observed data in Bulletin 113-3 were produced for the purpose of estimating irrigation requirements rather than modeling year-round hydrology, these data ignore winter-time evaporation, with zero values during non-irrigated months. To simulate evaporation in absence of irrigated cultivation, and the

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[3] California Irrigation Management Information System, online portal, http://wwwcimis.water.ca.gov/cimis/welcome.jsp, accessed 2007-2009.

resulting reduction in soil moisture, I substituted a Kc value of .5 for every zero value. Average monthly values for potential evapotranspiration for crop types are shown in Figure 9.

Irrigation schedules were simulated based on historical monthly patterns. Within the period where irrigation is active for each crop, the model triggered irrigation events when soil moisture fell below a threshold specified for each crop. An exception to this is rice, for which flood irrigation was specified for given time steps. This ponding behavior includes a release requirement to simulate periodic flushing of flooded rice fields with fresh water.

Total Applied Water Demand (TAWD) was estimated as

$$TAWD = \text{Consumptive Use of Applied Water} / \text{Irrigation Efficiency}, \qquad \text{Equation 5}$$

with initial figures taken from Bulletin 113-3 and data from Merced Irrigation District (MBK Engineers 2001). This served as the starting point for developing crop coefficients to mimic water demands based on climate inputs.

Where aggregated crop types contained multiple species of crops, calibration data was initially generated for each land use type using a weighted average of the approximate land use for each crop type (e.g., 4:1 nut trees:fruit trees, based on estimates of historical average land use), and refined in later iterations. Historical or future changes in cropping patterns over time were not simulated here, but could be in future versions.

The above calculations collectively define the amount of water demand at the crop. When combined with a factor reflecting conveyance losses to seepage and evaporation, these reflect the total demand for water at the diversion point in each time step. Thus, surface water diversions are a function of demands for water application, alternative sources of water supply such as groundwater, conveyance capacity, conveyance losses, institutional constraints such as water rights, and reservoir operations, as described below.

2.10 Urban demands and supplies

Urban demands are based on multiplying estimated or projected population in a given urban node by an estimated per capita water use level. Population projections are derived as described above. Per capita water use estimates are taken as the 'baseline' 1995-2005 values for the San Joaquin Valley from the State Water Resources Control Board's 20x2020 efforts (State Water Resources Control Board 2009), as 248 gallons per capita per day (342,618 liters per capita per year). Consumptive use in urban areas was assumed to be 30%.

I acknowledge that urban water use efficiency has increased over time, and is expected to continue to do so in future (Gleick 2003; Gleick et al. 2003; State Water Resources Control Board 2009). In Chapter 3, per-capita demands are modeled as decreasing over time based on scenarios of increasing water use efficiency, somewhat ameliorating projected population-driven increases in urban water use.

Urban supplies are mostly met by groundwater unless otherwise specified. Some urban areas have arrangements with Irrigation Districts for supply. In this model, Modesto Irrigation District supplies 40 MGD to the Modesto urban area, per its arrangement with the City of Modesto.

2.11 **In-stream flows and hydropower**

In addition to demands for water supplies for agricultural and urban uses, the model represents flows that are left in rivers for environmental purposes (in-stream flows), and releases from reservoirs for generation of hydropower. I describe logic for instream flows for each river basin separately below.

2.12 **Stanislaus River in-stream flows**

The New Melones Reservoir is operated for four purposes, fishery, water quality, Bay-Delta flow, and water supply, as formalized in the New Melones Interim Plan of Operations (USBR 2005).

2.12.1 Forecasting the Stanislaus Year Type Index

In practice, flow requirements for the year are based on New Melones storage at the end of February, plus forecasted inflows to New Melones for March-September. I operationalized the forecast data by regressing March 1 modeled snowpack[4] over the period from 1950-1999 against modeled March-September unimpaired flows in the Stanislaus River ($R^2 = .72$) to approximate a snowpack-based forecast.

I used this linear model as a heuristic representation of the forecast aspect of these indices, while acknowledging that the actual DWR forecast is based on other factors than snow surveys (e.g. long range precipitation forecasts based on teleconnections including El Nino-Southern Oscillation and Pacific Decadal Oscillation) (Leonardson et al. 2005). It is also important to note that this method (and the forecasting described in Section 2.13.1 and Section 2.14.1) assumes climate stationarity (Milly et al. 2008), which will not actually apply to future climate scenarios. Future work could address this by updating forecasting logic as the simulated hydrologic ‘record’ lengthens over the course of each climate change scenario.

WEAP can return calculated values for a previous (but not current) timestep for use in calculations. Thus, there is a one-month lag in calculations using this forecast (e.g. April 1997 will calculate ISF requirements based on the previous year’s forecast, and May 1997 will use the current year forecast).

The Stanislaus River index is used to determine minimum release schedules for each of the four purposes of the New Melones Reservoir. Priorities for each instream flow requirement are defined such that flow requirements are satisfied in the following order in each time step: 1) fisheries; 2) Proxy for D-1641 Bay-Delta flow requirements at Vernalis; 3) water supply. When water is not available for all of these purposes, the lower priority uses will be shorted first. As described below in Section 2.15, required Bay-Delta and VAMP flows are included within flow constraints specified through SWRCB and DWR modeling.

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[4] Locations of actual DWR snow course locations were used to choose catchments to construct a snow depth index. Catchments comprising the snowpack index were STN_21_3000, STN_16_2500, STN_19_2500, STN_09_2500, STN_05_2000, STN_22_2500. This is a subset of those described below in the Tuolumne Instream Flows section.

2.12.2 Stanislaus River fishery flows

Fishery flows are based on flow requirements of the 1987 Reclamation, Department of Fish and Game (DFG) Agreement and prescriptive use of Central Valley Project Improvement Act (CVPIA) 3406(b)(2) (USBR 2005). In practice, requirements are linearly interpolated between values for each year type. Here, I use the value for each year type as defined in Table 6 and Table 7.

2.12.3 Stanislaus River D-1422 flows

The State Water Resources Control Board Decision 1422 requires water to be released from New Melones reservoir to keep dissolved oxygen concentration above 7 mg/l at Ripon. The current WEAP model does not estimate water quality parameters. Instead, I use fixed releases at low-flow times of the year as a surrogate for these flows (Table 8), as represented in the CALSIM model (USBR 2005). USBR bears substantial responsibility for meeting water quality and flow requirements at Vernalis through releases from New Melones Reservoir. See Section 2.15 on page 44 for details.

2.13 **Tuolumne River in-stream flows**

2.13.1 SJR 60-20-20 Index forecasting

In-stream flow requirements in the Tuolumne River below Don Pedro Dam vary based on DWR's SJR 60-20-20 index (State Water Resources Control Board 1995, p. 24). The 60-20-20 index is computed for each year by using actual and forecasted values in the following equations:

$$\text{INDEX} = 0.6 * X + 0.2 * Y + 0.2 * Z, \text{ where} \qquad \text{Equation 6}$$

X = Current year's April – July San Joaquin Valley unimpaired runoff (MAF)

Y = Current October – March San Joaquin Valley unimpaired runoff (MAF)

Z = Previous year's index (up to a maximum of 4.5 MAF)

The geographical scope of the WEAP model presented here contains three of the four river basins included in this index (inflow to Millerton Lake on the San Joaquin River is not included in the current model). Thus, I developed an analogue by comparing output for the three basins in the WEAP model to historical data for each element of the index, and generating scaling factors for each element.

To generate scaled values for Y (Oct-Mar inflows), I ran the WEAP model from WY 1950-1999 (the period for which historical climate data were available), and regressed modeled full natural flows in the Stanislaus, Tuolumne and Merced Basins against historical full natural flows for the SJR Basin ($R^2 = .89$), and used the coefficient from this linear model (1.59) as a scaling factor for generating Y from each year's modeled data.

In practice, X is based on forecasted inflows, which depend substantially on snowpack measurements, among other factors. I used a GIS to select a sample of catchments near DWR's snow course sensors[5]. The model sums snow depths in the sample catchments to make an index of April 1 snow accumulation. I regressed modeled snow accumulation at Mar 1 time steps from 1950-1999 against modeled historical Apr-Jul SJR Basin flows ($R^2 = .60$), and used the results to scale modeled snowpack into the annual value for X.

The State Water Resources Control Board defines five year types for the SJR 60-20-20 Index (Table 9). As an illustration of the variability in the relationship between index, modeled, and historical values, over the 50 water years from 1950-1999 the index matches the historical actual flow index 31 times (62%) and comes within one step of the historical index 45 times (90%).

2.13.2 Tuolumne River in-stream flow requirements

Tuolumne River ISF requirements below New Exchequer Reservoir are based on Federal Energy Regulatory Commission (FERC) rules (Federal Energy Regulatory Commission 1996).[6] FERC defines seven year type descriptions with distinct corresponding flow prescriptions (Table 10). These year types differ from the SWRCB/DWR water year types described above (Table 9). In practice, FERC year type designations to be updated as the hydrologic record increases in length, and exact flow amounts are defined based on the exact 60-20-20 index value using interpolation between the values in Table 10. The current WEAP model uses the values in Table 10 directly based on threshold values for the index, and does not update for changes in distribution of index values over time, generally resulting in an underestimate of required flows.

2.14 **Merced River in-stream flows**

2.14.1 Merced River year type forecasting

In practice, two year types are defined for the Merced River based on forecasting. A normal year as defined by the FERC license for the Merced River occurs when forecasted April through July inflow to Lake McClure is equal to or greater than 450,000 AF, as published in DWR May 1 Bulletin 120.[7] A dry year as defined by FERC license is when forecasted April through July inflow to Lake McClure is less than 450,000 AF, as published in DWR May 1 Bulletin 120.

To simulate forecasting logic, I regressed an index for May 1 Merced River basin modeled snowpack against modeled June-July inflow to Lake McClure for WY 1950-1999 ($R^2 = .97$). I then used this linear relationship to model forecasted flows, add them to modeled April-May flows, and determine year type based on the threshold described above. The modeled forecast from WY 1950-1999 matches the actual DWR year type forecast 88% of the time, compared to a historical accuracy of the DWR forecast of 94% over the same time period (historical forecast data obtained from Steve Nemeth, CA DWR, pers. comm.)

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[5] Sample catchments were chosen as the median elevation catchment within each sub-watershed containing multiple DWR snow course stations, MER_06_3000, MER_05_2500, STN_21_3000, STN_16_2500, STN_19_2500, STN_09_2500, STN_05_2000, STN_22_2500, TUO_13_3000, TUO_10_2500. Snow course locations obtained from CA DWR (Steve Nemeth, CA DWR, pers. comm.)

[6] In the Tuolumne River, according to Article 37 (xx cite), water year classifications for FERC-mandated ISF requirements are based on cumulative occurrence of flows, and thus should be updated over time. Here, I have used values based on DWR historical data and have not implemented updating logic.

[7] CA DWR, Bulletin 120, "Water Conditions in California", pulblished four time per year, http://cdec.water.ca.gov/snow/bulletin120/. Accessed August 2009.

2.14.2 Merced River in-stream flow requirements

On the Merced River, in-stream flows are required for the Cowell Agreement Entitlement between Merced Irrigation District (ID) and senior downstream riparian users, Federal Energy Regulatory Commission (FERC) requirements, and the Davis-Grunsky contract between the State of California and Merced ID (MBK Engineers 2001).

To satisfy instream flows, "Merced I.D. operates to a target flow below Crocker-Huffman diversion dam equal to the Cowell Agreement adjudicated entitlement plus the FERC/Davis-Grunsky flow requirement. The flow below Crocker-Huffman Diversion Dam must be equal the greater of the Davis-Grunsky and FERC flows plus the Cowell Agreement Entitlement" (MBK Engineers 2001). Flow requirements are shown in Table 11.

2.15 **Delta water quality requirements**

2.15.1 Flow requirements at Vernalis

Vernalis marks the southern-most boundary of the legal Bay-Delta, and as such serves as a control point for water quality regulations for water flowing north into the Delta from the San Juoquin River. There are two main drivers of flow requirements at Vernalis; D-1641 and the Vernalis Adaptive Management Program (VAMP) (State Water Resources Control Board 1999a).

2.15.2 SWRCB D-1641 and VAMP

The State Water Resources Control Board Decision 1641 (D-1641) (State Water Resources Control Board 1999c), issued in 1999, accepts negotiated contributions of water made by other parties (e.g. water rights holders) towards meeting the goals of the 1995 Bay-Delta Water Quality Control Plan (State Water Resources Control Board 1995). The goals of the 1995 Bay Delta Plan are to protect beneficial uses through water quality objectives, specifically by managing salinity intrusion, dissolved oxygen, and flows and diversion in the Delta.

Because of the limited spatial extent of this modeling effort, because water quality modeling is outside the scope of this exercise, and because "factors to be controlled [by D-1641] are primarily related to flows and diversions" by water rights holders (State Water Resources Control Board 1995, p. 4), I used data from SWRCB modeling to simulate the contribution of each modeled basin to Vernalis flows. D-1641 requires the flow at Vernalis to be maintained during the February through June period based on the required location of the Delta salinity index X2 and the San Joaquin Basin Index. Endogenizing the Delta salinity trigger is beyond the scope of the present modeling. Instead, I have taken advantage of modeling studies carried out during the Environmental Impact Report process for D-1641. SWRCB and DWR conducted modeling using DWRDSM to determine the potential contributions of each watershed in the Central Valley to meeting potential Delta water quality requirements. I used the results of their modeling (State Water Resources Control Board 1999b Appendix 4; State Water Resources Control Board 1999a p. V25) as a proxy for flows released to meet water quality requirements, as depicted in Table 12. Note that in the Stanislaus River, these requirements were scaled upwards by 30% to better match observed releases.

2.16 **Hydropower**

Actual decisions on hydropower releases are made as a function of variables including seasonal energy prices, available storage and weather forecasts, flood control, and other factors beyond the scope of this modeling exercise. I simulated summer hydropower releases in each stream using an in-stream flow requirement object, using approximate historical summer flows as a starting point for this requirement and calibrating to observed flows and reservoir levels. Water released for this purpose is available for other uses downstream.

2.17 **Water system schematic**

This section describes the representation of the water resources systems in the three basins represented in this model. The reservoir systems vary in complexity, but I simplified representation of the minor reservoirs where possible to retain the operational characteristics of the system while increasing computational efficiency. The majority of the variability that is lost through this combination is likely due to daily variations in hydropower releases, and thus is justified in the current monthly time-step model.

2.17.1 Upper Stanislaus River water resources system

Three streams flow into the Stanislaus River above New Melones Reservoir; the North Fork Stanislaus, the Middle Fork Stanislaus, and the South Fork Stanislaus. The watershed contains numerous reservoirs of varying size (Figure 10). I simplified the representation of this system by representing the reservoirs on each of these streams as a single combined reservoir object. Figure 11 shows the conceptual model of this simplified representation. A daily historical mass balance of the system was calculated to generate calibration data, as described in Table 13. Missing data were estimated via linear interpolation where gaps were less than approximately one week in daily time series, and individual calibration time series were truncated where critical data were missing. “Demands” for Tuolumne Canal diversion from the Stanislaus River Basin are based on average historical values, and I assume that this water is used consumptively rather than contributing to Tuolumne River stream flow. Given the small volumes relative to overall stream flow, this assumption should not materially affect the results.

2.17.2 Upper Tuolumne River water resources system

The Tuolumne River has two major surface water rights holders: the City and County of San Francisco (CCSF) and MID/TID. Three reservoirs in the upper watersheds (Cherry Lake, Lake Eleanor, and Hetch Hetchy Reservoir) are owned and operated by CCSF, with the primary purpose being storage of water for diversion to the San Joaquin Pipelines (SJPL) to San Francisco for urban water supply.

Several tributaries join the main stem Tuolumne River before it flows into Don Pedro River; operationally, Cherry Creek and the upper Tuolumne River are important because of the facilities operated by the City and County of San Francisco on these streams (Figure 12). In reality, much of this infrastructure is intertied and operated for hydroelectric purposes varying greatly on daily and hourly time scales. The detailed operations do not effect monthly model presented here, and enable us to simplify the system spatially and temporally. I simplified this system by combining the Cherry Lake (Lake Lloyd) and Lake Eleanor systems into a single reservoir node. Figure 13 shows the conceptual model of this simplified representation.

Three categories of releases from Hetch Hetchy reservoir can be defined: a) Moccasin Tunnel releases destined for the San Joaquin Pipeline, b) Moccasin Tunnel Releases destined for Don Pedro Reservoir, and c) releases to the Tuolumne River. We simplified the system by grouping b) and c) into the Tuolumne River object, and a) into the San Joaquin Pipeline object. Instream flow objects below HH reservoir thus help drive minimum flows to b) and c). Hydropower was derived based on a time series of outflows through Moccasin tunnel. Note that for Hetch Hetchy operations, a shift in operating schedules was implemented after the drought from 1987-92 to a "water first" policy that puts hydropower production as a second priority to water supply for CCSF.

New Don Pedro Reservoir was paid for jointly by TID/MID and CCSF. The joint operation of the Tuolumne system is governed by the Raker Act (United States Senate 1913). In brief, "From April 15 through June 13, the Districts are entitled to the first 4,066 cfs or the Tuolumne River natural flow, as calculated at LaGrange, whichever is less; from June 14 through April 14, the Districts are entitled to 2,416 cfs or the natural flow, as calculated at LaGrange, whichever is less". CCSF has storage rights of 570,000 AF 'water bank' in New Don Pedro Reservoir. Since CCSF can only physically divert water to San Francisco from Hetch Hetchy Reservoir, they store 'virtual water' in New Don Pedro Reservoir. CCSF draws from the Water Bank by diverting water from daily flows to Hetch Hetchy that would otherwise fall under the MID/TID entitlement, and crediting TID the same amount from their water bank. A daily accounting assesses changes in water bank storage, taking into account all reservoir inflows and outflows and diversions to the SJPL.

Since the present model runs on a monthly time step, I created a monthly analogue for the Raker Act calculation based the relationship between monthly and daily calculations in a sample of daily historical data. I acknowledge that because individual events can provide much of the allocation of water to San Francisco's supply, this calculation is highly dependant on daily variability of streamflow, which is not captured at the monthly time step employed here. In addition, future changes in patterns of daily flow events could alter this relationship.

To simulate the water bank, I divided storage in New Don Pedro Reservoir into two reservoir objects. The upper object simulates the CCSF water bank, and the lower the portion of Don Pedro Reservoir with MID/TID storage. Note that while the CCSF water bank volume can temporarily increase under certain conditions, the simplified modeling of a constant 570,000 AF volume is justified (Bruce McGurk, SFPUC, personal communication).

To mimic system behavior in the Tuolumne river basin, I isolated the CCSF system (including reservoirs CCSFWB and upstream) by assigning higher priorities to the CCSF system objects above New Don Pedro than to the downstream objects including and below New Don Pedro. Thus, agricultural demands below DNP (e.g. MID/TID) can call for water in New Don Pedro's MID/TID storage pool, but can not call for CCSF supplies in the water bank. An instream flow object between CCSFWB and DNP calculates the MID/TID water right based on the Raker Act logic (scaled for the monthly time step), and draws water into the DNP storage partition.

Overall, CCSF water system has not been represented in fine detail in the current model version – much of the actual CCSF system demands and storage exists outside the domain of the current model. The Hetch Hetchy watershed also has a dry bias, which would need to be refined in future work.

A daily historical mass balance of the system was calculated to generate calibration data, as described in Table 14. Missing data were estimated where gaps were small by linear interpolation between known values, and calibration time series were truncated where critical data were missing. Reservoir storage goodness of fit statistics were calculated with simulated DNP storage as the sum of CCSFWB and DNP objects.

2.17.3 Merced River Basin

The Merced River Basin above New Exchequer Dam/Lake McClure is unimpaired, and thus no simplification was necessary. The basin was divided into four sub-watersheds based on locations of gages with historical records of streamflow for calibration purposes.

2.18 **Simulating system operations**

Given the representation of hydrology and water demands described above, WEAP constrains deliveries of water to a given node with operating logic based on specified preferences for water supply, priorities for water deliveries, and a simple simulation of reservoir operations that models rule curves and operator behavior.

2.18.1 Demand preferences and priorities

One of the key strengths of the WEAP platform is that it combines hydrology and water operations into a single modeling framework. It integrates the quasi-physical lumped-parameter hydrology model with a network optimization linear program (LP) (Yates et al. 2005). The LP allocates available water based on assigned priorities at each node, and can be programmed to model the statutory functioning of an appropriative water rights system.

Each demand node, agricultural catchment, and reservoir is assigned a ‘priority’ value. Subject to other constraints, the LP satisfies higher priority demands first up to the limit of available water, before moving to lower priority demands. This mimics much of the legal doctrine by which water is allocated in California, such as prior appropriation. In general, in this system there are a few classes of priorities, based on the seniority of water rights holders and the importance of regulations. First, senior water rights holders (usually the older irrigation districts) and in-stream flows generally hold top priority, along with riparian rights holders. Second, younger irrigation districts have lower priority. Third, urban areas may have very junior surface water rights, or no surface water rights, and tend to be reliant on groundwater or transfers from irrigation districts. This pattern follows from historical evolution of water use: a seniority system exists in California water law, with water rights inheritable as property rights. Farmers were generally the original settlers in the area, and under the Wright Act water districts generally had the capital to construct the storage facilities that enabled capturing streamflow, and the annual usufructuary rights to this streamflow, on larger scales. These Wright Act districts make up the unit of analysis for many of the demand nodes in this model. Urban areas grew later, after many of the streams were, legally or in practice, fully appropriated, and have had to obtain water from other sources such as groundwater or water transfers.

Each supply source for each demand node is assigned a ‘preference,’ such that the demands will draw first from the highest preference source, when water is available from both sources. Supply can be partitioned between sources.

2.18.2 Reservoir operations

Reservoirs are operated for water supply, flood control, and hydropower generation. The WEAP model simulates operation of reservoir objects based on their physical characteristics (e.g., storage capacity, volume-elevation curve) and operation parameters that reflect decisions based on balancing flood control, water supply, and the need for preserving carryover storage.

As appropriate for California's multi-purpose reservoirs that function for flood control as well as water storage, a *conservation zone* is specified that reflects flood rule curves that require space to contain winter flood flows and allow a reservoir to be filled for storage purposes by summer.

WEAP constrains releases of water using a ”buffer zone” concept. Reservoir levels are specified below which releases are limited in each time step to a percentage of the existing water in the reservoir. This parameter reduces the complex conditional logic by which actual operational decisions are made to an analogue for conservatism of reservoir operators.

A *buffer zone* is specified as a portion of the available reservoir storage in any given time step, and a *buffer coefficient* defines the fraction of water within that zone available for release. Thus, while the reservoir contains water above a certain level, all demands are met subject to other constraints. But when the reservoir falls below a given level, releases are constrained by the buffer coefficient. A smaller buffer coefficient mimics a more conservative operating regime, where more water is withheld for release in future time steps.

Values for physical parameters and operational rules such as flood control space were taken from published sources or derived from historical data (Table 3). Buffer levels and buffer coefficients were adjusted to approximate reservoir storage and releases over the calibration period.

2.18.3 Reservoir evaporation

Reservoir evaporation is modeled simply as the calculated surface area (m^2) of a reservoir in each time step multiplied by the evaporation rate (mm) in that time step. I modeled evaporation in the main reservoir in each watershed.

Evaporation rates are modeled as a repeating annual pattern based on historical average monthly values. New Melones Reservoir and New Exchequer Reservoir evaporation rates were estimated based on historical average figures for 1979-1989 found in MBK Engineers (MBK Engineers 2001). Monthly evaporation rates for Don Pedro Reservoir are based on SFPUC data provided for WY 1994 and 1995 (Bruce McGurk, pers. comm.).

Volume-elevation curves are used to approximate surface area based on reservoir volume in each time step. New Melones Reservoir and Don Pedro Reservoir volume-elevation curves were derived from historical data available from CDEC[8] and USGS[9]. As Don Pedro Reservoir is represented as two objects to portray the 'virtual storage' in the CCSF Water Bank, I partitioned the total derived Don Pedro Reservoir volume-elevation curve between the Don Pedro Reservoir object and the CCSFWB object in WEAP by the fractional storage available in each of the two. New Exchequer Reservoir volume-elevation curve is based on Merced ID storage and rating tables.

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[8] http://cdec.water.ca.gov/, accessed September 10, 2009.

[9] http://waterdata.usgs.gov/nwis, accessed September 10, 2009.

Overall model results are not highly sensitive to variations the evaporation rate, but future iterations could compute evaporation dynamically based on climate data.

2.18.4 Groundwater use

Groundwater use is observed within irrigation districts in the region even when surface water supplies are seemingly plentiful. To incorporate groundwater use into WEAP's priority and preference allocation scheme, I assigned a supply preference to each agricultural catchment for surface water. The total amount of demands that can be supplied by surface water are constrained to a percentage that reflects estimates of groundwater use in a district (USBR 2005). This in effect forces a minimum amount of groundwater pumping even when sufficient surface water is available, and allows increased groundwater pumping to meet demands when surface water deliveries are constrained by hydrology or operations.

In areas with no surface water supply, or limited surface water supply, groundwater use accounts for all demands, and no limits on groundwater use are currently modeled.

2.18.5 System losses and unknown terms

While California is a relatively data-rich system, substantial gaps exist. For example, system inefficiencies such as leaks, seepage, and evaporation are difficult to measure in complex systems, and are not systematically measured or recorded in the study area. Also, groundwater in California is not currently subject to regulatory oversight, and monitoring and reporting its use is not commonly conducted.

Without known values for such terms, I have taken a similar approach to other modeling efforts, by using closure terms to balance the operational water budget in each area around known values (USBR 2005). Broadly, I assigned values where they were measured or estimated in previous studies, and used closure terms for unknown parameters to simulate system performance. Within agricultural operations, this manifests as two major unknowns: 'System losses' include evaporation from canals and other structures, as well as inefficiencies not reflected in the representation of crop water demands. 'Groundwater use' includes pumping by Districts and urban areas and pumping by individual water users within district or non-district lands. The former may be recorded or estimated in some cases. The latter can in theory be estimated through analysis of records of power use by pumps, but such data are not available on this scale.

My approach to incorporate these parameters into the WEAP model was to 1) incorporate available data available data into the model for system losses and groundwater use, and 2) modify the terms such that model results are in accordance with other available data.

System losses are incorporated in two ways (Table 15). Where specific terms have been known or estimated based on monitoring or previous studies, they are incorporated as specific terms (e.g. canal evaporation) where practicable. Otherwise, they are lumped into a loss parameter, represented as groundwater seepage from each diversion.

While this approach can help better represent system behavior, it could be improved with the availability of better data for each of these parameters.

2.18.6 Interplay between demands and supply

Decisions in water supply are tradeoffs between supplying current demands for water and saving water for other purposes including carryover storage for future uses. Describing system behavior requires balancing priorities for allocation with constraints on releases.

As described in above sections, WEAP represents climate driven demands for consumptive use of applied water. In reality, total water use is greater than these demands alone. Flow is partitioned within diversion objects (canals) in WEAP between deliveries and system losses. The effect is to increase demands for river diversions above TAWD, simulated here as a lumped percentage attributable to seepage to groundwater, system spills, canal evaporation, and other system losses. Were more data available, this could be refined to partition system losses into specific categories. Deliveries to each catchment demand node are constrained to a maximum percentage of demands as described above, to drive some water withdrawals to groundwater.

To simulate changing deliveries under varying system water availability, reservoir operations rules, coupled with hydrology and reservoir conditions, further limit surface supplies when reservoir storage falls below a specified level. When surface water use is curtailed, for example when low reservoir levels trigger delivery limitations, simulating concern for carryover storage for the next year, the remaining demands are supplied through groundwater pumping. Currently, there is no constraint on groundwater use in the model. This constraint could be included with sufficient data on district-wide pumping capacity and assumptions of future pumping capacity.

We used data from a water balance conducted by DWR and USBR (USBR 2005) to parameterize the current model. Note that both my approach and the DWR water balance use closure terms to calibrate to known historical values (in this surface water flows gauged by USGS and other entities). Thus, actual groundwater use and system losses are unknown, and should be treated as estimates.

2.19 **Model representation of unimpaired surface water hydrology**

The model's representation of historical hydrology is depicted in Figure 14, Figure 15, and Figure 16, which compare WEAP outputs at the pour points representing the large dams at the base of each upper watershed with DWR reconstructed full natural flows. Figure 17 shows average monthly results over the same time period. Outputs from upper watersheds modeled without the inclusion of dams or diversions are compared below to DWR's reconstructed historical Full Natural flows at SNS Stan At Goodwin, TLG Tuolumne At LaGrange, MRC Merced NR Merced Falls.

The model captures historical annual and seasonal variation of flow patterns reasonably well. Goodness of fit statistics are shown in Table 16. Bias and root mean squared error (RMSE) are in the range reported for previous modeling efforts in the region using the Variable Infiltration Capacity model (VIC) (Maurer et al. 2002a) and WEAP (Yates et al. 2009). The Nash-Sutcliffe efficiency index (Nash and Sutcliffe 1970) also suggests reasonably good predictive power for the model.

2.20 **Model representation of managed water system**

2.20.1 Stanislaus River Basin

Table 17 shows goodness of fit statistics for reservoir inflows, storage, and releases in the reservoir objects in the Stanislaus River basin over the calibration period from WY 1981-1999. Figure 18 through Figure 31 show time series of modeled (black lines) and simulated (red lines) values.

2.20.2 Tuolumne River Basin

Table 18 shows goodness of fit statistics for simulated inflows, storage, and releases at nodes in the Tuolumne River Basin. Figure 32 through Figure 40 show time series of modeled and simulated values.

2.20.3 Merced River Basin

Figure 41 through Figure 43 show time series for inflows, storage, and releases at Lake McClure. Table 19 shows goodness of fit statistics for the Merced River Basin. The Merced River has no dams above New Exchequer/Lake McClure.

For all three basins, the time series show that the model captures seasonal and interannual variability, and statistics are within the range of previously reported modeling efforts for this region. A notable feature is the difficulty in calibrating the uppermost subwatersheds in the model. The significant and inconsistent bias in these areas may result from variability in climate input data in the representation of high elevation precipitation, as discussed above in Section 2.7.

2.21 **Surface water allocations**

Surface water deliveries at the Irrigation District or sub-district level are measured at points of diversion from the rivers into the canals which transfer water to irrigated and urban demand centers. Modeled deliveries are a function of demands, priorities, preferences, reservoir operations, and available water in a given time step, as described above.

The model represents the average annual diversions as depicted in Figure 44, Figure 45, and Figure 46. While the model exhibits some error in reproducing individual events, it does capture the overall patterns for diversions over the calibration time period, including the shift to lower diversions during the string of critical water years during the drought from 1987-1992 Table 20.

2.22 **Groundwater use**

Groundwater usage is represented based on unconstrained access to groundwater resources, given other priorities and preferences specified in the model. Simply put, given the paucity of available historical groundwater use data for the region, we allowed demand nodes to fill unmet surface water demands through groundwater pumping.

Our representation of groundwater use is within the range suggested by other studies. Table 21shows average groundwater use within the primary irrigation districts, compared to the range suggested by previous studies. Note that historical estimates are based on unspecified data sources (USBR 2005), and should be treated with caution.

2.23 **Discussion**

The model presented in this chapter represents annual and seasonal variability in streamflow, water demands, water deliveries, reservoir storage, streamflow, and other aspects of the hydrology and water operations of the Stanislaus, Tuolumne, and Merced River basins.

2.23.1 Significance

The WEAP model presented here has features that enable us to addressing key questions in climate impacts and adaptation as outlined in the Introduction and in later chapters. It enables endogenizing the analysis of climate impacts and adaptation to a hydrology and water operations model of the study area, as well as the integration of climate change scenarios with land use change scenarios and other drivers.

Other tools exist in California for modeling water supply, notably CALSIM (Draper et al. 2004; USBR 2005) and CALVIN (Draper et al. 2003) on the statewide scale, but also including many local and regional models built for specific planning purposes. The current model is intended to complement the strengths and limitations of these other existing tools. CALSIM is the dominant long-term planning model in the state, and represents in detail the statewide operations of the SWP and CVP and other systems. Its strengths and limitations are described in several detailed reviews (Close et al. 2003; DWR 2005; Brekke et al. 2006; Ford et al. 2006; Ferreira et al. 2005). CALVIN is an economic optimization model of the statewide water system. Both CALSIM and CALVIN are driven by historical time series of ‘rim flows’, and are driven by optimization engines with perfect foresight over the entire model run. The WEAP approach complements these models through its capability to endogenously represent climate-driven hydrology and demands with water operations, and the capacity to represent land use change as a driver of changes in agricultural demands. It also uses a more accessible user interface that could ultimately enable greater stakeholder engagement.

2.23.2 Model appropriateness, uncertainties and limitations

In modeling complex systems, a model that is too simple can lack nuance, and fail to represent the dynamics of the multiple processes that operate simultaneously to produce overall system behavior. On the other hand, a perfect model including all the intricacies of a complex system would likely be analogous to a 1:1 scale map: highly representative, but intractable to construct and ultimately too cumbersome to be useful. This framework implies a conceptual continuum from minimalist/oversimplified to detailed/overly detailed.

Overall, the WEAP model presented here is an appropriate tool for asking the questions posed by this dissertation, in part because it falls in most respects in between the extremes of the continuum defined above. Some notes on specific aspects follow.

Input data for calibration time period have the advantages of reproducing seasonal and annual climatic inputs fairly well, of being widely used in regional assessments and thus enabling future intercomparison of results, and of being aligned spatially and methodologically with downscaled GCM inputs for future climate scenarios. However, reproducing fine-scale weather patterns is notoriously difficult, especially in mountainous terrain. With data at 1/8 degree resolution, nuance can be expected to be lost, as described above in the climate inputs section. While the model performs well overall in reproducing historical streamflow, in some areas, notably high elevation areas, I found bias that might result from input data. Because sampling of historical climate is limited spatially and temporally, especially in high altitude areas, this may be a limitation that would require more work in the fields of meteorology and climatology to address.

The WEAP model runs on a monthly time step, which is on the coarse end of the detail continuum. While common in large-scale, long-term water planning models, a monthly time step limits the resolution of streamflow and other events. WEAP's algorithms provide a practical lower bound on the potential to run the model on a finer time step, since water needs to flow through to its final end point within each time step. This lower limit increases with increasing model scale. Thus, analysis of flood risk, sub-monthly instream-flow requirements such as pulse flows, and other applications requiring finer-scale hydrology must be left to other platforms.

Hydrology is modeled in WEAP using a quasi-physical lumped parameter approach, whereby land classes within each catchment object are combined and assigned common hydrologic responses. A more detailed approach might, for example, assign land classes and hydrologic response parameters to each segment of a grid covering the model domain, and route water between points on the grid (Flint and Flint 2007). This approach might enable closer calibration to historical hydrology. However, others have argued that more detail inherently comes with the dis-advantage of increasing uncertainty intrinsic to increasing the number of estimated parameters (Beven 1993; Beven 2001). Investigations of the impacts of model structure on climate change investigations would be a fruitful line of future inquiry.

Water operations in WEAP enable the model to represent satisfaction of competing current and future demands for water. Operations are defined through a combination of logical constraints (e.g. minimum instream flow requirements) and more general characteristics (e.g. reservoir buffer settings). The latter represents with a few parameters what in reality is a complex set of decisions that even in historical representation includes factors outside the model domain such as economics, long-range weather forecasts, political decisions, changing legal constraints, and so forth. One can think of the buffer concept as a way to represent the general degree of 'conservatism' in operations decisions. It has the advantage of flexibility, and the disadvantage that details of operational decisions and changes in reservoir operations logic can only be represented in a broad-brush sense. For long range planning scenarios such as those envisioned for this dissertation, this approach is a valid one given the tremendous uncertainty that exists in the details of future policy decisions. General changes in policy, such as adaptive changes in flood rules or reservoir tolerances, could be modeled as part of future efforts.

2.24 **Conclusion**

In this chapter, I have presented the development of a tool for studying climate impacts and adaptation in California water resources. The model represents the hydrology and water operations of the Stanislaus, Tuolumne, and Merced River Basins in California's San Joaquin Valley.

The model represents annual and seasonal variability in hydrology and water operations, and enables the development of analysis of future water conditions using projections of climate change, land use change, and population growth.

Next steps in the development of this tool could include extending the operations portions of the model and linkage with upstream and downstream hydrology and constraints on water supply. This would enable dynamic representation of delta water supply, and also enable dynamic representation of future operations scenarios. Other WEAP applications of similar scope and scale have been developed for other parts of California, and ultimately joining these efforts holds the promise for a statewide WEAP representation of California water supply.

The advantages of using WEAP for the study of climate change impacts and adaptation, including its endogenous representation of hydrology such that climate scenarios can be used directly to drive the model output, will be used in the study of California's water resources vulnerability and resilience to climate change.

2.25 Figures

Figure 4: Map of project area for case study. The Stanislaus, Tuolumne, and Merced Rivers flow from the Sierra Nevada Mountains to the San Joaquin River, and thence north towards the Sacramento-San Joaquin Delta, the "hub" of California's water supply system. The San Joaquin River is dry in most years upstream of the Merced, and flows north of the Stanislaus are constrained by water quality regulations. Source: (San Joaquin River Group Authority 2001).

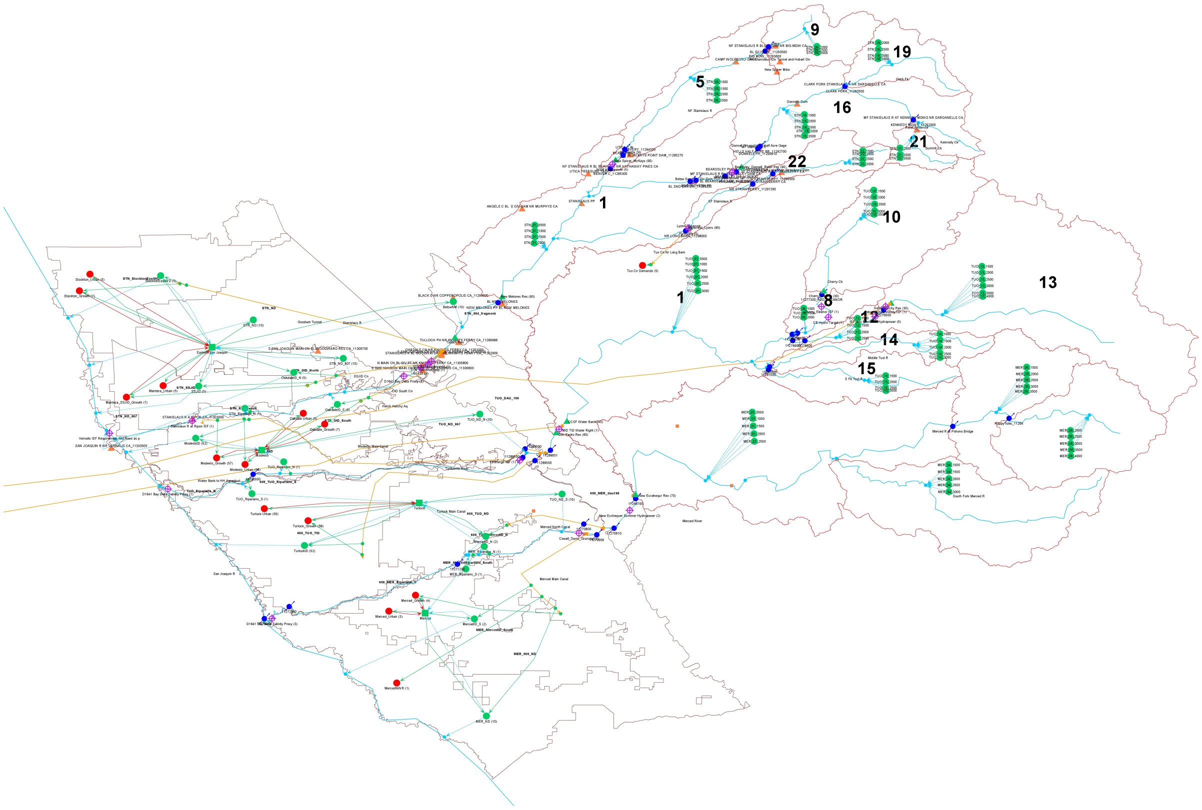


Figure 5: WEAP model schematic. Schematic of WEAP model. Rivers are in light blue, and canals and diversions in orange. Sub-watershed boundaries for the three river basins are shown in red on the right (east) of the figure, with catchment objects for each elevation band as green circles. In the valley floor on the left (west) of the schematic, urban centers are shown as red circles, agricultural demand sites as green circles, and groundwater nodes as green squares. Nodes are connected by green transmission links indicating supply sources, and runoff/infiltration links in blue.

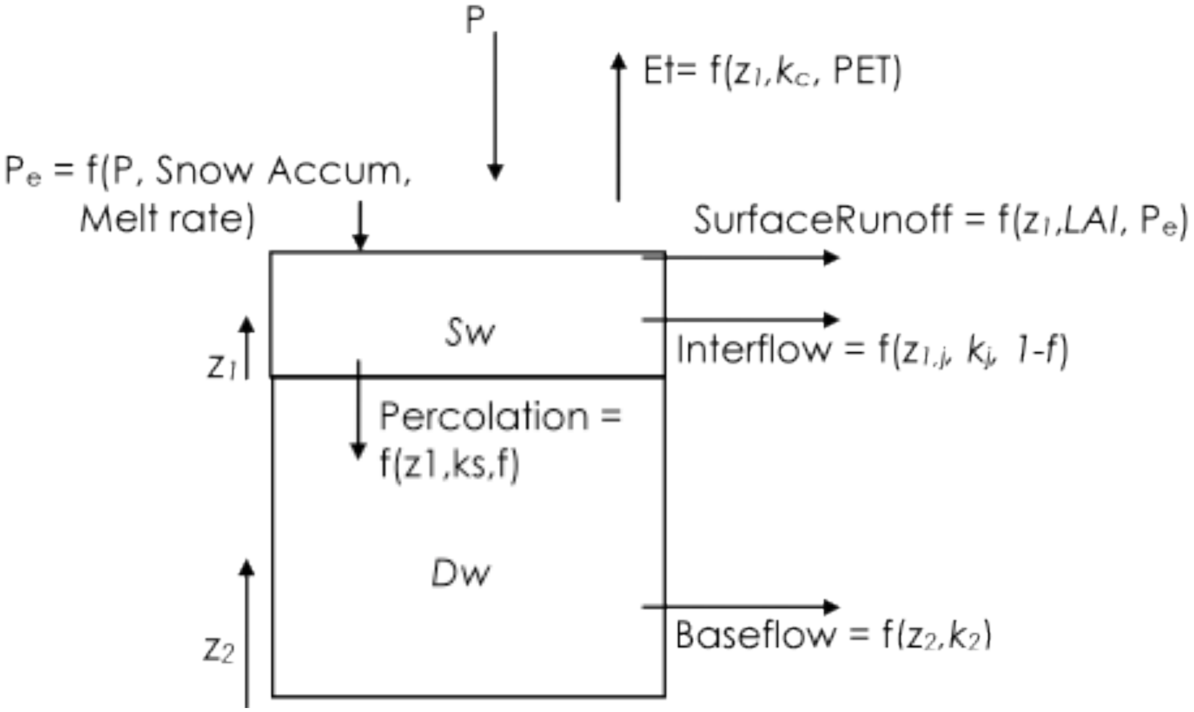


Figure 6: Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type. Source: Yates et al. (2005).

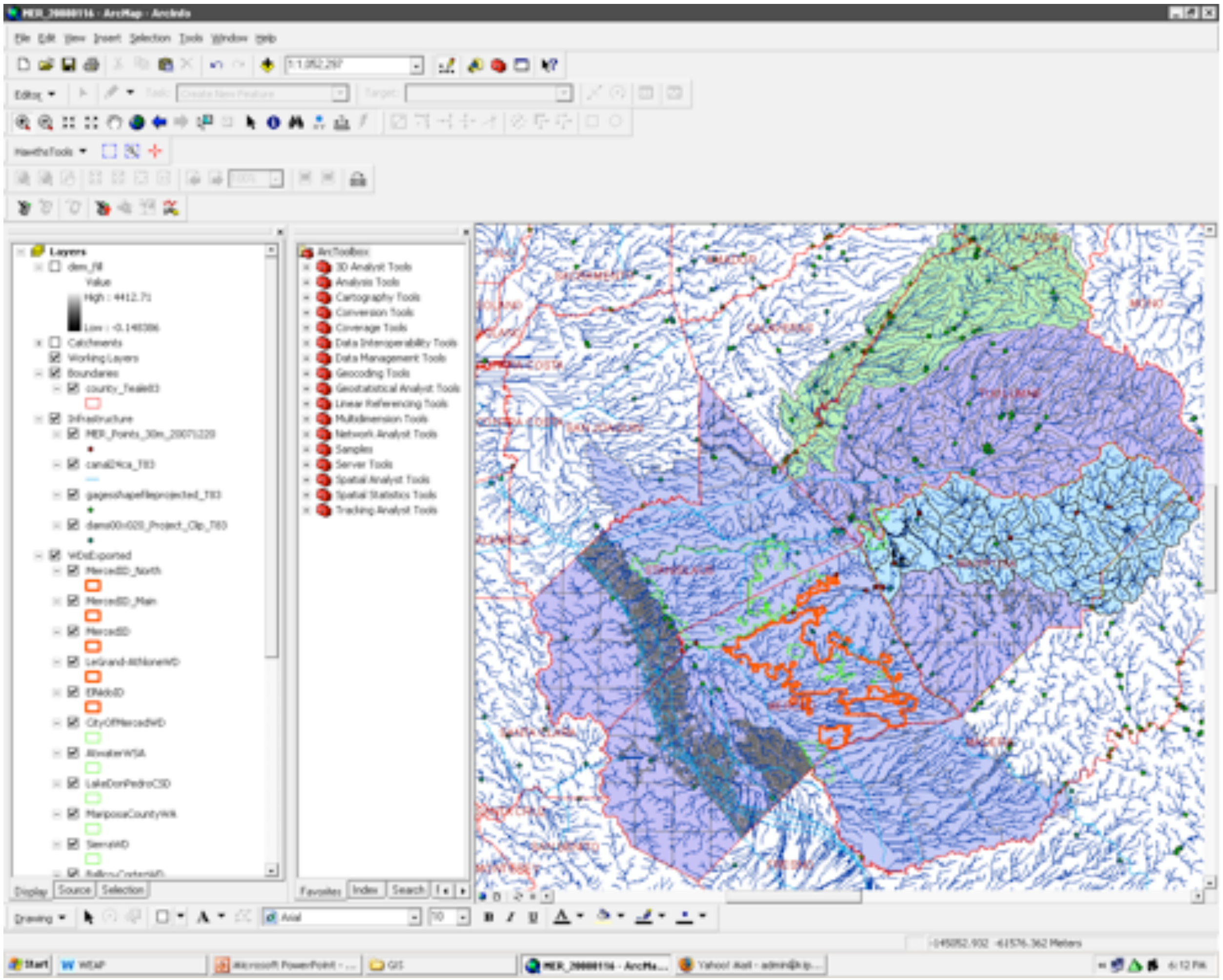


Figure 7: Screenshot from the ArcGIS model of the Merced, Tuolumne, and Stanislaus river basins. Visible are stream networks, watershed boundaries, irrigation district boundaries, dams and gages, and other features to be translated into the WEAP model.

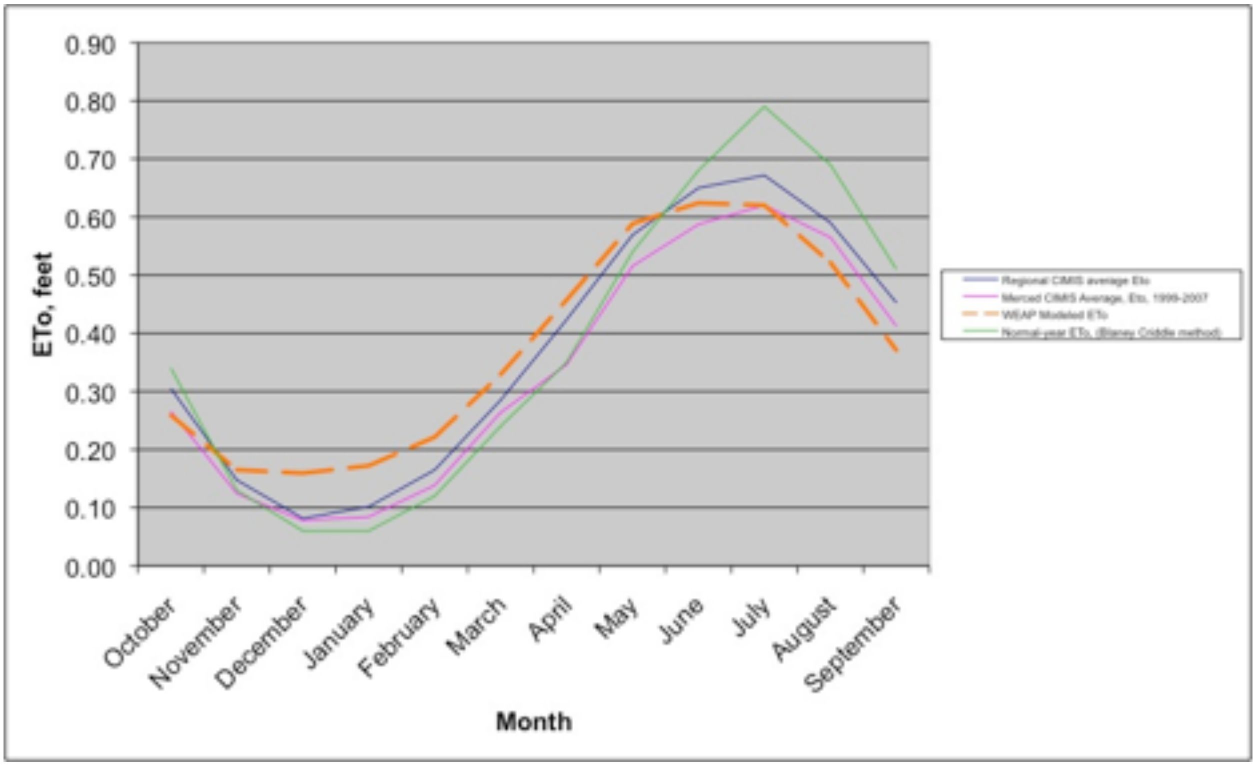
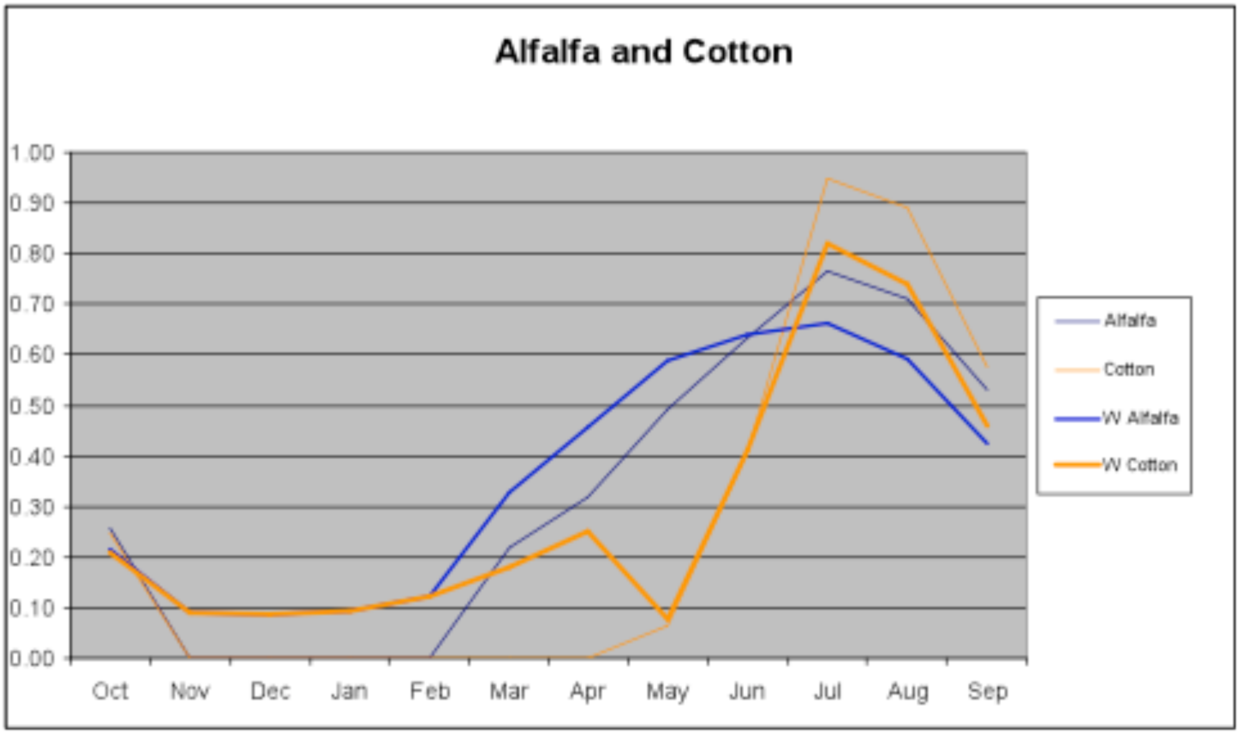


Figure 8: Reference potential evapotranspiration as represented by the WEAP model at the Merced CIMIS station.


Alfalfa and Cotton
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0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
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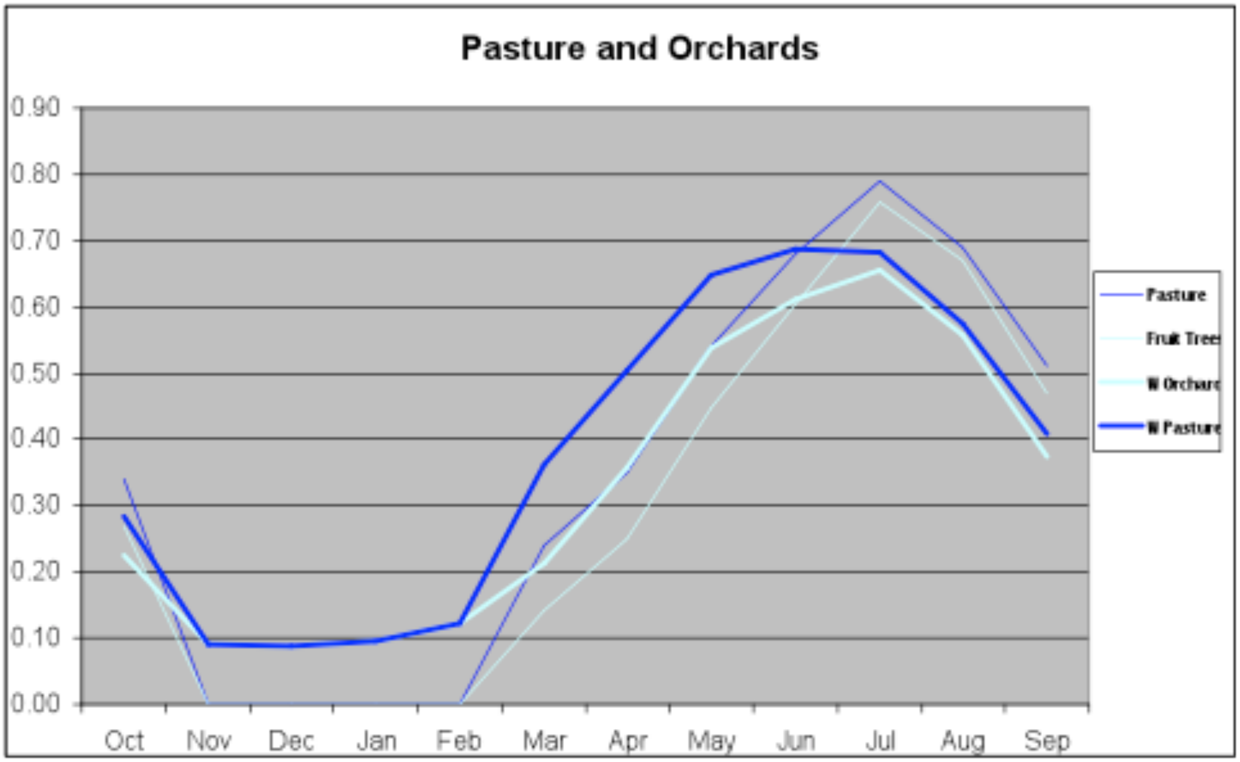
Alfalfa
Cotton
W Alfalfa
W Cotton


Pasture and Orchards
0.90
0.80
0.70
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Fruit Tree
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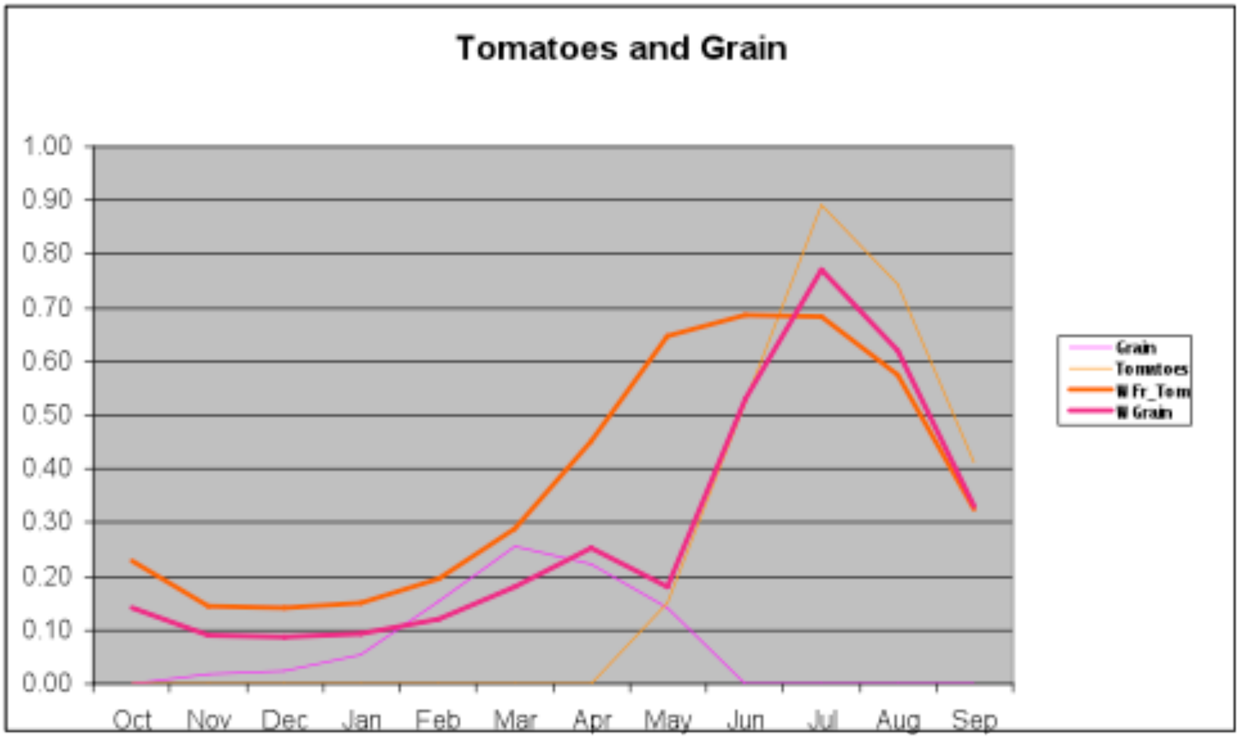
W Pasture


Tomatoes and Grain
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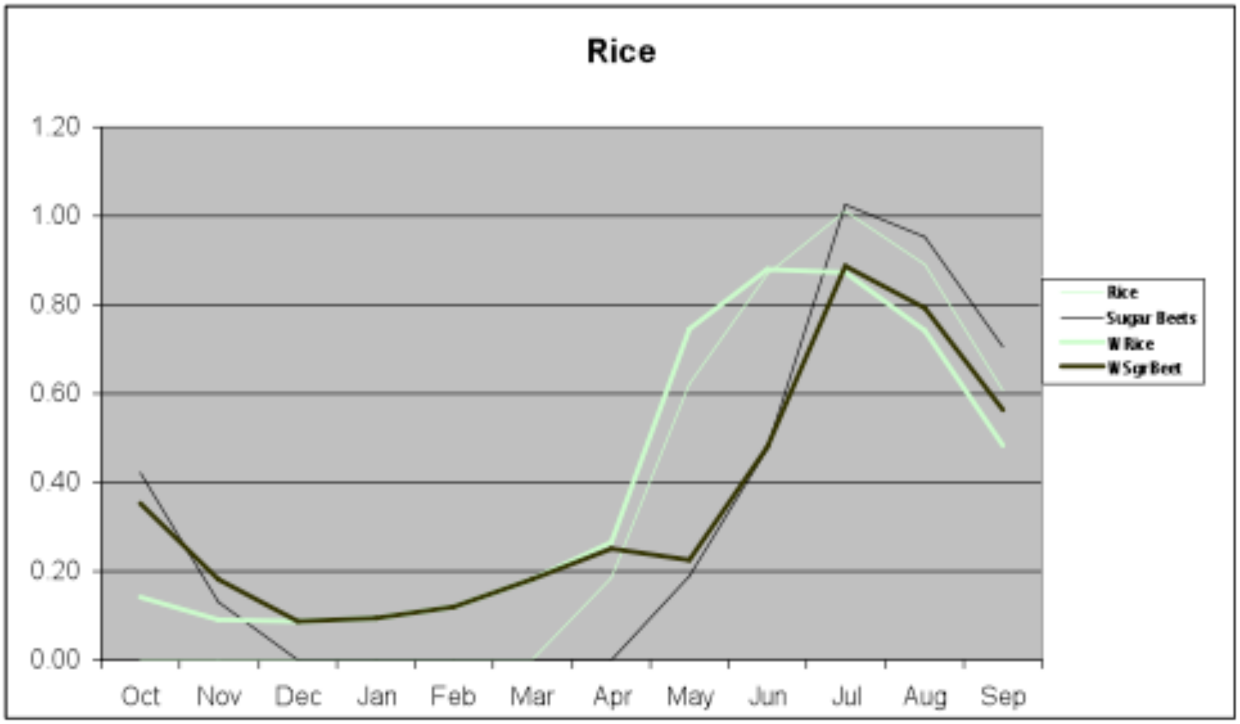
Rice
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Oct
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Jun
Jul
Aug
Sep
Rice
Sugar Beets
W Rice
W SgrBeet

Figure 9: Crop potential evapotranspiration for crop aggregations, in inches, with bold lines indicating WEAP modeled values and fine lines indicating measured values from DWR Bulletin 113.

Water Year 2007

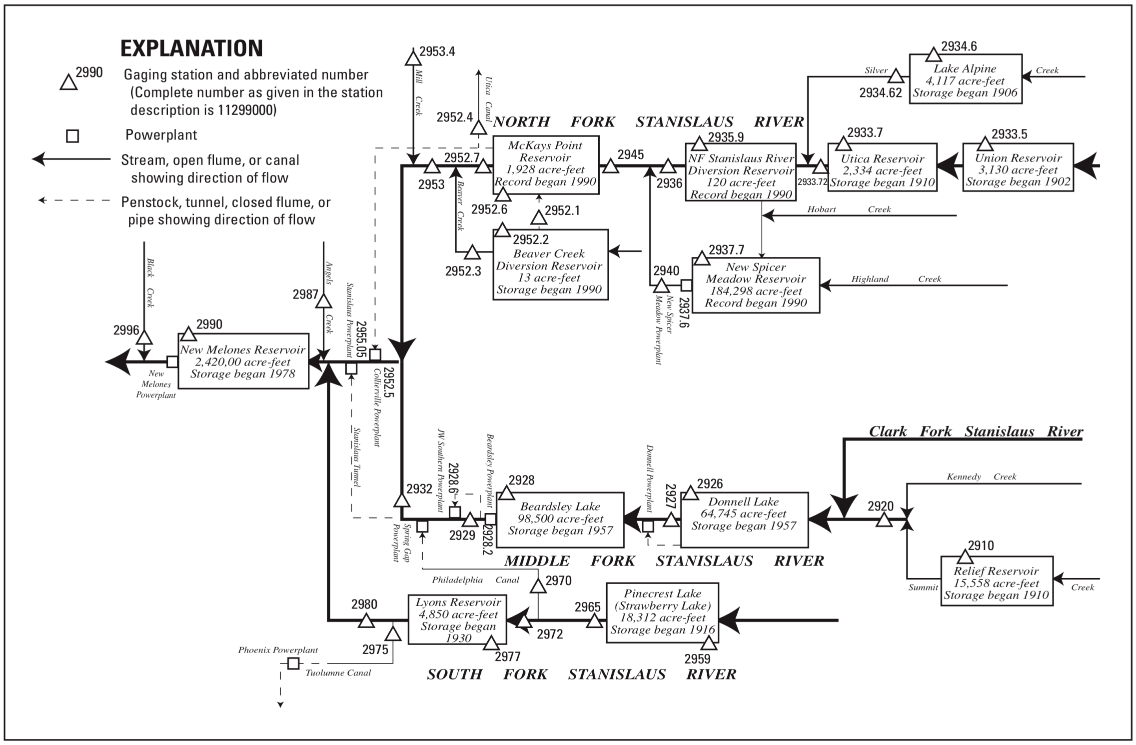

Figure showing diversions and storage in Stanislaus River Basin.

Figure 10: USGS schematic showing storage, diversions, and gages in the upper Stanislaus River Basin. Numbers on this figure abbreviate USGS gage numbers. The WEAP model uses a simplified version of this schematic as described in the text and in Figure 11 and Table 13.

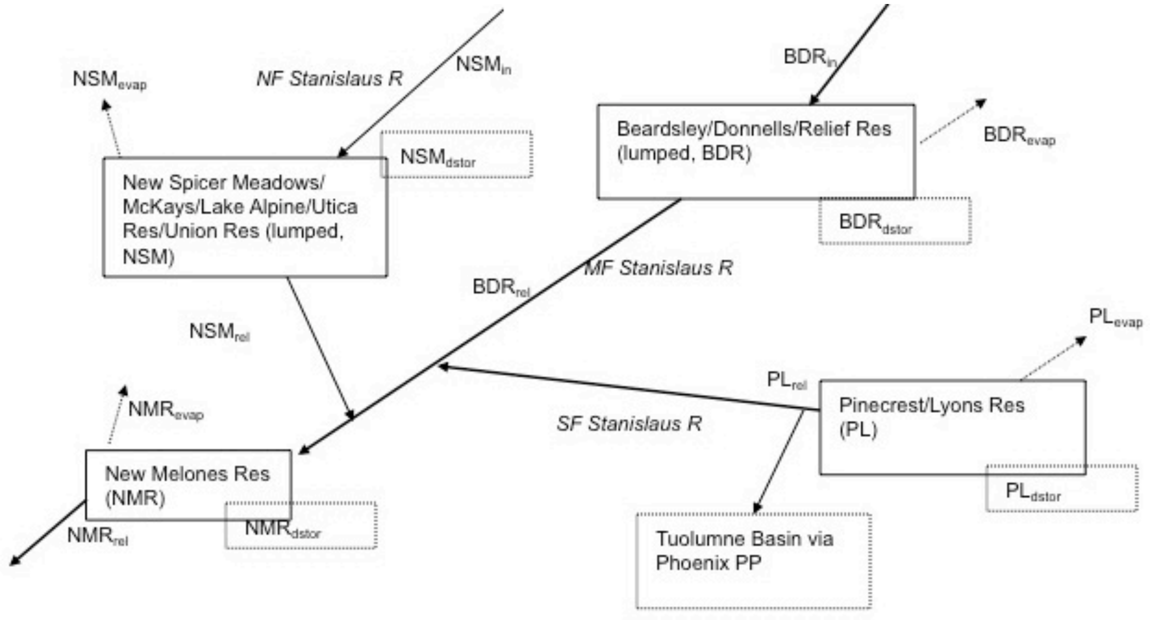

Figure 11: Conceptual model of simplified WEAP representation of the Stanislaus River Basin.

Water Year 2007

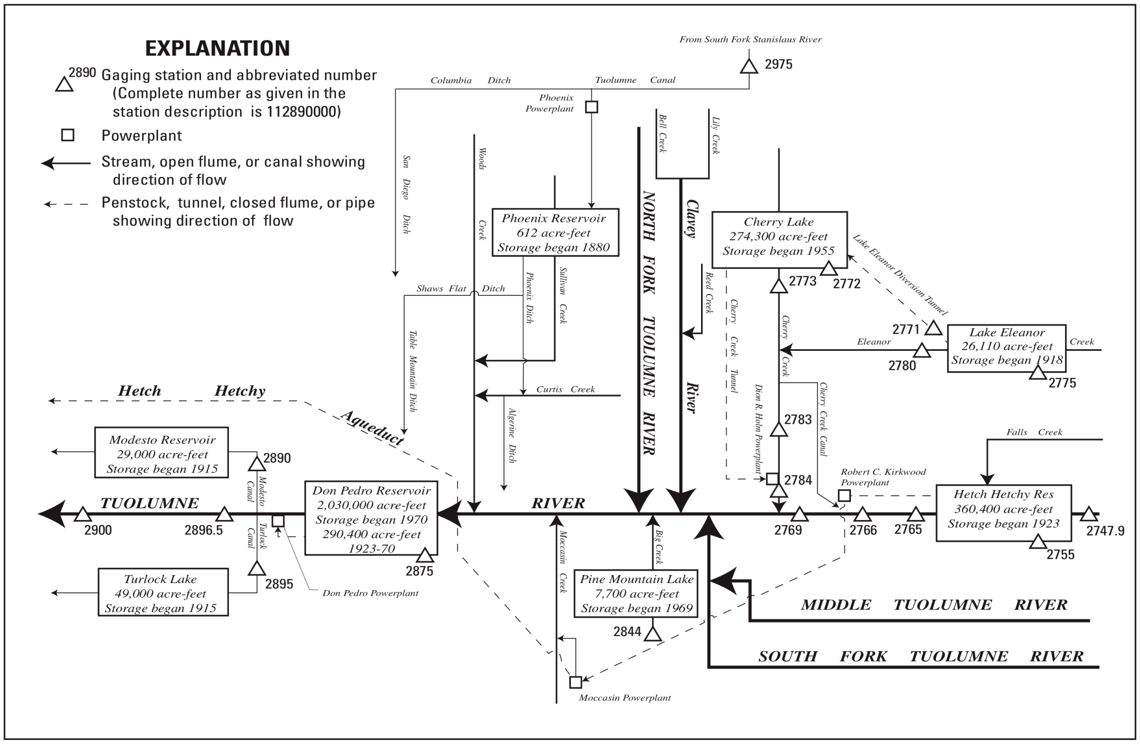

Figure showing diversions and storage in Tuolumne River Basin.

Figure 12: USGS schematic showing storage, diversions, and gages in the upper Tuolumne River Basin. Numbers on this figure abbreviate USGS gage numbers. The WEAP model uses a simplified version of this schematic as described in the text and in Table 14 and Figure 13.

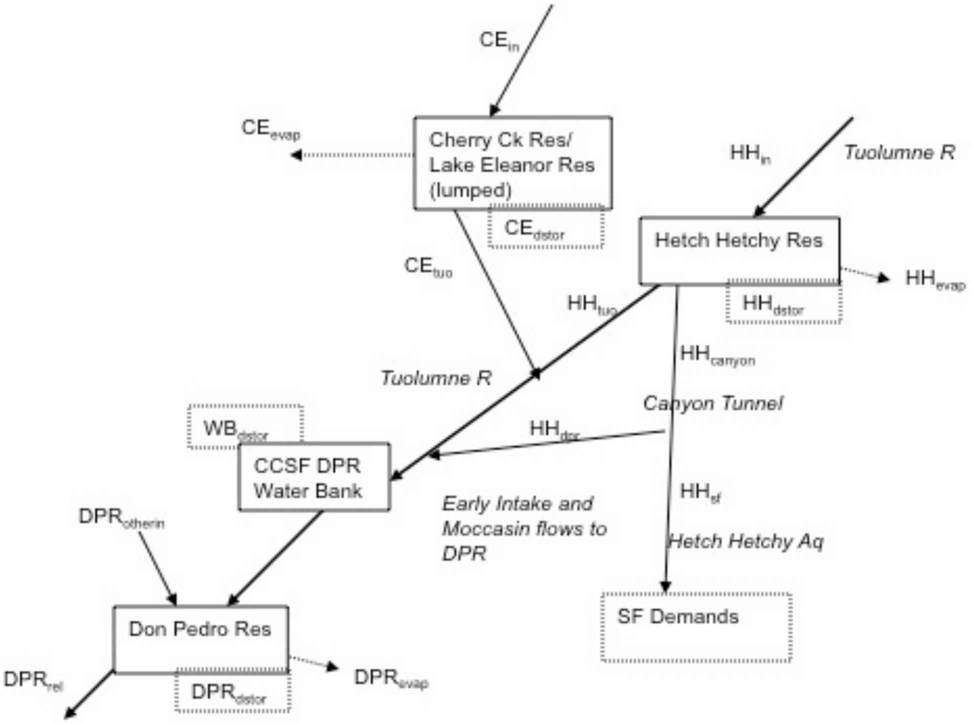

Figure 13: WEAP representation of Upper Tuolumne water resources system.

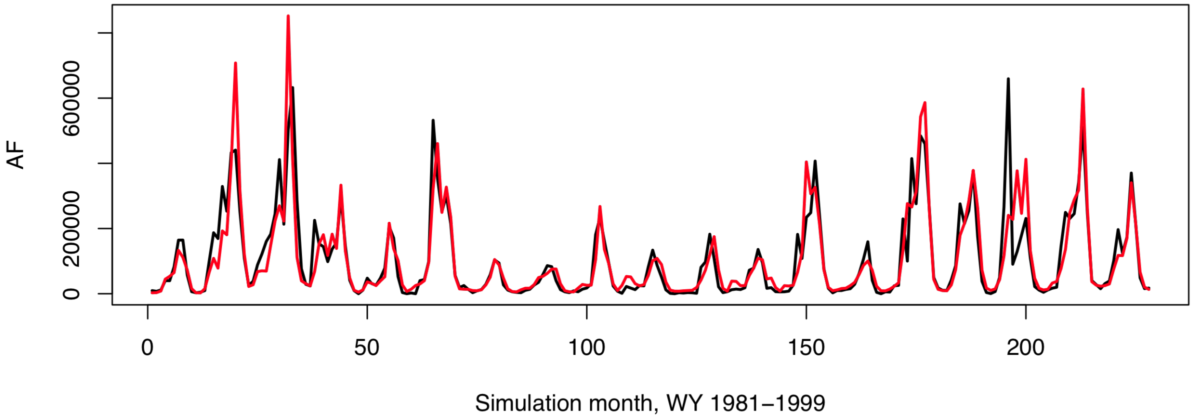

Figure 14: Unimpaired inflows to New Melones Reservoir, simulated (red) and observed (black) calculated Full Natural Flows (CA DWR).

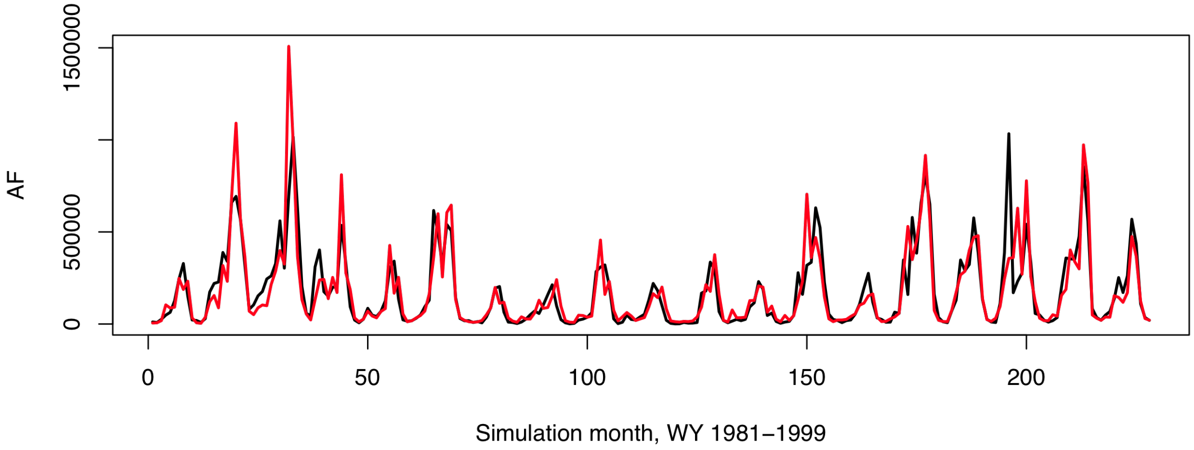

Figure 15: Unimpaired inflows to Don Pedro Reservoir, simulated (red) and historical (black) calculated Full Natural Flows (CA DWR).

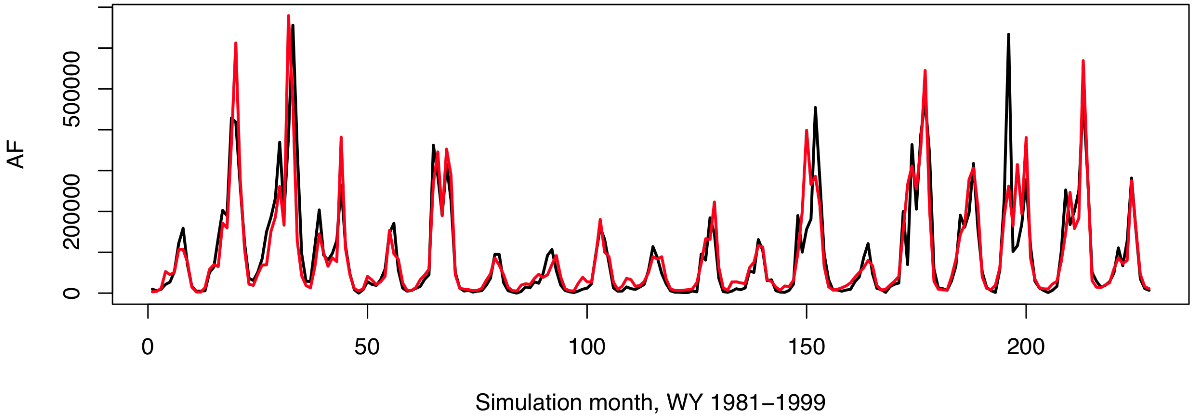

Figure 16: Unimpaired inflows to Lake McClure, simulated (red) and historical (black) calculated Full Natural Flows (CA DWR).

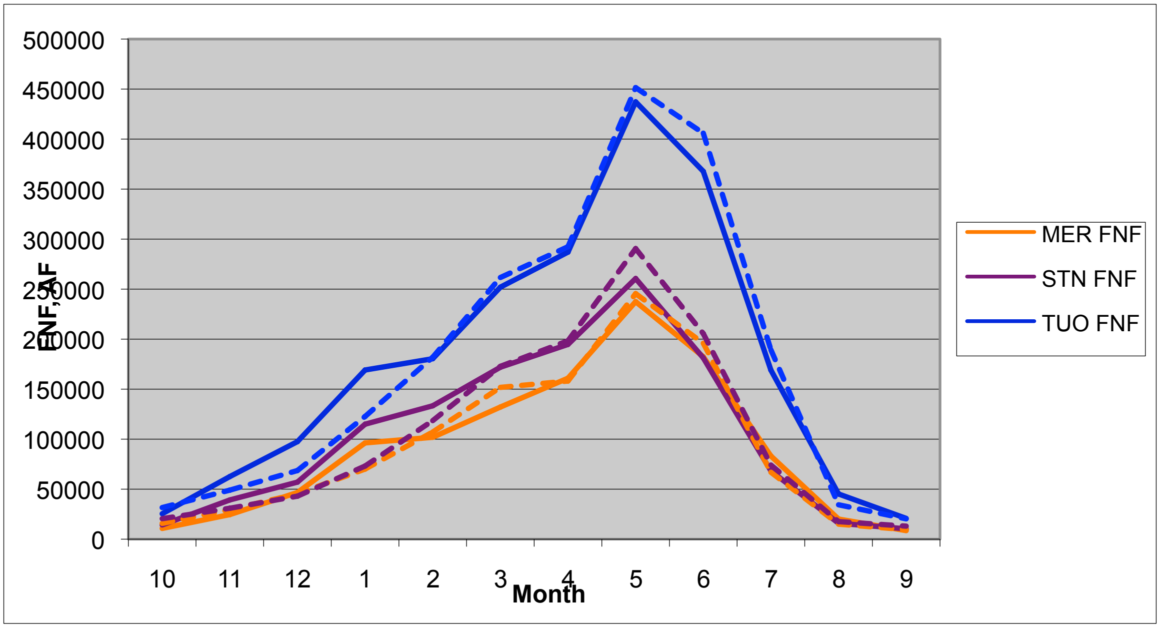

Figure 17: Simulated (dashed line) and DWR estimated average monthly unimpaired flows for the Stanislaus, Tuolumne, and Merced River Basins.

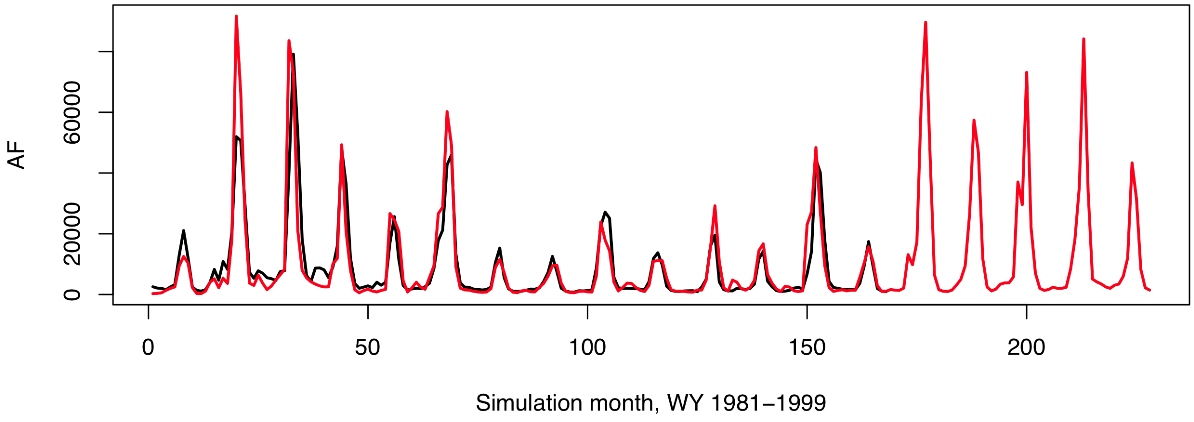

Figure 18: Clark fork streamflow. (Black = observed, Red = simulated in all figures).

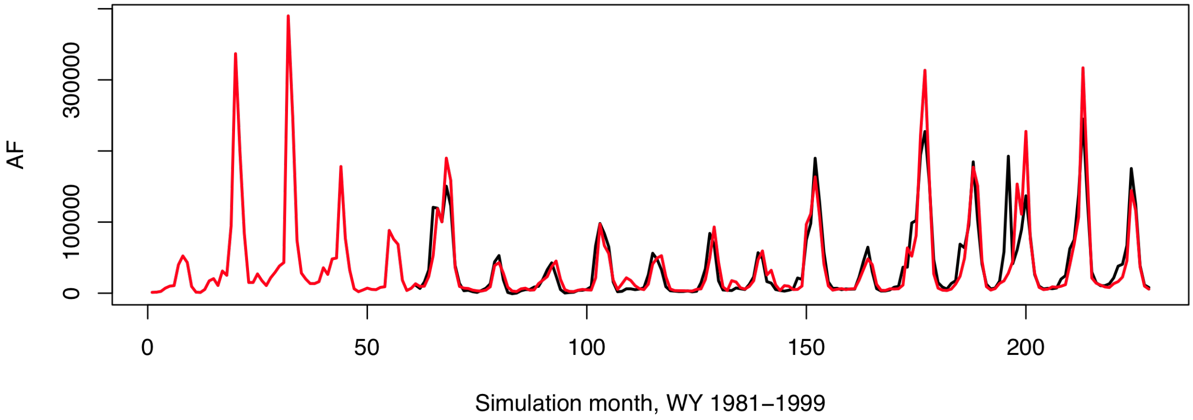

Figure 19: Inflows to Beardsley-Donnels Reservoir object.

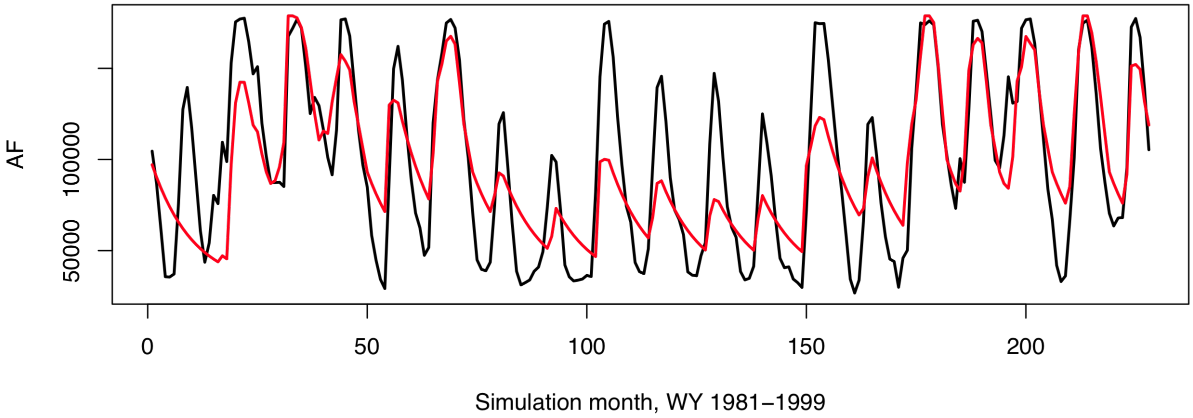

Figure 20: Reservoir storage in Beardsley Donnels Reservoir object.

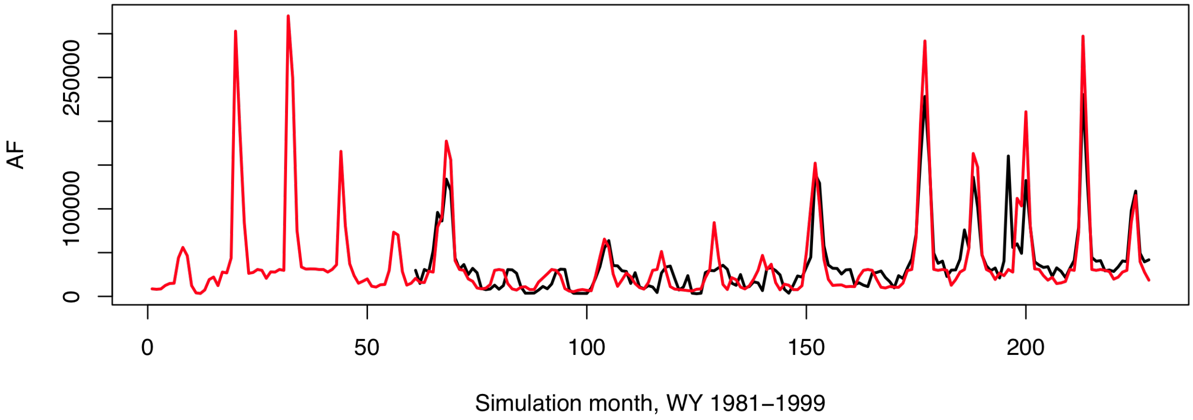

Figure 21: Releases from Beardsley Donnells Reservoir object.

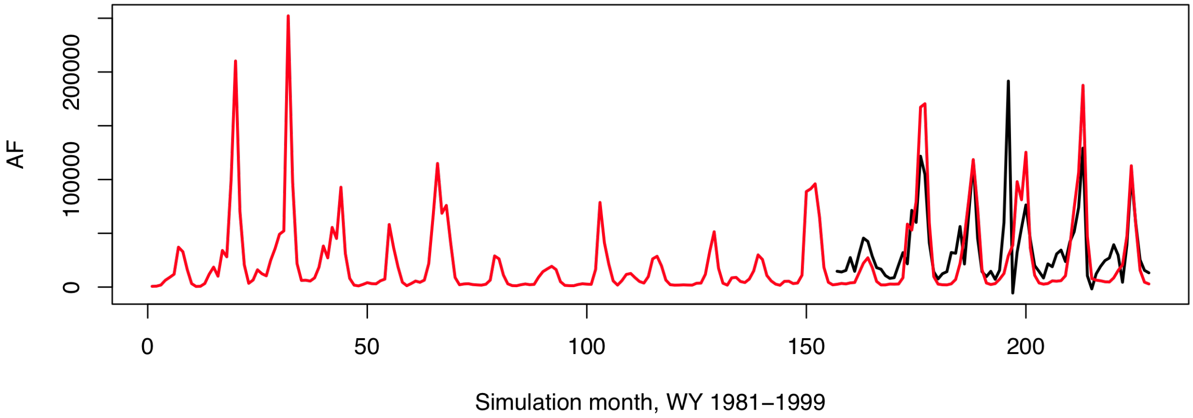

Figure 22: Inflows to New Spicer Reservoir object.

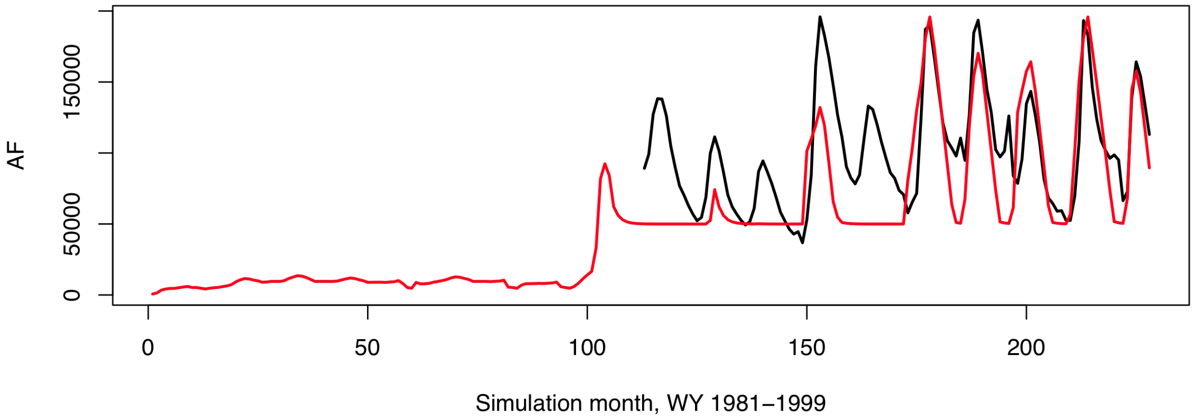

Figure 23: New Spicer Reservoir object storage (note that New Spicer Meadows Reservoir was constructed ca. 1991).

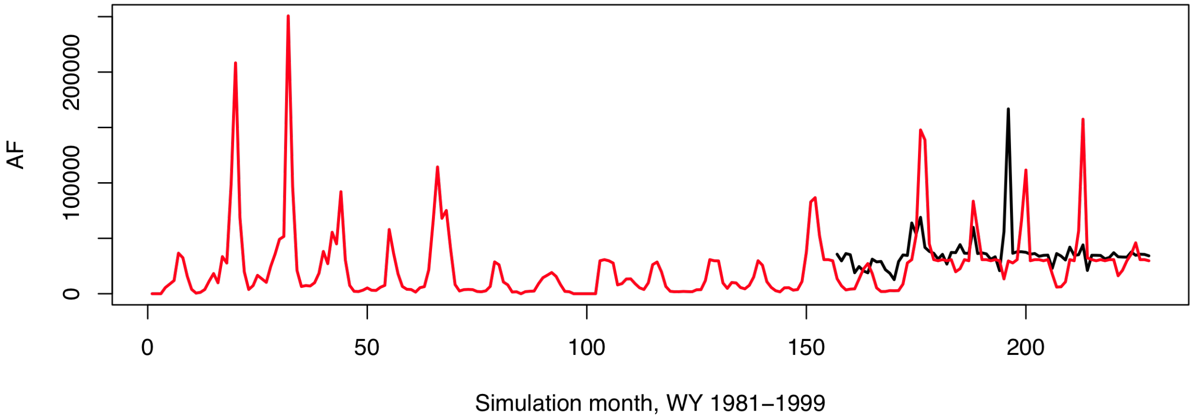

Figure 24: Releases from New Spicer Meadows Reservoir object.

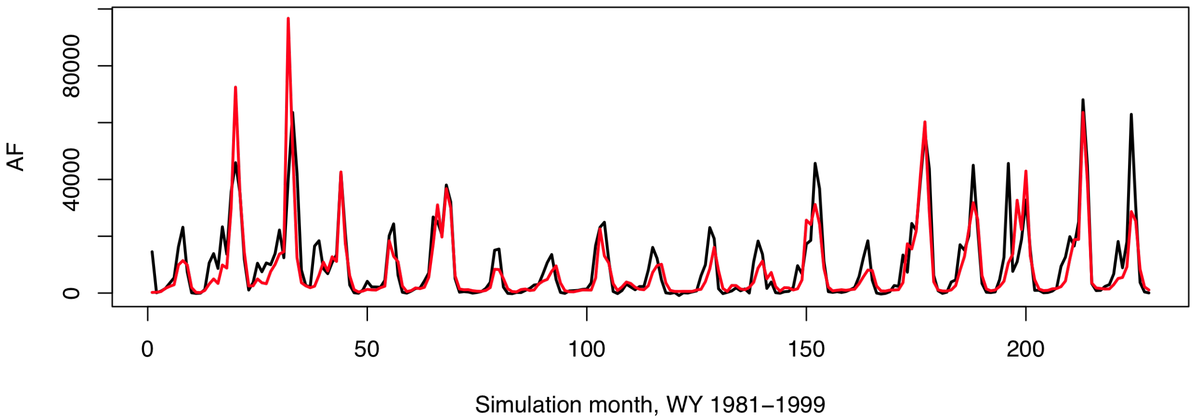

Figure 25: Inflows to Pinecrest-Lyons Reservoir object.

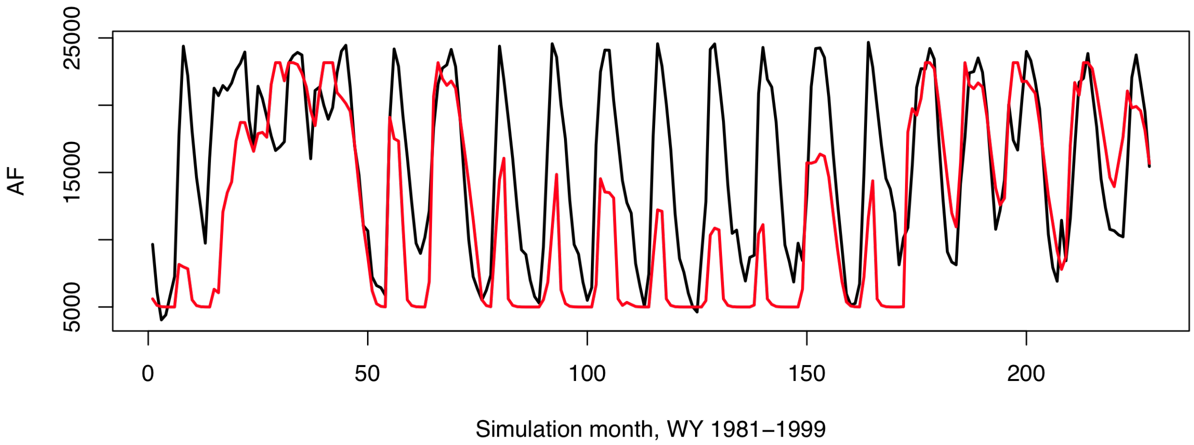

Figure 26: Pinecrest-Lyons Reservoir object storage.

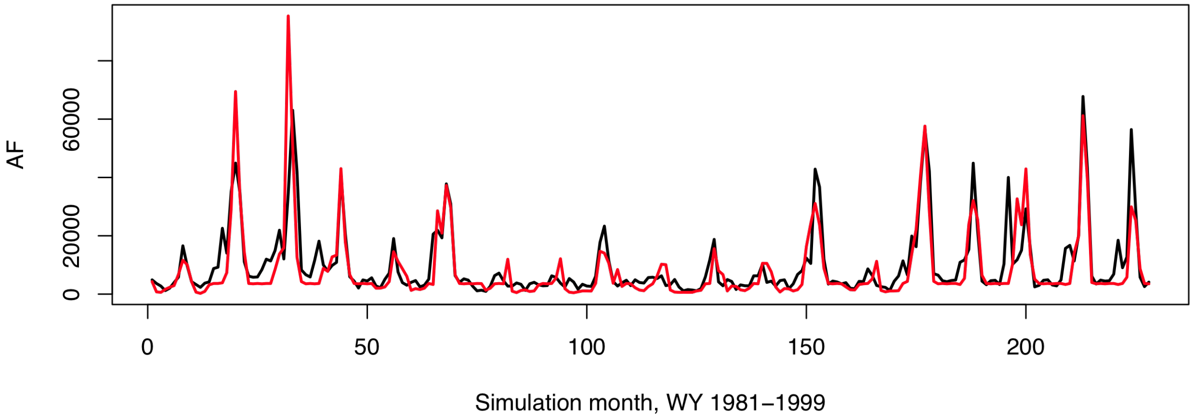

Figure 27: Releases from Pinecrest-Lyons Reservoir object.

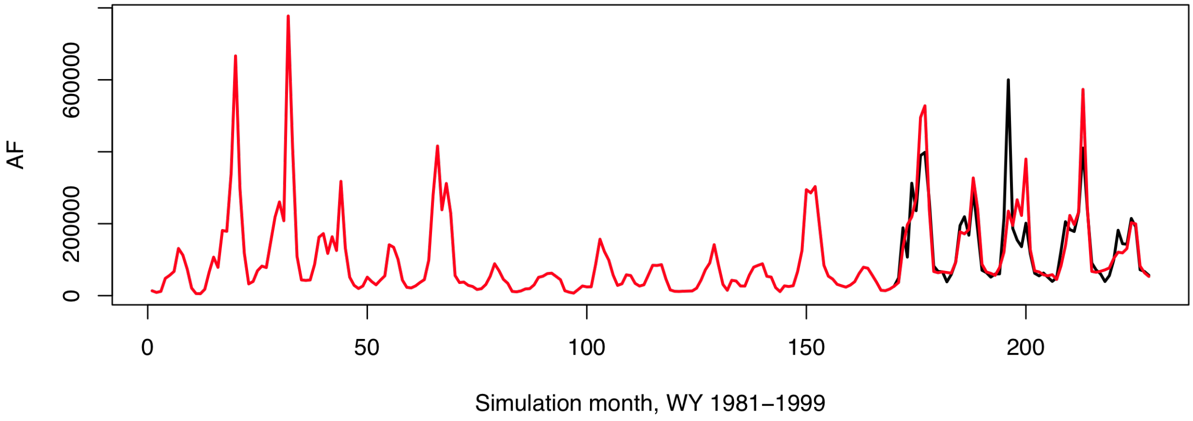

Figure 28: Inflows to New Melones Reservoir.

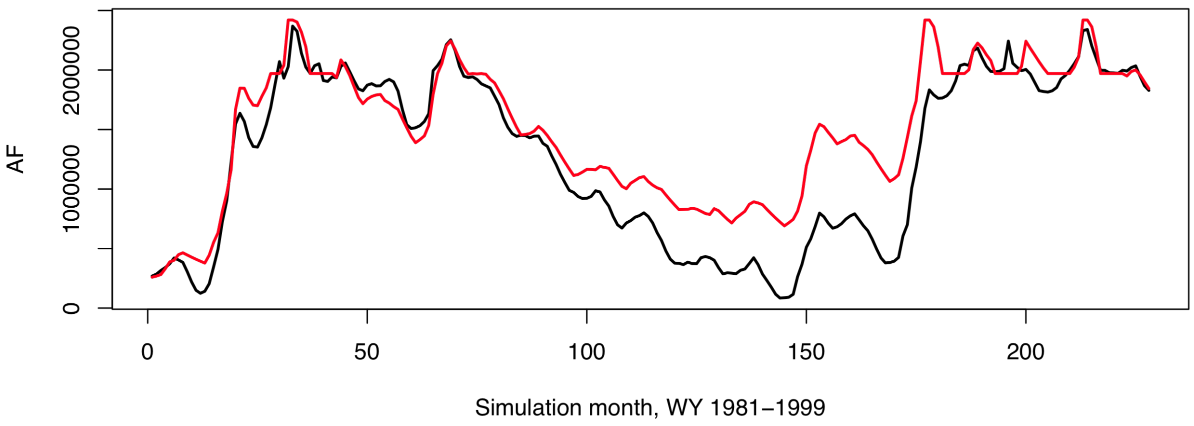

Figure 29: New Melones Reservoir storage.

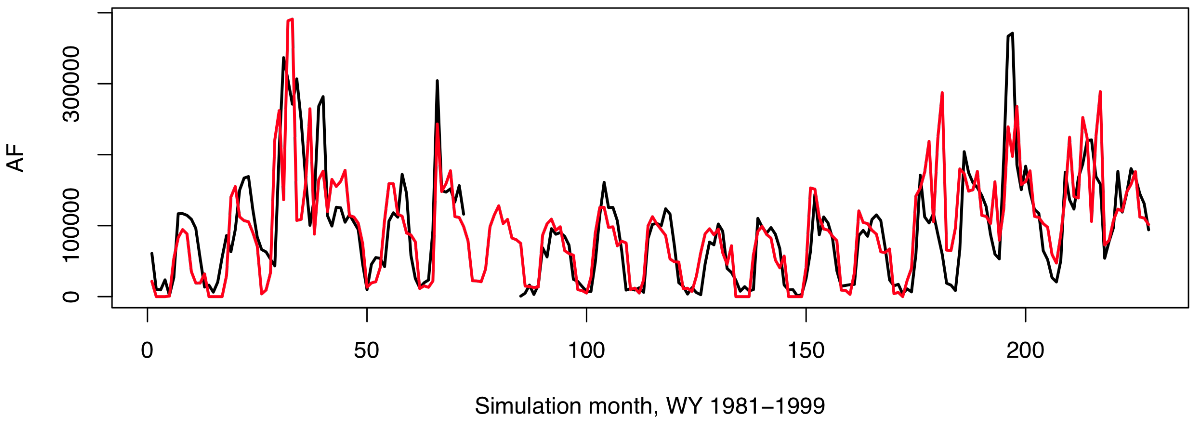

Figure 30: Releases from New Melones Reservoir. Gap in historical data indicates break between reconstructed data (earlier) and USGS data (later). Reconstructed data is based on a mass balance from available downstream data. These data do not formally include accretions/depletions between New Melones and Goodwin Diversion Dam. These data were corrected based on differences in reconstructed and reported NML release data during the period of available data, but this ad hoc unbiasing should be treated with caution.

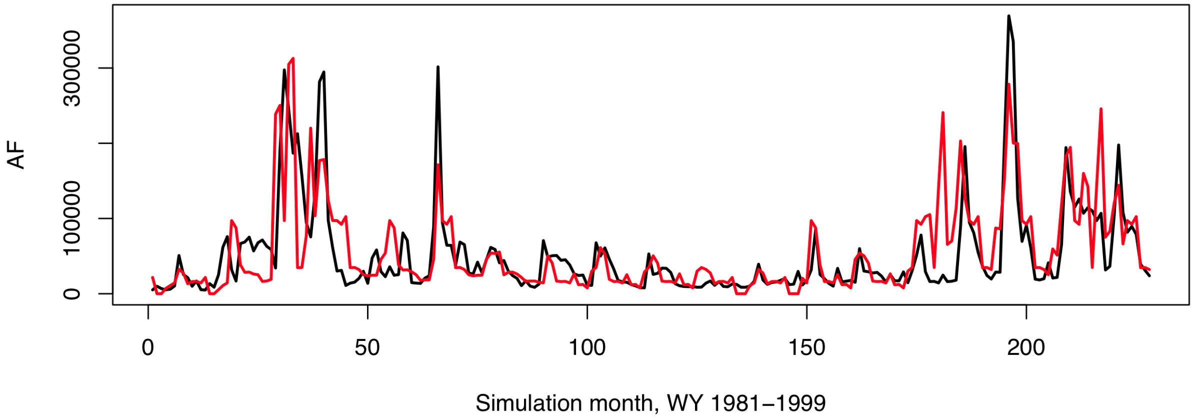

Figure 31: Flows below Goodwin Diversion Dam.

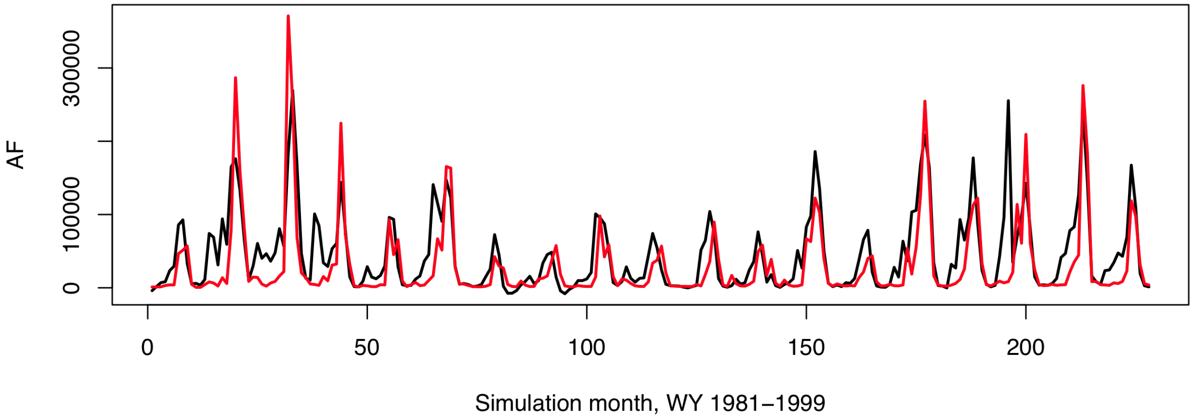

Figure 32: Inflows to Cherry-Eleanor Reservoir object.

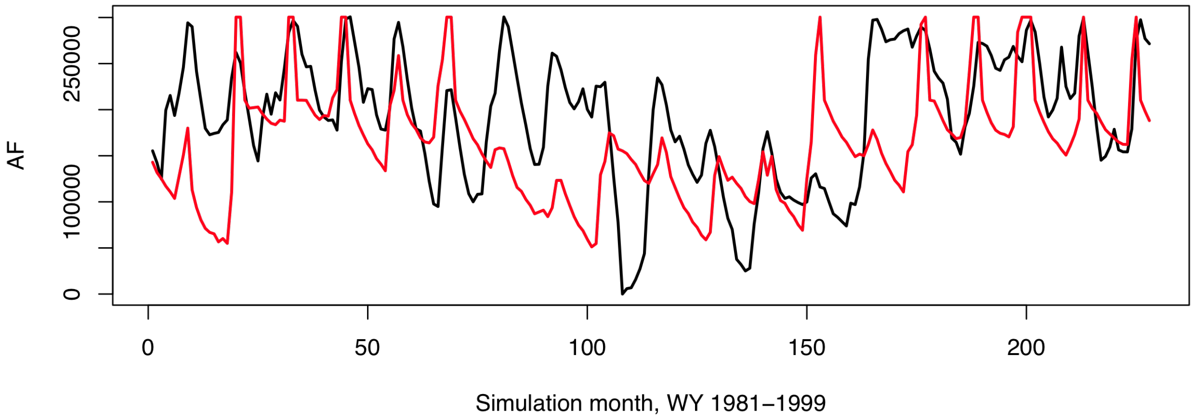

Figure 33: Reservoir Storage at Cherry-Eleanor Reservoir object.

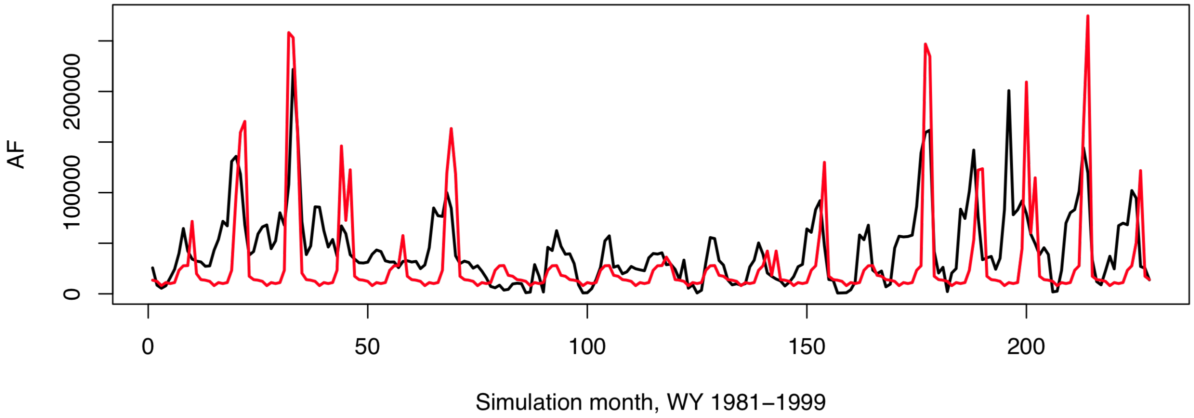

Figure 34: Releases from Cherry-Eleanor Reservoir object.

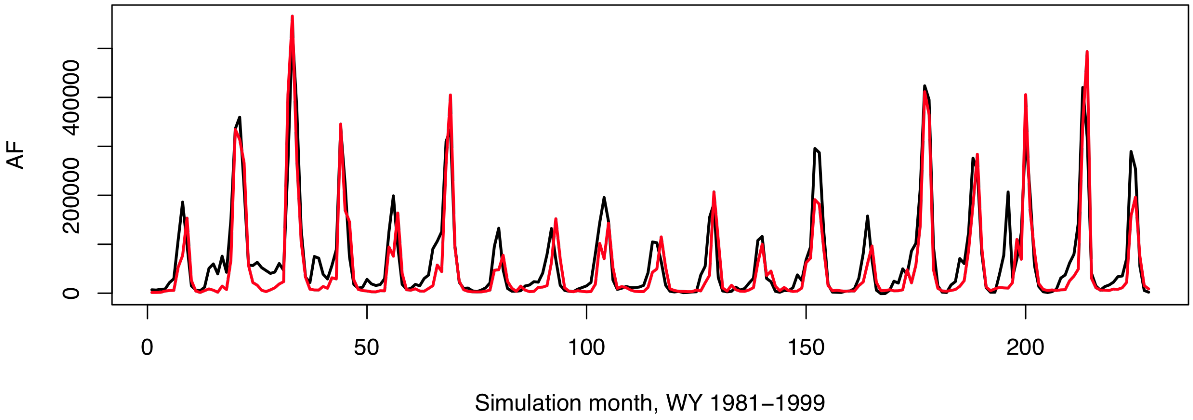

Figure 35: Inflows to Hetch Hetch Reservoir.

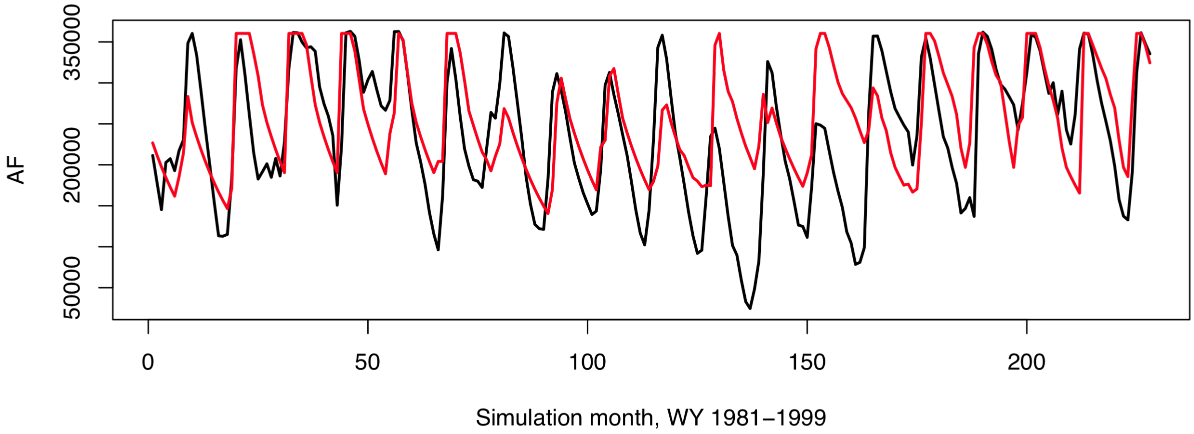

Figure 36: Hetch Hetch Reservoir object storage.

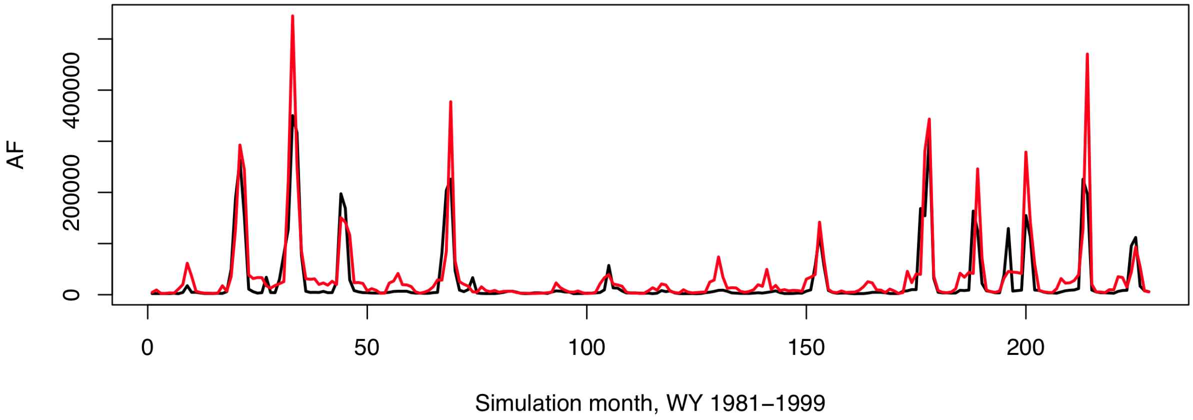

Figure 37: Releases from Hetch Hetchy Reservoir.

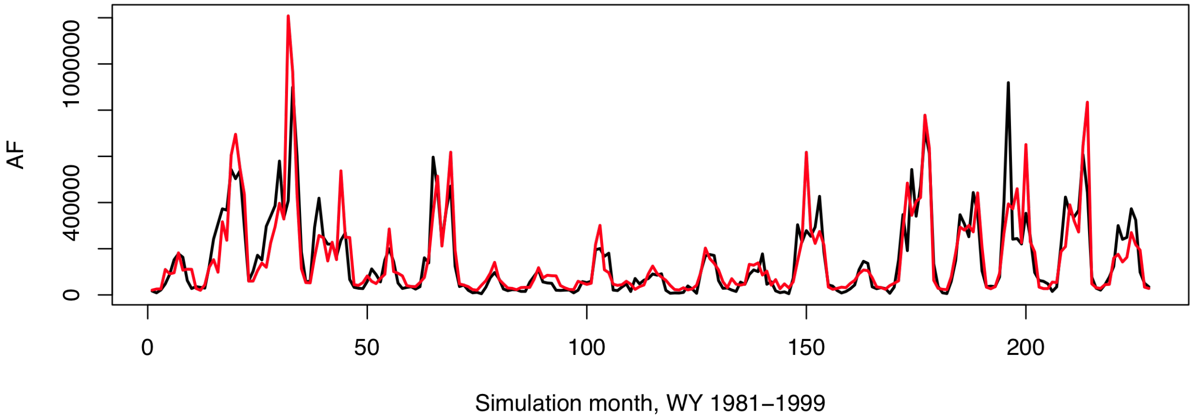

Figure 38: Inflows to Don Pedro Reservoir object.

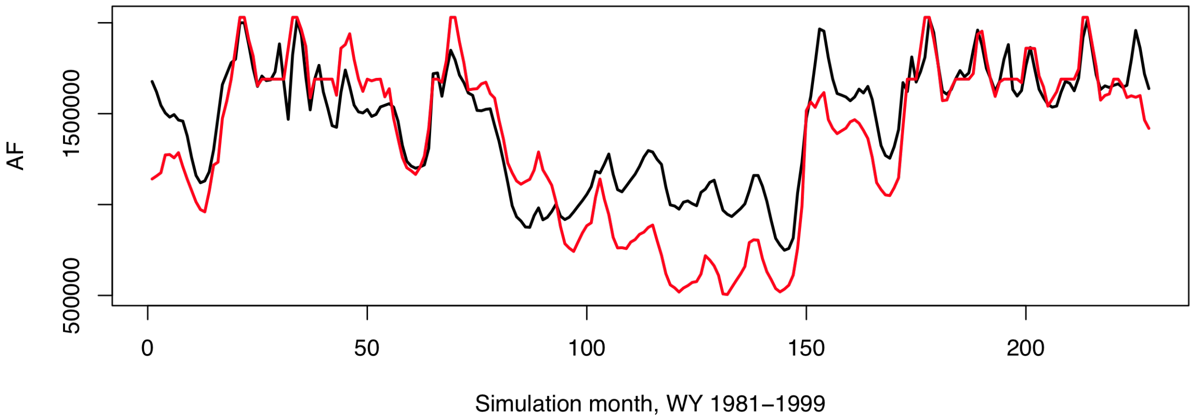

Figure 39: Don Pedro Reservoir storage.

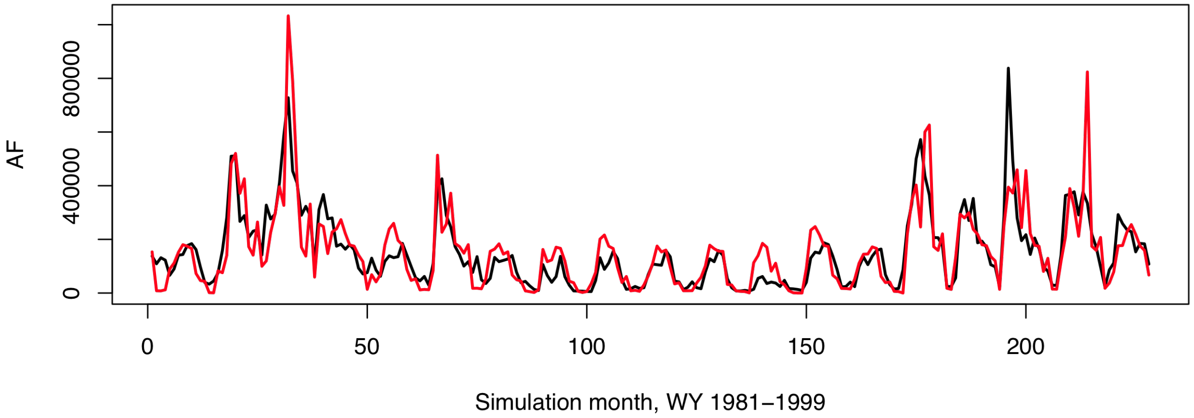

Figure 40: Don Pedro Reservoir releases.

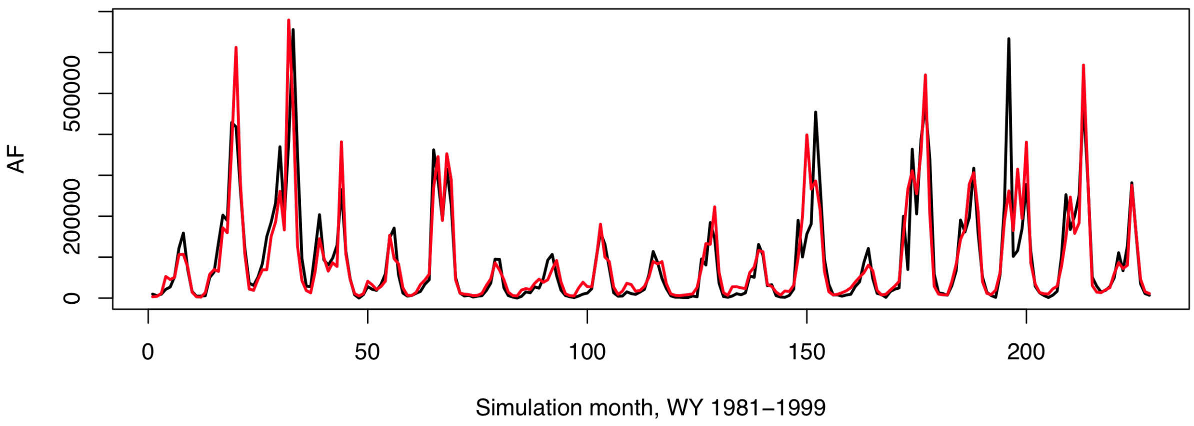

Figure 41: Merced River flows at Lake McClure.

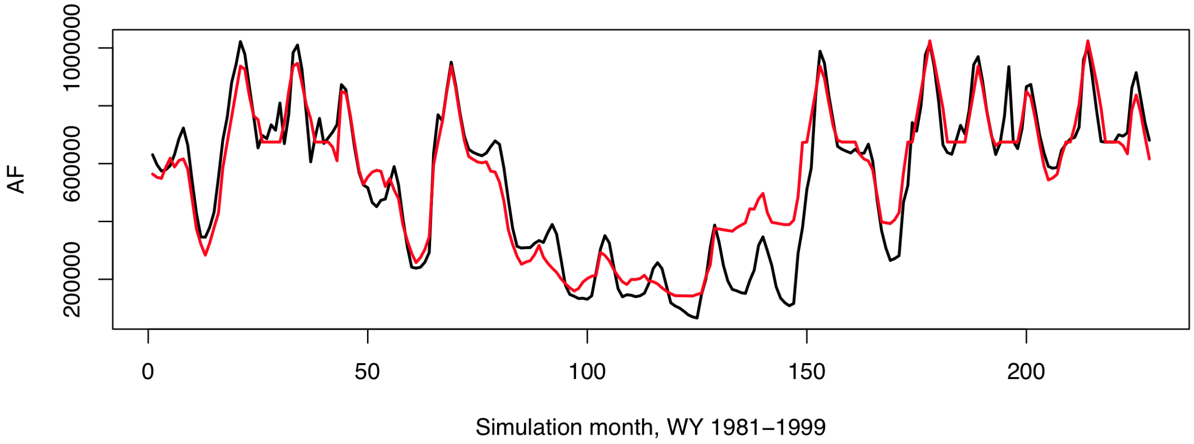

Figure 42: Lake McClure reservoir storage.

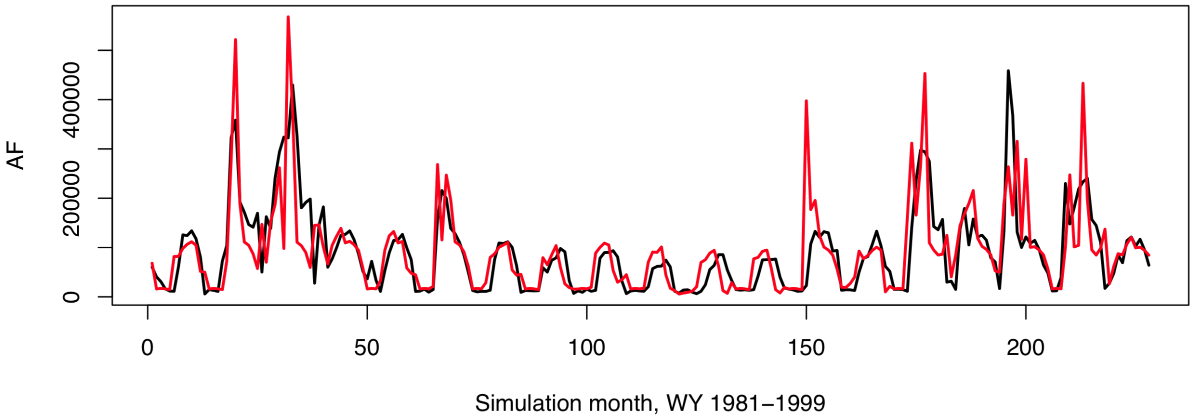

Figure 43: Releases from New Exchequer Reservoir object.

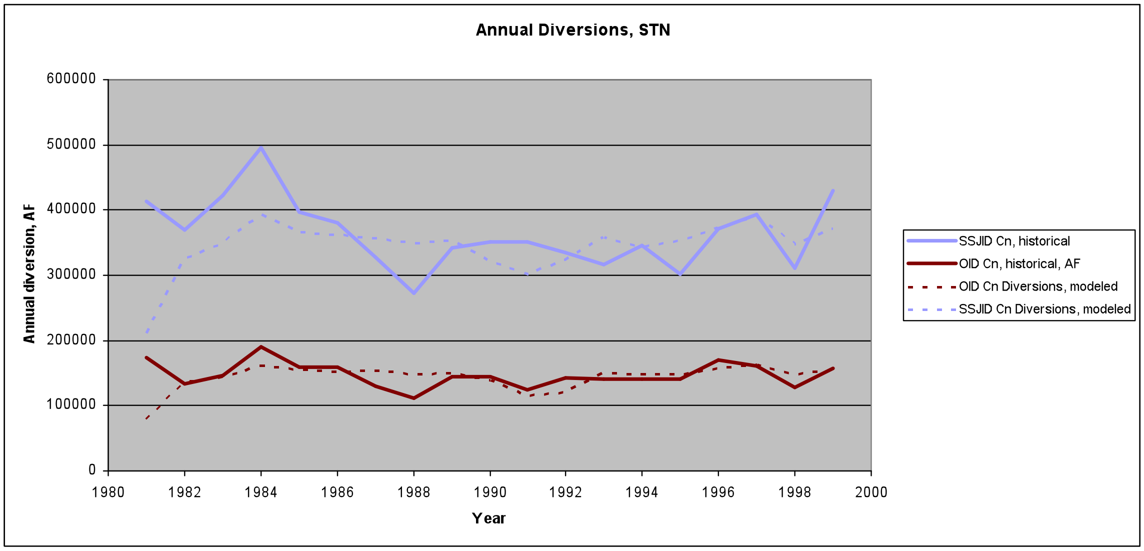

Figure 44: Modeled and historical annual diversions to irrigation districts in the primary irrigation districts in the Stanislaus River Basin, WY 1981-2000.

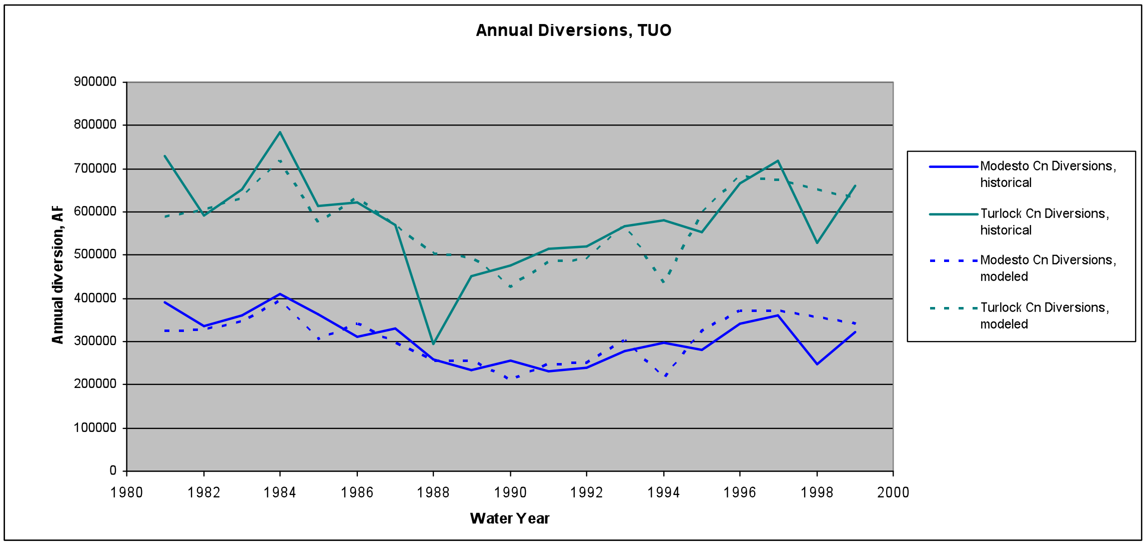

Figure 45: Modeled and historical annual diversions to irrigation districts in the primary irrigation districts in the Tuolumne River Basin, WY 1981-2000.

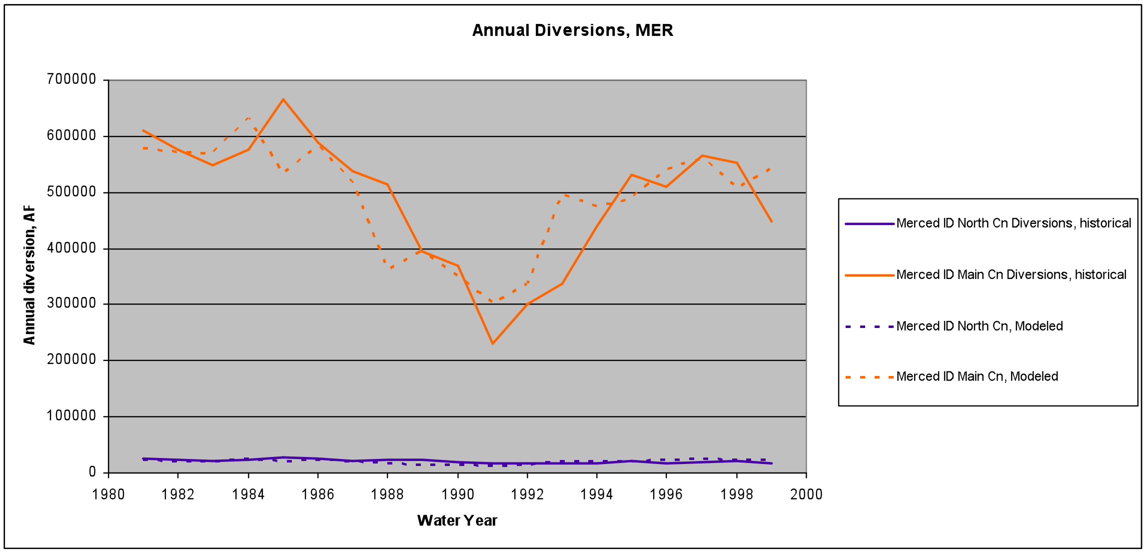

Figure 46: Modeled and historical annual diversions to irrigation districts in the primary irrigation district in the Merced River Basin, WY 1981-2000.

2.26 **Tables**

NLDC Codes	Land Use Classification
11,12, 90-99	WATER
21,22,23,23	URBAN
31,32	BARREN
41,42,43,	TREE
52	SHRUB
71	GRASSLAND
81,82	AGRICULTURE

Table 1: Simplified land use/land cover classifications for the upper watersheds, based on NLCD data.

WEAP Agricultural Land Use Classifications
Grain
Rice
Cotton
SgrBeet
Field
Alfalfa
Pasture
Pr_Tom
Fr_Tom
Truck
Orchard
Subtrop
Vine
Fallow
Other_Non_irr

Table 2: Land use/land cover classifications for hydrologic and demand modeling in the Valley floor, based on mapping from DWR DPLA spatial land cover surveys to a simplified version of DPLA's annual land and water use survey classes (www.landwateruse.water.ca.gov).

Dam Name(s)	WEAP Reservoir Object	Reservoir Name(s)	Basin	Owner	Operator	Purposes	Storage Capacity (AF)
New Exchequer	New Exchequer	Lake McClure	Merced	Merced ID	Merced County	STO, FC, IRR, REC, POW	1,032,000
Cherry Valley Lake Eleanor	CE	Cherry Lake Lake Eleanor	Tuolumne	CCSF	Hetch Hetchy Water and Power Hetch Hetchy Water and Power	STO, DIV, DOM, IRR, POW STO, DOM, MUN, POW	273,500 28,600
O'Shaughnessy	HH	Hetch Hetchy	Tuolumne	CCSF	Hetch Hetchy Water and Power	STO, DOM, MUN, POW	360,000
Don Pedro	CCSF Water Bank	Don Pedro	Tuolumne	MID/TID	Turlock Irrigation District	STO, DOM, MUN	570,000
Don Pedro	Don Pedro	Don Pedro	Tuolumne	MID/TID	Turlock Irrigation District	STO, IRR, DOM, MUN, POW, REC, FC	2,030,000 -570,000
Pinecrest Lyons	Pinecrest/ Lyons	Strawberry Lk Lyons	Stanislaus	PG&E	Pacific Gas & Electric Pacific Gas & Electric	Unspecified; STO, IRR, POW	18,312 4,850
Beardsley Donnells Relief	Beardsley_Donnells_ Relief	Beardsley Lk Donnells Relief	Stanislaus	Oakdale ID, SSJID PG&E	USBR USBR PG&E, Angels Camp	STO, IRR, POW (1); STO, POW	98,500+ 64,745+ 15,550
New Spicer Meadows Dam (built in1988) Spicer Meadows Dam (pre-1988) McKays (completed June 1989) Utica Reservoir Union Reservoir Lake Alpine	NSM	New Spicer Meadows Res McKays Point Res Utica Res Union Res Lake Alpine	Stanislaus	Unspecififed	Unspecified	Unspecified	Before 1989: 4062+ 2,334 + 3,130 + 4,117 = 13643; After 1989: 184,298+ 1,928+ 2,334 + 3,130 + 4,117 = 195807

Table 3: Physical characteristics of reservoir objects in WEAP model. Sources: USGS and California Data Exchange Center. (1) CDEC refers to Don Pedro Reservoir for reservoir purposes.

Subbasin	Subbasin Number	Groundwater Storage Capacity	Initial Storage	Specific Yield	Ground-water Budget Type (1)	Estimated historical groundwater balance
Eastern San Joaquin	5-22.01	51,200,000 af (2)	No estimate available from DWR, using 90% of total capcity (46,000,000 af) to start	7.3%	A	1963-1982, average annual overdraft of ~70,000 AF; 1990 estimated overdraft of 113,000 af/year.
Modesto	5-22.02	6,500,000 af to a depth of 300 feet	No estimate available from DWR, using 90% of total capacity (5,850,000 af)	N/A	B	~48,000 af/year of overdraft
Turlock	5-22.03	15,800,000 af to a depth of 300 feet	12,800,000 af stored in subbasin to a depth of 300 ft as of 1995	10.1%	B	Groundwater level declines are noted.
Merced	5-22.04	21,100,000 af to a depth of 300 feet	15,700,000 af of groundwater to a depth of 300 feet stored in this subbasin as of 1995.	9.0%	B	Groundwater level fluctuations are noted, but not as a groundwater balance.

Table 4: Groundwater sub-basin properties, as described in DWR Bulletin 118 updates. (1) Groundwater budget type is defined by DWR. Type A indicates a well-characterized basin where "much of the information needed to characterize the groundwater budget for the basin or subbasin was available"", although not verified by DWR. Type B is a use-based estimate of its groundwater budget, without thorough data or modeling, in which “enough data are available to estimate the groundwater extraction to meet local water use needs.” (2) Eastern San Joaquin storage capacity was extrapolated from a smaller area to the subbasin, and does not represent the results of a full-basin analysis.

Urban Node	Corresponding agricultural area	Urban Areas Represented	Population estimate	
			1980	2000
Turlock Urban	TurlockID	Turlock and vicinity	123520	163231
Merced Urban	MercedID_S	Merced, Atwater, Livingston and vicinity	111797	137834
Oakdale Urban	OakdaleID	Oakdale and vicinity	28492	34875
Manteca Urban	SSJID	Manteca, Ripon and vicinity	41529	66877
Stockton Urban	StocktonEastWD	Stockton and vicinity	272554	310717
Modesto Urban	ModestoID	Modesto and vicinity	154358	223463

Table 5: Description of urban center nodes and population estimates.

New Melones Storage plus Inflow threshold	0	1400	2269	2293	2421	2767	3000
Fishery Flow Determination	0 < index =< 1400	1400 < index =< 2269	2269 < index =< 2293	2293 < index =< 2421	2421 < index =< 2767	2767 < index =< 3000	> 3000
Fisheries allocation (TAF, approx.)	0	98.4	243.3	253.8	310.3	410.2	466.8
WEAP fisheries flow schedule	A	B	C	D	E	F	G

Table 6: Logic for determination of WEAP Stanislaus River minimum fishery flow schedules (cfs). Note that in practice requirements are linearly interpolated between the seven distinct flow schedules, while in the current model I use thresholds to determine which of the flow schedules in Table 7 is instituted. This results in a bias towards smaller fishery flow requirements. Index values refer to the Stanislaus River Index, as described above (TAF).

	A	B	C	D	E	F	G
October	0	110	200	250	250	350	350
November	0	200	250	275	300	350	400
December	0	200	250	275	300	350	400
January	0	125	250	275	300	350	400
February	0	125	250	275	300	350	400
March	0	125	250	275	300	350	400
April	0	375	900	900	1200	1500	1500
May	0	375	900	900	1200	1500	1500
June	0	0	200	200	250	800	1500
July	0	0	200	200	250	300	300
August	0	0	200	200	250	300	300
September	0	0	200	200	250	300	300

Table 7: WEAP representation of Stanislaus River fishery flow schedules. April and May monthly flow requirements are approximated by averaging the monthly scheduled flow with the April-May pulse volume to get an average monthly flow rate.

Month	Surrogate release volume (TAF)	ISF (cfs)
Jun	13.2	222
Jul	16.2	263
Aug	16.4	267
Sep	14.3	240

Table 8: Surrogate release volumes for D-1422 water quality requirements at Ripon on the Stanislaus River (TAF) and corresponding minimum flows in WEAP (cfs). After Table 6-8 in (USBR 2005).

Year Type	60-20-20 Index Value
Wet	3.8 =< Index
Above Normal	3.1 < Index =< 3.8
Below Normal	2.5 < Index =< 3.1
Dry	2.1 < Index =< 2.5
Critical	Index =< 2.1

Table 9: SWRCB San Joaquin Valley Water Year Hydrologic Classification. State Water Resources Control Board water year types for the San Joaquin Basin. These year types are used for the designation of Delta flow requirements, among other purposes (State Water Resources Control Board 1995).

Year Type		Critical & below	Median Critical	Interm. CD	Median Dry	Interm. D-BN	Median Below Normal	Interm. BN-AN
60-20-20 Index threshold (TAF)		<1500	1500	2000	2200	2400	2700	>3100
Month								
Oct	Cfs	125	125	150	150	180	188	300
Oct	Attraction pulse	none	none	none	none	1676	1736	5950
Nov	Cfs	150	150	150	150	180	175	300
Dec	Cfs	150	150	150	150	180	175	300
Jan	Cfs	150	150	150	150	180	175	300
Feb	Cfs	150	150	150	150	180	175	300
Mar	Cfs	150	150	150	150	180	175	300
Apr	Cfs	150	150	150	150	180	175	300
Apr	Outmigration pulse (AF)	5546	10046	16310	18530	17960	30014	44941
May	Cfs	150	150	150	150	180	175	300
May	Outmigration pulse (AF)	5546	10046	16310	18530	17960	30014	44941
Jun	Cfs	50	50	50	75	75	75	250
Jul	Cfs	50	50	50	75	75	75	250
Aug	Cfs	50	50	50	75	75	75	250
Sep	Cfs	50	50	50	75	75	75	250
Volume		**94000**	**103000**	**117016**	**127507**	**142502**	**165002**	**300923**
(ac-ft.)								

Table 10: WEAP implementation of FERC instream flow requirements at LaGrange on the Tuolumne River. October attraction pulse flows and April and May outmigration pulse flows for

salmon are approximated as additional required flow rates divided evenly between April and May.

Month	Davis Grunsky Crocker-Huffman Dam to Shaffer Bridge	Normal Year	Dry Year	Cowell Agreement Entitlement	Total Normal Year	Total Dry Year
Oct	0	50	37.5	50	100	87.5
Nov	180-220	100	75	50	250	250
Dec	180-220	100	75	50	250	250
Jan	180-220	75	60	50	250	250
Feb	180-220	75	60	50	250	250
Mar	180-220	75	60	100	300	300
Apr	0	75	60	175	250	235
May	0	75	60	225	300	285
Jun	0	25	15	250	275	265
Jul	0	25	15	225	250	240
Aug	0	25	15	175	200	190
Sep	0	25	15	150	175	165

Table 11: Merced River flow requirements driving minimum releases from New Exchequer Reservoir (cfs, left columns). Right two columns (grey) are WEAP operationalizations of Normal and Dry year minimum flows below Crocker-Huffman. According to the requirements, flow below Crocker-Huffman Diversion Dam must equal the greater of the Davis-Grunsky and FERC flows, plus the Cowell Agreement entitlement. See definitions of normal and dry year, and description of forecasting logic, in the text. The Cowell agreement contains provisions in some months for flow reductions based on Merced River daily natural flows, which I have not attempted to include in the modeling given the monthly time step. Davis-Gunsky Flows are operationalized as 200 cfs. October FERC Flows are average values of the given October minimum flows.

Wet Year												
Watershed	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Stanislaus River	342				684	732	1361	1187	538			
Tuolumne River	602				1080	1073	1933	1870	1076			
Merced River	260				630	585	1042	1008	521			
Above Normal Year												
Watershed	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Stanislaus River	342				666	699	1160	976	403			
Tuolumne River	602				1044	1057	1630	1529	823			
Merced River	260				612	569	874	829	403			
Below Normal Years												
Watershed	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Stanislaus River	342				432	472	857	716	269			
Tuolumne River	602				666	699	1227	1138	555			
Merced River	260				396	374	655	618	269			
Dry Years												
Watershed	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Stanislaus River	358				450	472	706	553	235			
Tuolumne River	634				702	699	992	862	454			
Merced River	260				414	374	538	472	218			
Critically Dry Years												
Watershed	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**
Stanislaus River	293				162	195	454	374	118			
Tuolumne River	520				270	309	655	585	235			
Merced River	211				162	163	353	325	118			

Table 12: Proxy for estimated D-1641 flow requirements from the Stanislaus, Tuolumne, and Merced Rivers. Monthly required flows (cfs) based on 1922-1992 average unimpaired flows and DWRSIM Study 1995C06F-SWRCB-469 data, using Flow Alternative 5. These tables are based on modeling conducted by DWR using DWRDSM to assess potential contributions of each stream to meeting Vernalis flow requirements as part of the Environmental Impact Report for the

1995 Bay Delta Plan. I used these results as a proxy for required releases in each stream for purposes of meeting D-1641 requirements.

Model node	**Description**	**Data source**	**Data available for calibration period**
BDR	*Beardsley, Donnells and Relief Reservoirs*		
BDRstor	End of month storage in BDR reservoirs	Donnells (11292600), Relief (11291000), Bearsdley (11292800).	Data for Relief before WY 1986 are spotty, and are estimated in daily mass balance via regression (R^2 = .77) against historical daily values from Donnells.
BDRdstor	Change in storage at BDR	BDRstor	As above
BDRin	Inflows to BDR reservoirs	BDRdstor + BDRrel + BDRevap	WY 1986 onwards
BDRrel	Releases below BDR	Beardley Powerhouse, (11292901) represents combined releases below BDR reservoirs	WY 1986 onwards
BDRevap	Evaporation from BDR		
PL	*Pinecrest and Lyons Reservoirs*		
PLstor	End of month combined storage, PL	Lyons (11297700), Pinecrest (11295900)	WY 1981 onwards
PLdstor	Change in storage in PL	Plstor	WY 1981 onwards
PLevap	Evaporation from PL Reservoirs		
PLrel	Releases from PL	11298000 + 11297500 + 11297000	Yes
PLin	Inflows	PLdstor + PLrel + PLevap	
NSM	*New Spicer Meadows plus McKays, Utica, Union, and Lake Alpine Reservoirs*		
NSMstor	End of month storage at NSM	New Spicer Meadows (11293770), McKays Point Reservoir (11295260), Alpine (11293460), Union (11293350), Utica (11293370)	New Spicer Meadows Dam was built in 1988. USGS records date from 1990 for this reservoir. Other dams have records starting in WY 1981.
NSMdstor	Change in storage in NSM	NSMstor	

NSMevap			
NSMrel	Releases for NSM are the sum of streamflow below Beaver Creek, plus releases to Utica Canal and hydropower releases to the Stanislaus Powerhouse	11295300 + 11295240 + 11295505	Records for 11295505 releases begin WY 1994.
NSMin	Inflows to NSM	NSMdstor + NSMrel + NSMevap	See NSMrel

Table 13: Historical data for Upper Stanislaus River representation. Numbers refer to USGS gages.

Model Node	**Description**	**Data source**	**Data available for calibration period**
HH	Hetch Hetchy Reservoir/O'Shaunnesey Dam		
HH_{stor}	End of month storage	11275500 and SFPUC	Yes
HH_{dstor}	Change in storage over each time step	see HHstor	Yes
HH_{tuo}	Releases from Hetch Hetchy Reservoir directly to the Tuolumne River	11276500	Yes
HH_{canyon}	Releases from Hetch Hetchy Reservoir to Canyon Tunnel (part of this flows to San Francisco via the San Joaquin Aqueduct/Hetch Hetchy Aqueduct, part of this flows to Don Pedro Reservoir)	SFPUC	Yes
HH_{sf}	Flows in the Hetch Hetchy Aqueduct to SF Bay Area	Monthly data from SFPUC	Yes
HH_{dpr}	Returns from Canyon Tunnel to Don Pedro Reservoir via Early Intake or Moccasin	Hhcanyon - HHsf	Yes
HH_{in}	Calculated inflows to Hetch Hetchy Res	HHdstor + HHtuo + HHcanyon	Yes
HH_{evap}	Evaporation/Accretion from HH	SFPUC	Yes
CE	*Cherry Lake (Lake Lloyd) plus Lake Eleanor*		
CE_{stor}	End of month storage	11277500 + 1127200; SFPUC	

CE_{dstor}	Change in storage over each time step	CE_{stor}	Yes
CE_{in}	Calculated inflows to Lake Lloyd and Lake Eleanor	CEin = CEdstor + CEtuo + CEevap	Yes
CE_{evap}	Evaporation/Accretion from Cherry Lake and Lake Eleanor	SFPUC	Yes
CE_{tuo}	Releases from Cherry Lake to Cherry Creek Tunnel and Cherry Creek, plus releases from Lake Eleanor to Eleanor Creek	11278400	Yes
SF Demands	SF Bay Area demands on HH water system	Based on average monthly San Joaquin Pipeline flows, 1978-2008, and 'typical' diversion patterns (Bruce McGurk, SFPUC, pers. comm.)	Yes
DPR	*Don Pedro Reservoir*		
DPR_{in}	Calculated inflows to DPR	DPRtuo + DPRdstor + DPRevap	Yes
DPR_{dstor}	Change in storage over each time step	11287500	Yes
DPR_{tuo}	Releases from DPR to Tuolumne River, approximated by COMB FLOW TUOLUMNE R + MODESTO CN + TURLOCK CA	Approximated by 11289651	Yes
DPR_{evap}	Evaporation from Don Pedro Res	Evaporation rate is an approximated monthly time series based on SFPUC data for WY 1994 and 1995.	

Table 14: Historical data for Upper Tuolumne River representation. Numbers refer to USGS gages.

		System losses	SW constraint, % of total demand	Canal evaporation	Max surface water diversion
STN	**OID S**	If year type is critical, 20%, otherwise 30%	72%	0%	
	OID N	25%	82%		
	SSJID	25%	82%	0%	
TUO	**Modesto Main**	38%	85%	0%	
	Turlock Main	30%	75%	0%	
MER	**Merced ID N**	33%	75%	2%	100 cfs
	Merced ID Main	27%	70% before 1991, 60% after	2%	2000 cfs

Table 15: Parameters used to force groundwater/surface water allocation of supply to Districts. See text for description.

	STN	TUO	MER
Nash-Sutcliffe (unitless)	0.73	0.68	0.75
Bias	-0.3%	-0.2%	0.5%
RMSE	63%	64%	63

Table 16: Goodness-of-fit statistics for unimpaired hydrology representation for the period from WY 1981–1999.

Watershed	Node	Result	RMSE	Nash-Sutcliffe Efficiency Index	Bias (%)
STN	Clark Fork	Unimpaired flows	66	0.72	20.3
STN	Beardsley-Donnels Res	Inflows	53	0.78	4.0
STN	Beardsley-Donnels Res	Storage	28	0.66	-1.2
STN	Beardsley-Donnels Res	Releases	48	0.69	4.1
STN	New Spicer Res	Inflows	48	0.21	-31.4
STN	New Spicer Res	Storage	26	0.08	-52.3
STN	New Spicer Res	Releases	48	-1.95	-33.4
STN	Pinecrest-Lyons Res	Inflows	76	0.68	-15.2
STN	Pinecrest-Lyons Res	Storage	41	-0.04	-21.3
STN	Pinecrest-Lyons Res	Releases	75	0.60	-14.9

STN	New Melones Res	Inflows	N/A	N/A	N/A
STN	New Melones Res	Storage	27	0.76	17.5
STN	New Melones Res	Releases	58	0.46	1.9
STN	Below Goodwin Dam	Flows	94	0.39	N/A

Table 17: Goodness of fit statistics for reservoir inflows, storage, and releases in the Stanislaus River Basin. Bias is not reported for flows below New Melones, as reconstruction of missing NML flow data required ad hoc adjustments to historical data to account for accretions between New Melones Reservoir and Goodwin Diversion Dam. Note that intercomparability of statistics may be limited in some cases because of the different lengths of the time series of historical data.

Watershed	Node	Result	RMSE (%)	Nash-Sutcliffe Efficiency Index	Bias (monthly, %)
TUO	Cherry-Eleanor Res	Inflows	87	0.46	-30.4
TUO	Cherry-Eleanor Res	Storage	41	-0.25	-14.4
TUO	Cherry-Eleanor Res	Releases	97	-0.35	-29.3
TUO	Hetch Hetchy Res	Inflows	63	0.78	-22.9
TUO	Hetch Hetchy Res	Storage	30	0.25	8.0
TUO	Hetch Hetchy Res	Releases	149	0.56	39.4
TUO	Don Pedro Res	Inflows	67	0.63	2.4
TUO	Don Pedro Res	Storage	15	0.56	-5.4
TUO	Don Pedro Res	Releases	59	0.57	1.4

Table 18: Goodness of fit statistics for Tuolumne River Basin model nodes over the calibration period from WY 1981-1999. Note that intercomparability of statistics may be limited in some cases because of the different lengths of the time series of historical data.

Watershed	Node	Result	RMSE (%)	Nash-Sutcliffe Efficiency Index	Bias (%)
MER	New Exchequer Reservoir	Inflows	63	0.76	0.5
MER	New Exchequer Reservoir	Storage	16	0.88	1.8
MER	New Exchequer Reservoir	Releases	72	0.38	1.3

Table 19: Inflow, storage, and releases at Lake McClure on the Merced River.

Basin	**Model node**	**Historical Average Diversions**		**Modeled average diversions**		**Model bias**	
		1981-1999	**1987-1992**	**1981-1999**	**1987-1992**	**1981-1999**	**1987-1992**
STN	**SSJID Cn**	364819	329912	344741	334544	-6%	1%
	OID Cn	147543	133268	143433	137900	-3%	3%
TUO	**Modesto Cn**	307414	257889	307521	253404	0%	-2%
	Turlock Cn	583839	470919	577227	494855	-1%	5%
MER	**Merced ID North Cn**	21211	20450	20725	15752	-2%	-23%
	Merced ID Main Cn	489237	391267	492012	377811	1%	-3%

Table 20: Annual historical and modeled diversions to irrigation districts, WY 1981-2000.

	Modeled			**Estimated Historical minimum pumping**	
	Average	**Min**	**Max**	**Low**	**High**
OakdaleID_S	48701	39227	90477	20001	43501
SSJID and Oakdale ID N	82450	57130	194381	62000	62000
ModestoID	87260	38052	153602	38501	64501
TurlockID	240268	147651	359790	157500	190000
Merced ID	201629	129395	304877	7800*	182900*

Table 21: Groundwater use by district. Note that range of groundwater use minimums include the sum of district and non-district pumping, except in the case of Merced ID, which includes district pumping only. Sources: (CH2M Hill 2001; USBR 2005).

2.27 **References**

(2006a). Air pollution: greenhouse gases. California Health and Safety Code. **Division 25.5**.

(2006b). Electricity: emissions of greenhouse gases. Public Utilities Code.

(2006c). Vehicular emissions: greenhouse gases. California Health and Safety Code.

Barnett, T. P., J. C. Adam and D. P. Lettenmaier (2005). "Potential impacts of a warming climate on water availability in snow-dominated regions." Nature **438**(7066): 303-309.

Beven, K. (1993). "Prophecy, Reality and Uncertainty in Distributed Hydrological Modeling." Advances in Water Resources **16**(1): 41-51.

Beven, K. (2001). "How far can we go in distributed hydrological modelling?" Hydrology and Earth System Sciences **5**(1): 1-12.

Brekke, L. D., R. Field and N. Parker (2006). Model Error Analysis of the CalSim II San Joaquin River Representation. Operations Management 2006: Operating Reservoirs in Changing Conditions, Sacramento, California, USA, ASCE.

CADWR (2007). California Land and Water Use, California Department of Water Resources.

CH2M Hill (2001). Merced Water Supply Plan Update Final Status Report - Merced Water Supply Plan Land Use and Water Demand Model. Merced, CA, City of Merced, Merced ID, UC Merced.

Close, A., W. M. Hanneman, J. W. Labadie, D. P. Loucks, J. R. Lund, D. C. McKinney and J. R. Stedinger (2003). A strategic review of CALSIM II and its use for water planning, management, and operations in Central California, Report to the California Bay Delta Authority Science Program and Association of Bay Area Governments**:** 129 pages.

Dettinger, M. D., D. R. Cayan, M. Meyer and A. E. Jeton (2004). "Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099." Climatic Change **62**(1-3): 283-317.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund and R. E. Howitt (2003). "Economic-Engineering Optimization for California Water Management." Journal of Water Resources Planning and Management **129**(3): 155-164.

Draper, A. J., A. Munévar, S. K. Arora, E. Reyes, N. L. Parker, F. I. Chung and L. E. Peterson (2004). "CalSim: Generalized Model for Reservoir System Analysis." Journal of Water Resources Planning and Management-Asce
130(6): 480-489.

DWR (1975). Bulletin 113-3: Vegetative Water Use in California. Sacramento, CA, California Department of Water Resources.

DWR (2003). California's Groundwater, Bulletin 118, Update 2003. Sacramento, CA, Department of Water Resources, California Resources Agency.

DWR (2005). CalSim-II Model Sensitivity Analysis Study: Technical Memorandum Report Sacramento, CA, Department of Water Resources, California Resources Agency.

ESRI (2007a). ArcGIS 9.2. Redlands, CA, ESRI.

ESRI (2007b). ArcHydro Toolkit. Redlands, CA, ESRI.

Federal Energy Regulatory Commission (1996). Order Amending License and Dismissing Rehearing Request, Turlock Irrigation District and Modesto Irrigation District, Project Nos. 2299-024 and -031.

Ferreira, I. C., S. K. Tanaka, S. P. Hollinshead and J. R. Lund (2005). "Musings on a model: CalSim II in California's water community." San Francisco Estuary and Watershed Science **3**(1 (March 2005)): Article 1 (http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art1).

Flint, L. E. and A. L. Flint (2007). Ground-Water Recharge in the Arid and Semiarid Southwestern United States - Chapter B Regional Analysis of Ground-Water Recharge USGS Professional Paper 1703-B.

Ford, D., L. Grober, T. Harmon, J. Lund and D. McKinney (2006). Review Panel Report San Joaquin River Valley CalSim-II Model Review.

Getches, D. H. (2003). Constraints of Law and Policy on the Management of Western Water. Water and Climate in the Western United States. William M. Lewis Jr. Boulder, University Press of Colorado**:** 183-234.

Gleick, P. H. (1987). "Regional Hydrologic Consequences of Increases in Atmospheric Carbon Dioxide and Other Trace Gases." Climatic Change **10**(2): 137-161.

Gleick, P. H. (2003). "Water use." Annual Review of Environment and Resources **28**: 275-314.

Gleick, P. H., D. Haasz, C. Henges-Jeck, V. Srinivasan, G. Wolff, K. Kao Cushing and A. Mann (2003). Waste Not, Want Not: The Potential for Urban Water Conservation in California. Oakland, CA, Pacific Institute**:** 165 pp.

Hanemann, W. M. (2007). How California Came to Pass AB 32, the Global Warming Solutions Act of 2006. CUDARE Working Paper 1040, Department of Agricultural & Resource Economics, U.C. Berkeley**:** 30.

Joyce, B., S. Vicuna, L. Dale, J. Dracup, M. Hanemann and D. Purkey (2006). Climate Change Impacts on Water for Agriculture in California: A Case Study in the Sacramento Valley - FINAL REPORT. Sacramento, CA, CEC PIER.

Kiparsky, M. and P. H. Gleick (2003). Climate Change and California Water Resources: A Survey and Summary of the Literature, California Energy Commission**:** 35 pp.

Kiparsky, M. and P. H. Gleick (2005). Climate Change and California Water Resources. The World's Water 2004-2005. P. H. Gleick. Washington, D.C., Island Press.

Knowles, N. (2000). Hydroclimate of the San Francisco Bay-Delta Estuary and Watershed, University of California, San Diego, La Jolla, CA**:** 292.

Knowles, N. and D. R. Cayan (2002). "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." Geophysical Research Letters **29**(18): 1891.

Knowles, N. and D. R. Cayan (2004). "Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed." Climatic Change **62**(1-3): 319-336.

Koczot, K. M., A. E. Jeton, B. J. McGurk and M. D. Dettinger. (2005). Precipitation-runoff processes in the Feather River Basin, northeastern California, with prospects for streamflow predictability, water years 1971–97, U.S. Geological Survey Scientific Investigations Report 2004–5202**:** 82.

Leonardson, R., L. Dale, S. Vicuna and J. A. Dracup (2005). On the accuracy of streamflow predictions under climate change: Draft Report. Berkeley, CA, California Climate Change Center.

Lundquist, J., B. Huggett, H. Roop and N. Low (2009). "Use of spatially distributed stream stage recorders to augment rain gages by identifying locations of thunderstorm precipitation and distinguishing rain from snow." Water Resour. Res. **45**.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier and B. Nijssen (2002a). "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States&#42." Journal of Climate **15**(22): 3237-3251.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier and B. Nijssen (2002b). "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." Journal of Climate **15**(22): 3237-3251.

MBK Engineers (2001). Merced Water Supply Plan Update Final Status Report Exhibit 1: MRSIM. Sacramento, CA, City of Merced, Merced ID, UC Merced.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier and R. J. Stouffer (2008). "CLIMATE CHANGE: Stationarity Is Dead: Whither Water Management?" Science **319**(5863): 573-574.

Multi-Resolution Land Characteristics Consortium (2001). National Land Cover Data Set, U.S. Environmental Protection Agency.

Nash, J. E. and J. V. Sutcliffe (1970). "River flow forecasting through conceptual models part I — A discussion of principles." Journal of Hydrology **10**(3): 282–290.

National Atlas of the United States (2006). Major Dams of the United States, National Atlas of the United States.

Natural Resources Conservation Service (2006). U.S. General Soil Map (STATSGO) for California. , United States Department of Agriculture.

Parson, E. A. and K. Fisher-Vanden (1997). "Integrated Assessment Models of Global Climate Change." Annual Review of Energy and the Environment **22**(1): 589-628.

Sanstad, A. H., H. Johnson, N. Goldstein and G. Franco (2009). Long-run socioeconomic and demographic scenarios for California, Draft Report. Sacramento, CA, California Climate Change Center

Schwarzenegger, A. (2005). Executive Order S-3-05, State of California.

State Water Resources Control Board (1995). Water Quality Control Plan for the San Francisco Bay/ Sacramento-San Joaquin Delta Estuary Sacramento, CA, California Environmental Protection Agency.

State Water Resources Control Board (1999a). Final Environmental Impact Report for Implementation of the 1995 Bay/Delta Water Quality Control Plan: Volume 1. Sacramento, CA, State Water Resources Control Board, California Environmental Protection Agency. **Volume 1**.

State Water Resources Control Board (1999b). Final Environmental Impact Report for Implementation of the 1995 Bay/Delta Water Quality Control Plan: Volume 2, Technical Appendices. Sacramento, CA, State Water Resources Control Board, California Environmental Protection Agency. **Volume 1**.

State Water Resources Control Board (1999c). Water Right Decision 1641, In the Matter of: Implementation of Water Quality Objectives for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary; A Petition to Change Points of Diversion of the Central Valley Project and the State Water Project in the Southern Delta; and A Petition to Change Places of Use and Purposes of Use of the Central Valley Project. Sacramento, CA, State Water Resources Control Board, California Resources Agency.

State Water Resources Control Board (2009). 20x2020 Water Conservation Plan Draft Final Report. Sacramento, CA, California Environmental Protection Agency.

Stewart, I. T., D. R. Cayan and M. D. Dettinger (2004). "Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario." Climatic Change **62**(1-3): 217-232.

Stine, S. (1994). "Extreme and Persistent Drought in California and Patagonia During Medieval Time." Nature **369**(6481): 546-549.

Thornton, P. E., S. W. Running and M. A. White (1997). "Generating surfaces of daily meteorological variables over large regions of complex terrain." Journal of Hydrology **190**(3-4): 214-251.

United States Senate (1913). An Act Granting To The City And County Of San Francisco Certain Rights Of Way In, Over, And Through Certain Public Lands, The Yosemite National Park, And Stanislaus National Forest, And Certain Lands In The Yosemite National Park, The Stanislaus National Forest, And The Public Lands In The State Of California, And For Other Purposes [Raker Act]. Hetch Hetchy Reservoir Site Hearing Before The Committee On Public Lands United States Senate Sixty-Third Congress First Session On H. R. 7207.

URS (2008). Delta-Mendota Canal Recirculation Initial Alternatives Information Report Sacramento, CA, Bureau of Reclamation and CA DWR.

USBR (2003a). Canals for California USBR at 1:24,000-scale, 10th edition, 2003-12-01, U.S. Bureau of Reclamation, Mid-Pacific Region, MPGIS Service Center.

USBR (2003b). Private Water Districts for California 1:24,000-scale version 1.6, U.S. Bureau of Reclamation in coordination with the California Department of Water Resources

USBR (2003c). State Water Districts for California version 1.1, U.S. Bureau of Reclamation in coordination with the California Department of Water Resources

USBR (2005). CALSIM II San Joaquin River Model (DRAFT). Sacramento, CA, U.S. Bureau of Reclamation, Mid Pacific Region.

USBR (2006). Federal Water Districts - Mid-Pacific Region version 4.0, U.S. Bureau of Reclamation

USDA (2006). Soil Survey Geographic (SSURGO) Database, United States Department of Agriculture.

USGS (2007a). National Elevation Dataset, United States Geological Survey.

USGS (2007b). National Water Information System, United States Geological Survey.

Vicuna, S. and J. Dracup (2007). "The evolution of climate change impact studies on hydrology and water resources in California." Climatic Change **82**(3): 327-350.

Yates, D., D. Purkey, J. Sieber, A. Huber-Lee, H. Galbraith, J. West, S. Herrod-Julius, C. Young, B. Joyce and M. Rayej (2009). "Climate Driven Water Resources Model of the Sacramento Basin, California." Journal of Water Resources Planning and Management **135**(5): 303-313.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee (2005). "WEAP21 - A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics." Water International **30**(4): 487-500.

Young, C. A., M. I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J. F. Mount, V. K. Mehta, D. Purkey, J. H. Viers and D. Yates (2009). "Modeling the Hydrology of Climate Change in California's Sierra Nevada for Subwatershed Scale Adaptation." JAWRA Journal of the American Water Resources Association **45**(6): 1409-1423.

3 Chapter 3 - Response of water resources in an urbanizing region to ensembles of climate change, population growth, and land use change projections

3.1 Introduction

This chapter presents a modeling experiment that compares and combines potential impacts on water demands and supply reliability from climate change, population growth and urbanization in the Stanislaus, Tuolumne, and Merced River Basins.

One of the most robust findings in climate impacts research is that climate change will alter hydrology and water resources around the globe. In California, two decades of studies of projected climatic impacts on water systems have progressed from hydrologic systems, to agricultural systems, to water storage and conveyance systems (Vicuna and Dracup 2007). Analysis has also extended into impacts on multiple sectors (e.g. Hayhoe et al. 2004), while studies have increased in sophistication, detail, and scope of analysis.

Adding urgency to the challenge posed for future planning by of climate change, the impacts of population growth and land use change have not been adequately addressed, nor do they currently garner as much attention as climate change impacts. Calls for such work continue (e.g. Pielke Sr. et al. 2009), emphasizing both the uncertainties in climate prediction, and the need to develop risk assessments for resource availability. Consideration of multiple global and regional *stressors* simultaneously will be necessary to better understand the context for such risk assessments. This is explicitly acknowledged in discussions of climate impacts and adaptation (IPCC 2007), but integration of other drivers of change with climate impacts studies remains fertile ground for research.

Hydrologists suggest that impacts of land use change, which is often concomitant with population growth, represents an understudied but clearly important frontier in the understanding of hydrologic processes (DeFries and Eshleman 2004). One approach to studying such questions is through detection and attribution studies, which analyze historical data to determine the relative effects of, for example, climate, population, and land use on hydrology. Urbanization appears capable of offsetting or augmenting flow decreases or increases from climate change, and of reducing sensitivity of mean annual streamflow to temperature changes in a U.S.-wide historical study (DeWalle et al. 2000). At the scale of a small suburban basin, land use change has had only a small effect on evapotranspiration, with increasing ET driven by climate (Claessens et al. 2006). Seager et al. (2009), finding no anthropogenic climate signal in a recent Southeastern U.S. drought, received media attention for the observation that population may have been at the root of the water shortage, but did not directly investigate the supposition.

A complimentary approach uses scenario modeling to integrate projections of various drivers of water supply and demands into hydrology models for sensitivity analysis of future system change. Previous work includes the modeling results of Vorosmarty et al. (2000), which suggested that at a global scale, population growth will have a greater impact on water supply availability than will climate change, as domestic and industrial demands driven by population growth will outpace increases in irrigated agriculture driven by climate warming. Particularly germane to the present study, Groves et al. (2005) modeled California urban and irrigated agricultural water demands based on 3-10 hydrologic regions over a 25 year planning horizon, using ‘top-down’ methods similar to those presented in this chapter. Groves et al. (2005) modeled urban water demands based on urban demand units and per-unit water demands; agricultural demands using statewide agricultural land use changes, cropping changes favoring higher-value crops, and changes in per-acre crop water demands; and environmental water demands based on current regulations and practices. Results projected increases in urban demands and decreases in agricultural demands across the four future scenarios of statewide change in these factors, consistent with those presented in this chapter at a finer spatial scale.

This chapter describes a method for a multiple impacts approach to analysis of projected demands at the level of irrigation districts, which are important institutional units for agricultural water supply in the state. The goal is to characterize and compare modeled impacts on water demands in set of geographically proximate water supply systems in California’s Central Valley due to climate change, population growth, and urbanization, mediated by changes in water use efficiency.

Results project shifting patterns of water demands that could alter the water supply landscape. Increasing population growth may lead to decreased local water demands under scenarios that take climate change, population growth, urbanization, and urban water use efficiency into account.

3.2 **Methods, scenarios and assumptions**

3.2.1 Methods overview

I model the impacts of four drivers of change to the water resources systems of the Stanislaus, Tuolumne, and Merced River Basins in the Central Valley of California: climate variability and change, population growth, urbanization, and water use efficiency. Figure 47 describes a conceptual overview of the Integrated Assessment modeling used for the analysis described here. In brief, the core of the Integrated Assessment is a hydrology/water operations model, described in depth in Chapter 2 of this dissertation. The model was calibrated to the historical period of 1981-1999, and then run with data described below with projections for the three drivers of change, plus different pathways for water use efficiency.

3.2.2 Integrated hydrology and water operations model

I provide a simple conceptual overview of the hydrology/operations model here, and it is described in detail in Chapter 2. The model is built on a monthly time step using the WEAP21 platform (Yates et al. 2005; Young et al. 2009). While the entire model is dynamically integrated, the model can be described conceptually as a three-part framework. The first is a physical hydrology module, which uses a quasi-physical lumped parameter water balance approach to route incoming fluxes of water and energy through a spatially explicit representation of catchment-scale land use/land cover, soil depths, elevation and topography, and other physical aspects of the basins. The primary output of this module is a climatically driven representation of streamflow.

The second aspect is a representation of demands for water. This takes the form of agricultural demands which are a function of monthly climatic parameters and the crop mixes for each Irrigation District, urban demands which are a function of population and per capita water use, and environmental demands represented by the regulatory regime which calls for condition-dependant instream flows at various river and stream reaches. More details follow for specific assumptions and scenarios.

It is important to note that the present analysis defines demands as the demands at the surface water diversion point for each irrigation district area, and the demands at each respective urban area. This includes inefficiencies in conveyance and intra-system use that are parameterized in the WEAP model. I chose to represent demands this way because a) available data for calibration are limited to these diversion points, and b) river diversions are the legally and operationally relevant metric for water use at the district scale.

Third, the streamflow representation and the representation of demands interact dynamically with the operations portion of the model, which overlays a spatially explicit model infrastructure that stores and conveys water throughout the basins, and the operating rules by which they are operated to satisfy human and environmental water demands. The operating rules are a simplified but robust representation of water allocation within each time step based on the priorities and preferences for each demand node.

Groundwater is represented based on sub-basins of the San Joaquin Valley Groundwater Basin, as defined by the California Department of Water Resources (DWR 2004). The present model represents groundwater simply as a stock that is drawn from to satisfy demands in accordance with defined preference and priorities, and recharged based on hydrologic conditions.

3.2.3 Climate scenarios

I used 1/8-degree reconstructed historical climate data (Maurer et al. 2002) to calibrate the model over the time period from 1981-1999, as described in Chapter 2. For future climate projections, I used 1/8-degree downscaled GCM output produced for the California Energy Commission Public Interest Energy Research Program (PIER) to drive the climate scenarios (Cayan et al. 2009). These data are downscaled from six GCMs, each run over two emissions scenarios, all chosen from among the Intergovernmental Panel on Climate Change Fourth Assessment activities (Table 24). Climate projections thus reflect variability in climate projections resulting from differences in emissions scenarios and climate sensitivity among GCMs.[10]

3.2.4 Population growth and urbanization scenarios

Urbanization has been projected to increase with overall population growth in California over coming decades (Landis and Reilly 2003; Sanstad et al. 2009). In addition to its direct impacts on increased water demands, increased population growth as described above will also result in land use change in the Central Valley in the form of conversion of agricultural land to housing and other urban uses.

To generate urbanization and population growth scenarios, I used spatially explicit urban population projections for California through 2100, generated by Sanstad et al. (2009) based on econometric relationships driven by physical and institutional characteristics of the State. The rasterized projections are based on econometric modeling (Landis and Reilly 2003) that resolves urbanization and population density at a 250 m resolution. Three population projections ("High,"

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[10] Note that I have not attempted to weight models based on their credibility, or skill at post-diction of historical climate. Previous efforts suggest limited value for such exercises, and that ensemble 'completeness' is more important that ensemble weighting. (Brekke et al. 2008).

“Medium,” and “Low”) are used at 25-year intervals, beginning in 2000 and ending in 2100. This method allowed us to generate population projections specific to each demand area (urban center and corresponding Irrigation District) using a GIS. This is important because the institutional boundaries represented in the WEAP model (e.g. municipalities, water districts) do not coincide with counties, which form the unit of analysis in other population projections.

To describe land use during the calibration period, I used a GIS of the study area (described in Chapter 2) to overlay institutional boundaries (i.e. Irrigation District borders) on land use surveys from DWR. For the base case of each agricultural node in the model, total area and cropping patterns are derived from the intersection of institutional boundaries and land use surveys. To develop future scenarios of urbanization, I first overlaid the gridded projections of future urbanization. For each scenario, in each time step, for each agricultural model node, I found the intersection of 1) the irrigation district boundary for the model node and 2) urbanized cells. The resulting intersection defines the urban area within each model node in a given time step. Subtracting urbanized area from the total area within the irrigation district boundary gives the remaining agricultural area, after adjusting for pre-existing urban area. Because the footprint of the three urbanization projections are very similar across population projections, with population density the main difference, I developed only two urbanization scenarios: a baseline based on DWR surveys in 1995 and a projection based on the ‘Mid’ scenario of Sanstad et al. (2009).

To estimate urban population, I simply summed the population within each irrigation district boundary. My approach assumes that even cells with low population density are ‘urbanized’ in the sense of removing cropland from production and requiring a new source of water supply. This is a reasonable assumption given exurban development trends in California (e.g. Duane 1999).

I included projected population only within the district areas of the case studies, which represent over 90% of the total projected population in the study area. For Merced ID and Oakdale ID, I used population projections for the main area of the district, coincident with the current urban center in each area (Table 23).

Using these methods, I generated three scenarios of joint population/urbanization growth, corresponding to the “High”, “Mid” and “Low” scenarios described by Sanstad et al (2009). Figure 48 shows institutional boundaries of the model nodes in the agricultural portion of the study area (including additional areas within the three counties on the West side of the San Juoaqin River), with the projection for urbanization and exurban growth through 2100 from (Sanstad et al. 2009). Substantial increase in urban area, and corresponding decrease in agricultural area, is clearly visible in the figures over the course of the century.

Figure 49 shows the three population projections within each node in the WEAP model. Substantial growth is apparent in all three projections, as is substantial variability among the projections.

3.2.5 Urban water use efficiency

Urban water demands are calculated for each node as the product of per capita water use (L per person per time step) and population (urban node population in each time step). These values can change seasonally and annually in the WEAP model, allowing for representation of population growth (as described above) and increases in water use efficiency. Baseline levels of per capita urban water use in the model are taken from estimates for the region for 1995-2005 as 248 gallons per capita per day (342,618 liters per capita per year) (State Water Resources Control Board 2009).

In California, scenarios of future water use generally suggest that trends towards greater efficiency will continue. I used a range of estimates from multiple sources in the literature to generate scenarios for WUE trends over time (Table 22).[11] Table 22 shows 13 scenarios for future water use efficiency, based on research reported by CALFED Bay-Delta Program (CALFED Bay-Delta Program 2006), Groves et al. (Groves et al. 2005), the Pacific Institute (Gleick et al. 2005), and the State Water Resources Control Board (State Water Resources Control Board 2009). These reports do not attempt to project past 2020 or 2030. Beyond those years, I assume that WUE will continue to increase, although at a decreasing rate after the easiest opportunities for conservation are realized. I assume a linear increase in WUE beyond the last scenario year modeled, with the final value equal to

$$WUE_{2100} = WUE_{2030} + .25 * WUE_{2030}$$

as shown in Table 22. Where the reports cited below estimate conservation potential separately for different regions of California, I used values for the San Joaquin Hydrologic Region, with the exception of '20x2020 – overall.'

Below I detail the sources for urban water use efficiency projections.

Baseline. The baseline scenario assumes no change in water use efficiency.[12]

CBDA The CALFED Bay-Delta Program Water Use Efficiency Program (CALFED Bay-Delta Program 2006) defined conservation scenarios for each hydrologic region in California for 2030, based on modeling of adoption of best practices and other factors. They produced six projections for conservation for the year 2030, which range from 10% to 24% increase in WUE for the San Joaquin Hydrologic Region (Table 22). Note that Projection 1 is defined as the "Reasonably foreseeable" case given code-induced conservation plus existing opportunities for investment in WUE from Proposition 50, and Projection 6 is defined as the "Technical Potential," an upper limit on water savings. Others have disputed whether this constitutes an upper limit (Gleick et al. 2003), as described below.

Groves Groves et al. (2005) quantified projections for total statewide water demand. I normalized the urban water use coefficients (Table 17 in Groves et al. 2005) used in each of their projected scenarios for 2030 to generate additional water use efficiency scenarios (Table 22).

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[11] In reality future water use efficiency might be conditional on population conditions (more growth may lead to more pressure on water sources and thus to more pressure to conserve water) or climate (reduced supply could similarly lead to pressure to conserve). We did not attempt to model this conditionality, treating WUE as independent from other aspects of each scenario. We also did not attempt a formal expert elicitation to assign weights to the scenarios. Such ideas could be explored in future work.

[12] We do not model a scenario with decreasing WUE because none of the projections include it, and because it would be inconsistent with historical experience and with expected behavior under increased water scarcity and decreased supply reliability.

Pacific Institute Gleick et al. (2005) use the same modeling framework as do Groves et al. (Groves et al. 2005), but instead use a scenario with urban water conservation potential of approximately 33%, based on detailed study by Gleick et al. (2003).

20x2020 California's recently legislated efforts to foster water conservation are aimed at a statewide average 20% reduction in per capita water use by the year 2020, with an interim target of 10% reduction by 2015 (State Water Resources Control Board 2009). This average value is reflected in Scenario "20x2020 – overall" in Table 22. According to SWRCB planning documents (State Water Resources Control Board 2009), however, the reductions would be distributed throughout the state based on baseline (1995-2005) regional water use. The specific target for the San Joaquin Valley Hydrologic Region would be 30% by 2020, as reflected in Table 22.

3.2.6 Water rights and water supply

Studies of projected climate impacts on hydrology have become quite common in the literature. Impacts on water resources systems are following suit (Vanrheenen et al. 2004; Tanaka et al. 2006). Water systems including storage and conveyance mediate the climate signal by buffering changes in magnitude and timing of runoff. However, one might expect the distribution of impacts to be strongly conditioned on institutional constraints and assumptions such as water law and operations policies, as these constraints drive the operation of system for given hydrologies. The following section describes current legal background for water allocation, and my treatment of future legal scenarios.

3.2.6.1 Legal background

Projections of land use change show conversion of Central Valley agricultural land to urban and exurban area, but it is not clear how such urbanization will affect water supply.

Modeling future institutional constraints for future water management is fraught with uncertainty. Laws, policies, and operational requirements and norms all carry great weight in determining water management. Water management has historically been a conservative and risk averse business (Lach et al. 2005; Rayner et al. 2005).

Relatedly, water law has been historically conservative and slow to evolve, in part because water rights cases can take years or decades to resolve, and in part because water rights holders seem to have a high certainty equivalent in these disputes, often preferring to settle disputes rather than risk losing a case. However, institutional constraints are more malleable than physical ones, and it is easy to find examples of political pressure threatening or changing even the strongest elements of the law.

Within water law, the interface between land use change and water has been receiving increasing attention (Arnold 2005a; Arnold 2005b). However, the modeling described in this dissertation suggests changes on a broader scale than those considered in such scholarly works. Namely, what might happen if urban encroachment within Irrigation District lands serves to dramatically change the amount, type, and timing of water demands such that existing water rights become less well suited to meeting demands?

Broadly, three options exist for future water supply of urbanized areas within irrigation districts.

1. newly urbanized areas within ID lands will enjoy surface water supply at higher priority with agricultural portions of those lands,
2. newly urbanized areas within ID lands will enjoy surface water supply at equal priority with agricultural portions of those lands,
3. newly urbanized areas within ID lands will enjoy access to surface water supply, but at lower priority than agricultural portions of those lands,
4. newly urbanized areas within ID lands will not have access to ID surface water, instead needing to rely on groundwater or water transfers for their supply, or
5. options outside of the current water rights framework, including new legislation.

I base my modeling of future water supply on current water law, as expressed in option 3) above. Note that because number 5) strays into more speculative territory, I leave this option for future work using different methods, such as collaborative scenario-building processes involving stakeholders or robust decision making analysis. I describe the rationale for this choice below.

3.2.6.2 Legal control of quantity of water use

In most US states, one of two doctrines dominates water rights law. Riparian doctrine, more common in Eastern states with historically plentiful water, allows owners of property adjoining streams to divert water for use on their property. Prior appropriation doctrine means that appropriative surface water rights are predicated primarily on amount and timing of historical diversions. The doctrine of 'first in time, first in right' gives legal priority for usufructuary rights to the entity on a stream who first built facilities and diverted water (the "senior" rights holder), over those which began diverting water in later years ("junior" rights holders). A senior water right must be fully satisfied before the next junior rights holder can begin any diversions, and so on down the list of priority.

California is a 'mixed-doctrine' state, meaning that both doctrines exist side by side in the same basins. Both types of water rights are represented in the model, but in these basins the appropriative water rights dominate in amount. Although I dynamically include riparian water rights holders' demands and deliveries in the WEAP model, I focus on the appropriative water rights in the analysis.

In California, groundwater use is largely unregulated (Sax 2002), and only recently have requirements been introduced for statewide groundwater monitoring.

3.2.6.3 Legal control of type and place of water use

Case law is generally consistent on the general question of rights and responsibilities of Irrigation Districts. The California Supreme Court ruled in Jenison v. Redfield that

> The ultimate purpose of a district ...is the improvement, by irrigation, of lands within the district … Such a district holds all property acquired by it solely in trust for such ultimate purpose, and can divert it to no other use. It has to do solely with the irrigation of lands within the district, and cannot appropriate water to any other purpose.

While the exact circumstances of the urbanization scenarios used in the modeling scenarios described in this chapter do not seem to match in scope and scale, the principle is clear.

In addition, water rights normally have an assigned "purpose of use." While this purpose of use can technically be changed through a regulatory process involving the appropriate regulating entity, it is difficult to accomplish. Unless this purpose of use is changed, diverted surface water can be used only for this specific purpose.

3.2.6.4 Legal control of timing of water use

Along with the historical basis of priority and type of use, water rights contain specified timing of diversions. Irrigation diversions are typically limited to the season in which they have historically taken place, namely the irrigation season from about April to September. Urban demands, while driven to a certain extent by annual patterns, are far more consistent throughout the year. Thus, even were the purpose of use malleable, there could be a gap in supply for half the year for urban surface water end users. In the current work, I model diversions from the river at this point as constrained by the timing currently included in water rights of senior, agricultural water rights holders.

3.2.6.5 Potential for legislative action on water law

As noted above, the law evolves slowly, but is by its nature malleable. If constituents demand change, legislators can alter law to meet new interests. One way in which this could happen might be legislative decision, possibly forced by future scarcity or drought crisis, declaring urban use as a higher priority beneficial use than agricultural use. In that case, option 1) above would prevail.

3.2.6.6 Current modeling assumptions

Given the inherent unpredictability of future legal changes, I programmed the WEAP model to constrain diversions and deliveries based on the following flexible logic, which will enable future exploration of various institutional changes. Amount and timing of water rights are represented coarsely. If the total diversions to the main canals in the Stanislaus and Merced Basin over the course of a water year exceed total annual water rights, no more agricultural or urban surface water diversions are allowed for the rest of the water year. This in essence assumes that the current maximum water right will not be increased on these fully appropriated streams. Timing of all diversions is limited to the current irrigation months of April to September, per water rights and historical patterns of diversion.

A rigid purpose of use, as described above, would make little intuitive sense given the scenarios described below – it is difficult to imagine water rights remaining unchanged if the result would be surface water unused by local urban demands within ID lands as agricultural demands dip below annual ID water rights. Thus, for the purposes of this dissertation I model a shift at 2034, before which no urban deliveries are made, and after which a specified percentage of surface water deliveries to urban demands is enabled at a priority immediately below agricultural use, within the same timing of use. I assume that this additional use will apply only to population growth over 2000 levels within ID lands, and that current population will continue to be supplied as modeled for the year 2000.

Whether or not the future of agriculture and urban use of the Central Valley unfolds along the lines of the scenarios described, these scenarios may be instructive about the potential consequences of business as usual for future water supply, and represent opportunities to explore the future institutional landscape.

3.2.6.7 Other approaches to representing shifting supply and demand

Other approaches have been used to represent future water allocation. Notably, the CALVIN modeling effort led by Jay Lund (Draper et al. 2003) is a statewide economic optimization model which routes water around the state to the highest value use subject to assigned constraints such as storage and conveyance.

In a sense, CALVIN's optimization approach represents a counterpoint to the simulation approach described here. Broadly speaking, while it specifies physical, environmental, and policy constraints, a fundamental assumption is that economic value of use will drive water allocation decisions, dominating many existing and future institutional constraints on evolution of water allocation. In contrast, my scenarios approach examines institutional (legal) drivers, and user-defined changes can examine representations of potential future policies.

Both methods have their strengths and weaknesses. Because of optimization with perfect foresight, CALVIN may produce optimistic results when used in adaptation (Tanaka et al. 2006). In contrast, a scenarios approach to policy may enable the modeler to have more control over design of scenarios, but does not represent the evolution of optimal or creative solutions outside the imagination of the user.

3.2.7 Computational details

Modeling and ensemble multiple scenarios with a model of this size and complexity requires some computational and organizational effort. The WEAP model described in Chapter 2 takes over three hours for a single 100-year run on currently available workstations, and generates monthly time series data for each model node. To perform calibration and simulation runs, I built a cluster of seven workstations with dual or quad core processors of ~3.0 GHz and 8GB RAM, running Windows XP or Windows 7. A SuperSpeed RAMDisk[13] enabled accessing additional RAM above 32-bit Windows' 4GB limitation so as to make a larger RAMDisk. For data management, I used software from Evolving Logic (CARs)[14] to alter input parameters for each run based on Latin Hypercube or full factorial sampling of the set of input scenarios or parameters, and to collect output data for each run into a single database.[15] Post-processing and data analysis of the WEAP and CARs output was accomplished with the R statistical package.[16]

3.2.8 Scenarios and units of analysis

I collected time series of results for modeled water demands and deliveries to agricultural, urban, and environmental demand nodes in the WEAP model under a full factorial combination of each climate/land use/population/WUE scenario described in Table 24. Figure 51 through Figure 55 and Table 25 through Table 27 show aggregated results at the beginning of the century (2005-2034), mid-century (2035-2064) and end of century (2070-2099).

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[13] www.superspeed.com. Assistance with software generously provided by Neil Sullivan of Superspeed.

[14] www.evolvinglogic.com. Software generously provided by David Groves of Evolving Logic and RAND Corporation.

[15] I gratefully acknowledge research funding from a CALFED Science Fellowship and a NSF Doctoral Dissertation Research Improvement Grant for enabling development of hardware and software infrastructure described here.

[16] www.r-project.org

Results for urban and agricultural water are grouped based on the diversion canal within each basin (Table 23). This choice reflect institutional and physical constraints as described above, and emphasizes the degree to which impacts will fall differently on different water rights holders as well as the place-specific nature of future changes to the landscape of California water.

3.2.9 Reliability metrics

Reliability metrics can assign a binary metric for each iteration, where a given time point is determined either to a failure or success state based on a threshold condition, and reliability is a probabilistic measure of rate of success (Hashimoto et al. 1982; Loucks and Van Beek 2005). I use the quantity-based reliability measures suggested by Dracup et al. (2005), which incorporate a measure of the degree of failure based on the amount of shortfall below the threshold:

$$R_{ij} = 1 - \frac{(Demand_{ij} - Delivery_{ij})}{Demand_{ij}}\ if\ Demand_{ij} \geq Delivery_{ij}; if\ not\ R_{ij} = 1 \qquad \text{Equation 7}$$

is collapsed into an a overall reliability measure

$$R_{i} = 1 - \frac{\sum_{j}(Demand_{ij} - Delivery_{ij})^{+}}{\sum_{i} Demand_{ij}}, \qquad \text{Equation 8}$$

where *i* represents a given demand point or group of demand points, and *j* represents timesteps. The $^{+}$ indicates that negative values are replaced with zero values so as not to bias the analysis in the case of overdelivery at a given time step.

As described in Chapter 2, I have calibrated the WEAP model to include a historical preference for some groundwater supply for each agricultural demand node. Thus, I normalize the reliability calculations to exclude this groundwater supply – that is, groundwater use forced by historical preference does not reduce reliability statistics for surface water. This may overestimate reliability, as I am not able to separate preference for groundwater by users within an irrigation district from forced use of groundwater based on shortages.

3.3 **Results: demand sensitivity to scenario ensembles**

Figure 51 through Figure 55 show time series of simulated urban and agricultural water demands for the areas listed in Table 23. Table 25 through Table 27 show corresponding descriptive statistics for the sets of scenarios.

3.3.1 Agricultural demands

As described above, agricultural demands are modeled as a function of land use and climate. Figures 5a through 9a and Table 25 show the impacts of scenarios of climate change and urbanization on water demands.

Climate projections introduce variability into agricultural demands, as well as an increase in mean annual water demands, due to increasing potential evapotranspiration with higher temperatures. Projected climate warming leads to small increases (median projected increases of 1-3% at mid-century and 2-10% at end of century) in modeled per-acre agricultural demands, given static agricultural practices. When urbanization is included in the projections, however, agricultural water demands decrease over the course of the century. The urbanization effect is an order of magnitude greater than the climate-driven increase absent urbanization (Table 25). In effect, urbanized acreage replaces irrigated acreage, and thus decreasing agricultural production and water demand.

The effect of decreasing agricultural demands with increasing urbanization is repeated across the case study area, with the exception of the northern section of Oakdale ID and the northern section of Merced ID, which have little projected urbanization. However, both of these areas are relatively small, the overall effect on both Oakdale and Merced is consistent with the pattern of decreasing agricultural demands. Both the absolute and relative effects vary across the Irrigation Districts modeled here, but the pattern is consistent in sign and magnitude relative to climate impacts (Table 25).

3.3.2 Urban demands

The result of modeled urban water demands is substantial increases over the course of the century, which are only somewhat moderated by projected increases in water use efficiency. Urban demands are modeled simply as a function of population and water use efficiency, as described above. Figure 51b through Figure 55b and Table 26 show simulated urban demands. With population projections alone, urban demands increase across the study area in response to the rate of population growth. While such increases are moderated by the addition of water use efficiency projections, on the whole rates of population increases in the scenarios used here are too large for projected WUE scenarios to completely moderate, as indicated by the overlap in the boxplots in Figure 51b through Figure 55b.

3.3.3 Combined urban and agricultural demands

Figure 51c through Figure 55c and Table 27 show model results for combined urban and agricultural demands. The dominant effect in these basins is the signal from urbanization: reduced demands from removal of agricultural land from production exceed increased demands given the set of scenarios defined in this work. While aggregate demand is sensitive to all factors, the signal from urbanization dominates that from climate or population.

Table 33 describes the new results of combinations of modeled stressors given the projections used in the modeling presented here. The effects of each stressor individually have been discussed, and are shown on the diagonal.

In most cases, even where effects combine destructively, the net effect is unambiguous. The dark shaded cells below the diagonal show the net results when two stressors are modeled simultaneously. Urbanization again dominates the effects of the other three stressors in pairwise combination. Even absent the urbanization effect, all population growth scenarios, even with WUE included, result in increased urban demands that outweigh the climate-induced increase in agricultural demands. Urbanization exacerbates this effect by taking agricultural land out of production. Absent population growth and urbanization, the total increase in demands from climate change is comparable to the total decrease from urban water use efficiency changes by mid-century, with the climate signal stronger by end of century in response to the decreasing rate of water use efficiency improvements.

When three of the four stressors are modeled simultaneously (Table 33, above diagonal), with the fourth held constant, urbanization dominates in each case it is included, leading to a net negative trend in demands, and when it is excluded from the analysis, projected demands rise.

3.4 **Results: Water supply reliability**

3.4.1 Hydrology

Details on model calibration are presented in Chapter 2. Modeled hydrology responds to climatic inputs including precipitation and temperature. Precipitation in the selected models shows an overall drying trend, with approximately 5-10% decreases in average annual projected precipitation in northern California by late century (Cayan et al. 2009), resulting in lower modeled streamflow. Table 28 shows model hydrology sensitivity to temperature change, as indicated by the shift in timing of streamflow with rising temperature. The present model is somewhat less sensitive to temperature by this measure than other efforts have described (Young et al. 2009), and thus may have a relatively muted climate response when compared to other such studies (Vicuna et al. 2007).

3.4.2 Agricultural water supply reliability

Table 29 describes four scenario sets used to generate model runs for comparison of the effects of these combinations of variable on demands. Each scenario set was run under the ensemble of six downscaled climate models, and results are presented for A2- and B1-forced GCMs.

Simulated agricultural water supply reliability is presented in Table 31. Results for S10 (climate change only) shows high supply reliability across the study area for agricultural users in these basins, in accordance with historical patterns for the senior water rights holders with ample storage in these basins (Vicuna et al. 2007). Agricultural supply reliability appears more sensitive to population and urbanization than it is by climate under these scenarios. A combination of slightly increased agricultural demands with climate impacts on hydrology results in decreases by end of the century in most of the case study areas. Reliability is slightly higher in B2 as opposed to A1 scenarios.

As with demands, and likely because of the demand response, other factors appear to have stronger influence on supply reliability than does climate in this model. When population growth alone is represented, agricultural supply reliability decreases to a greater extent than from climate change alone. As expected, the addition of water use efficiency (S12) mitigates the reliability impacts, but not entirely. When urbanization is included (S13), the picture changes. Projected agricultural supply reliability increases in all cases by mid-century. This pattern is the result of decreasing agricultural and overall demands under urbanization, counterbalanced by decreases as urban demands increase at end of century.

3.4.3 Urban water supply reliability

Urban reliability results are presented in Table 32. Simulated urban reliability is universally lower than for agricultural reliability. Again, as expected, water use efficiency increases urban supply reliability by reducing demands, and including urbanization causes a further increase by reducing agricultural demands leaving more supply for urban uses. Including urbanization (S13) increases urban supply reliability in the model, as decreased agricultural demands leave more water available for lower priority urban uses.

3.5 **Discussion**

3.5.1 Multi-stressor impacts on demands

I have modeled the impacts of multiple stressors on urban and agricultural water demands in three basins in California's Central Valley. As modeled, individual stressors have contrasting effects on the variability of demand projections.

Given the assumptions in this study, projected climate warming leads to small increases (median projected increases of 1-3% at mid-century and 2-10% at end of century) in modeled per-acre agricultural demands, given static agricultural practices. Per-acre urban water use varies, but the population densities projected here result in demands less than current and projected per-acre agricultural water use.

A central result is the relative importance of urbanization on water demands: as agricultural land is converted to urban uses, overall water demands decrease dramatically. The net effect is an intuitive shift in demands from agricultural to urban, and a perhaps counter-intuitive decrease in overall demands under population growth when urbanization is taken into account.

The importance, and limitations, of water use efficiency as a strategy for balancing future water demands driven by population growth, is highlighted by these results as well. Modeled simply as it is here, WUE may approximately offset climate change impacts on agricultural demands, absent population growth. However, in the context of the projected population growth in the region, urban demands will rise in even the low growth and high WUE scenarios. Among the range of estimates, increases in WUE can offset projected population growth somewhat, but substantial increases in urban demand are projected with or without WUE improvements by mid-century. Comparisons with baseline water use would show even greater increases.

In presenting a counterpoint to previous work comparing population growth and climate change as drivers of water resources impacts (Vörösmarty et al. 2000), the demands analysis presented here emphasizes the importance of place-based studies of water resources impacts. The type and degree of urbanization described here are likely representative of a specific type of growth. Suburban sprawl and exurbanization are common in California and the western U.S. in areas where geography allows for it (Duane 1999). The three basins describe here are relatively homogenous in terms of their proximity to large swaths of agricultural land, and relative proximity to transportation corridors and larger urban centers. These characteristics emphasize the place-specific nature of these changes, and the importance of local studies for informing future policies on impacts and adaptation.

Unsurprisingly, the inclusion of multiple stressors dramatically increases the range of variability exhibited in studies of demands when compared to climate-centric impacts studies. In these results, much of the variability lies in the urban demands as compared to the agricultural ones (Figure 51 through Figure 55). However, this is partly an artifact of the availability of scenarios used in this modeling: Population and WUE projections each cover a wide range. In contrast, we are limited to a single urbanization projection, and do not vary agricultural practices, both of which result in less variability in future agricultural demands than likely exist. These sources of uncertainty can be incorporated into future efforts.

3.5.2 Multi-stressor impacts on supply reliability

The results presented here illustrate system attenuation of the climate change signal: as impacts move to higher order impacts, flexibility in the system buffers the response. In particular, reservoir storage is a key variable – with the ability to store multiple years worth of water supply, severe and protracted drought events are necessary to reduce storage levels below the buffer, and begin to limit supply.

As noted above, the sensitivity of hydrology in the present model calibration is less than previous efforts in this region. That being said, the climate signal appears in results for supply reliability, but is largely dominated by the signal from demand changes from population growth and urbanization.

It is worth noting again two assumptions of the simulations. First, institutional constraints specified in the model (Section 3.2.6) are a key driver of this result. Limiting timing of diversions to those currently allowed for agricultural purpose water rights, while adding additional urban demands, leaves much of the year with demands but no additional surface supply. Further, with urban supply modeled as second in priority to agricultural, the probability of supply shortfall is naturally greater than for the higher priority user. Different institutional scenarios would clearly change the results, and possibly substantially. The message is that additional exploration of institutional scenarios could be a fruitful area of future exploration. That the water rights and regulatory regime is a large determinant of system behavior is well understood. Its magnitude relative to the other stressors described here has not yet been explored in scenarios modeling to my knowledge, and it may also represent a large 'lever' that could be taken advantage of in water resource planning.

3.5.3 Interactions between climate, land use, urbanization, and water use efficiency

Table 33 depicts qualitatively the combined effects of scenarios of climate change, land use change, urbanization, and water use efficiency on water demands. Urbanization, for the scenario available for the case study area, has the greatest magnitude of impact, resulting in decreases in total water demands regardless of what it is combined with. Population also increases demands, particularly towards the end of century in all three scenarios. Climate change has smaller demand-side effects, but this should be taken in the context of its larger hydrologic and supply-side impacts. Based on how it is modeled here, urban water use efficiency does not balance population growth, but it does mute somewhat the projected total increase.

3.5.4 Limitations

As with all modeling efforts, the one described here has some limitations and room for future improvements. The analysis focuses on impacts of major uncertainties for water resources: climate change, land use change, and population growth. There are other aspects of uncertainty in this exercise, which I acknowledge here as possibilities for future exploration. Constant proportions in cropping patterns are not a realistic assumption, although they are unlikely to change the primary conclusions of this study. I did not model changes in agricultural water use efficiency in the physical representation of irrigated water use. Future work could implement changes in agricultural water use efficiency (Cooley et al. 2008), response of cropping patterns to drought (Joyce et al. 2006; Purkey et al. 2008), and change in crops to favor products with higher economic value (Groves et al. 2005). I also leave model structure uncertainty and hydrology parameter uncertainty (Ajami et al. 2007) for later work.

Scenarios incorporating such improvements could be developed in future iterations of work on this topic. My model does not incorporate adaptation to any of these stressors. For example, cropping patterns will change in response to climate change and urbanization, as well as to global economic factors.

In the approach presented here, agricultural demands are sensitive to climate and urbanization scenarios, but not population and WUE, and urban demands as modeled are sensitive to population and WUE only, not to climate. The approach is reasonable given that the data used the best available data for the region, and given the magnitude of the relative impacts.

To address all of these limitations, more detailed modeling would be possible. However, given results from previous studies, the chief drivers of demands in such efforts would be expected to remain urbanization and population growth.

Recall from Chapter 2 that the present model has been adapted for the current study in several ways: it has a monthly time step, larger elevation bands, and a different sub-watershed structure than the version we presented previously (Young et al. 2009). The recalibration, and the different sensitivity, prompts questions about equifinality – different model structures and parameter sets may lead to similar model results (Beven 2000). This issue can arise particularly in models of this nature, where the number of input parameters exceeds the amount of calibration data available. The present analysis thus may show relatively muted response to climate, when compared with other studies of this nature.

Finally, my model considers impacts from multiple stressors on a single variable, namely human demands for urban and agricultural water use. As studies of a single impact on multiple variables (Hayhoe et al. 2004) represented a step forward in climate studies, and as multi-stressor impacts on a single variable are a step forward from single-impacts studies on single variables, future work will need to incorporate multi-stressor, multi-impact studies to draw a sufficient picture of possible futures during the next part of the Anthropocene.

3.6 Conclusions

I have presented a multi-stressor analysis of projected future impacts on urban and agricultural water demands and supply reliability in California's Central Valley. Including spatially explicit projections of urbanization and population growth, as well as climate change projections and water use efficiency estimates, in estimates of future water demands results in a richer picture of the future water resources landscape. The results presented above suggest that existing scenarios of climate change, urbanization, population growth, and water use efficiency can combine to produce a more complex set of projections of future urban and agricultural water demands than considerations of any of these factors alone, and that climate change may not be the dominant stressor on future water supply when attenuation of the climate change signal by the water system is taken into account.

A number of broad conclusions can be drawn from the set of results presented above. There may be differential effects of population and land use change on urban and agricultural water demands, and the magnitude of the effects is substantial in comparison to those from climate alone. This highlights the importance of considering land use as a driver of system change, and in particular when invoking population growth as a driver of change. Also, the results highlight the limitations of climate impacts assessments that do not incorporate other major stressors.

The place-specific, spatially explicit nature of these analyses compliments previous path breaking global-scale efforts (Vörösmarty et al. 2000). If, to paraphrase Tip O'Neill, 'all water is local', further work is needed before robust generalizations about the relative effects of anthropogenic stressors on future water resources can be made.

The implications of these results for water resources institutions are potentially profound. In a system of water rights with prescribed based on historical and ongoing use of specific types, changes of the type and magnitude described here are unlikely to be accommodated by the existing system of allocation. In practical terms, the data highlight the importance of actively considering land use and population alongside the considerable progress on incorporating climate change into California water policy. However, the work presented here constitutes the next stage in this conversation, rather than any information actionable by policy makers. Further work can tackle the essential and difficult tasks of taking these broad ideas into useable realm, through establishing credible probabilities for these or other scenarios (Hall et al. 2007), robust analysis of suites of policy choices (Groves and Lempert 2007), collaborative approaches to science and decision-making (Kallis et al. 2009; Norgaard et al. 2009), or some combination of these and other methods.

Finally, all of the anthropogenic stressors described here, including climate change, urbanization and population growth on the scale projected for California, will clearly have profound effects beyond those described here for water demands: altered flood regimes, changes in groundwater use and recharge, substantial impacts on water quality, displacement and changes to natural habitat, impacts on local, regional and global food supply, and a broad suite of local socioeconomic changes are just a few examples of subjects that will warrant further exploration for future planning.

3.7 Figures

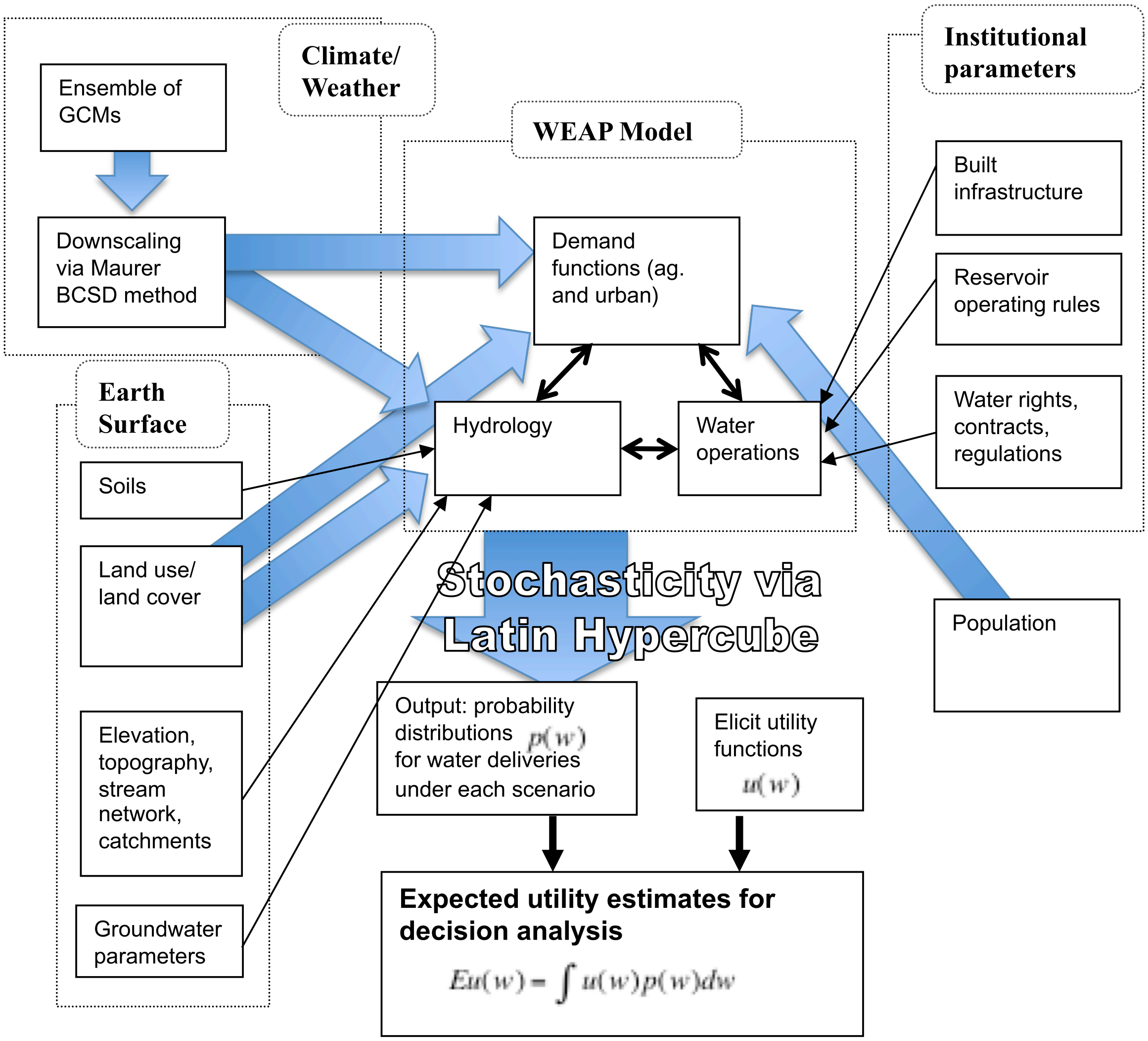
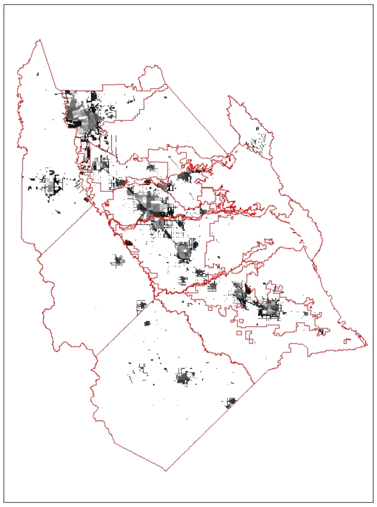
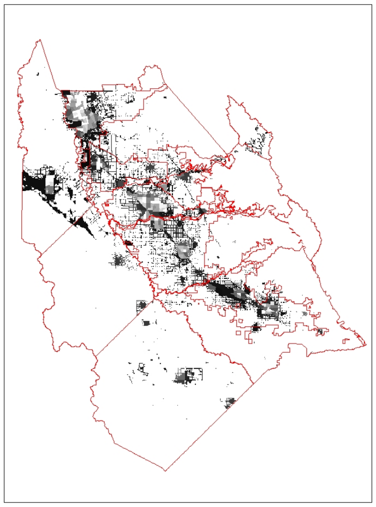


Figure 47: Conceptual model of Integrated Assessment with risk and decision analysis. Thin dark arrows indicate parameters that will be treated deterministically in this analysis. Fat blue arrows indicate parameters for which I will develop estimates of variability in future projections, using Latin Hypercube simulations in the case of large parameter ensembles, or in the case of this dissertation through a full factorial analysis using the computational methods described in the text. The blue arrows are the focus of the work presented in the present chapter.



a)



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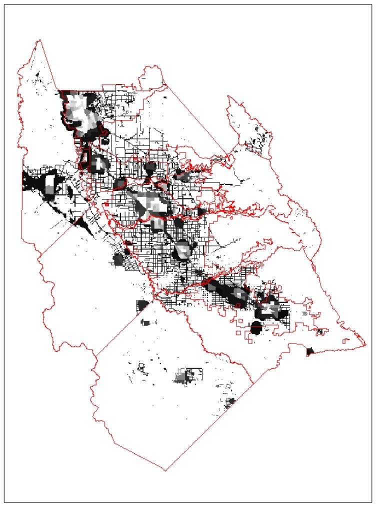

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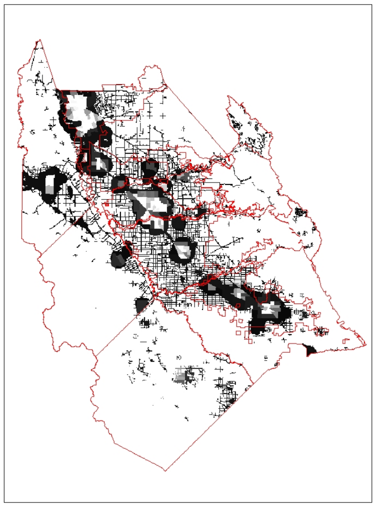

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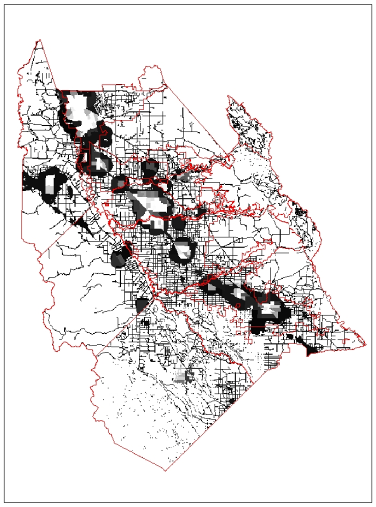
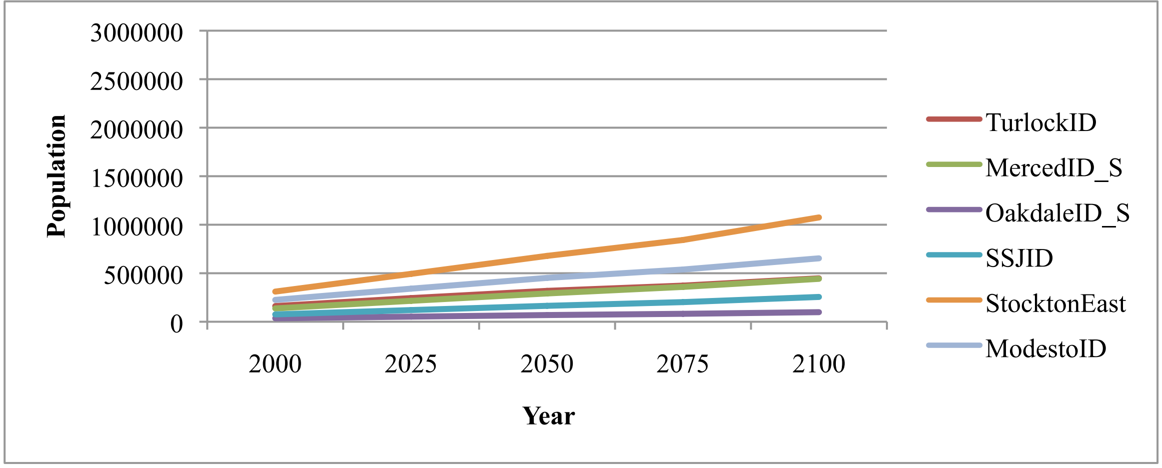


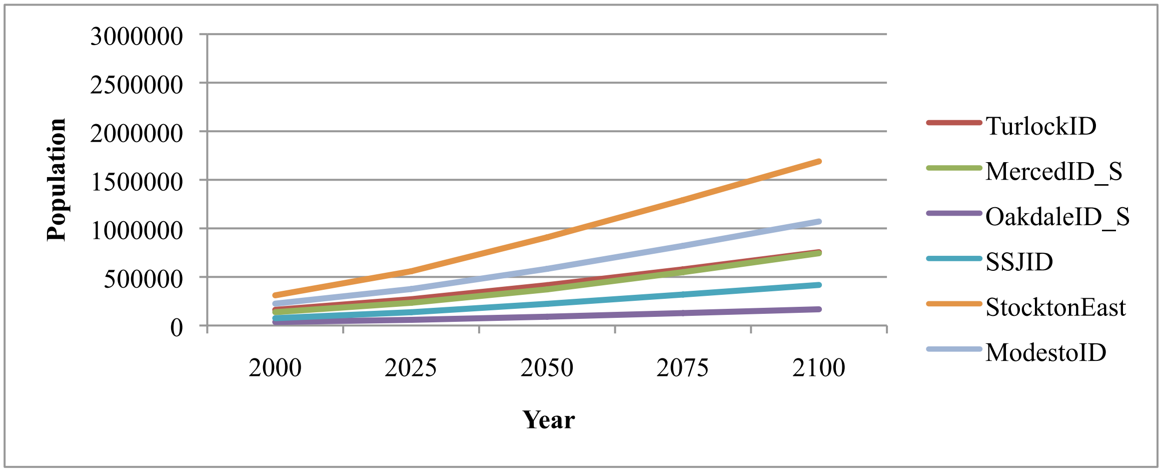
e)

Figure 48: Urbanization and population projections ("Mid" scenario) for the study area, for a) 2000, b) 2025, c) 2050, d) 2075, and e) 2100. Data from (Sanstad et al. 2009). Grayscale areas indicate urbanized areas, with lighter areas in the centers of each population mass indicating higher density. Thick red lines are county lines, and thinner lines are Irrigation District and Water District boundaries.

a)



b)



c)

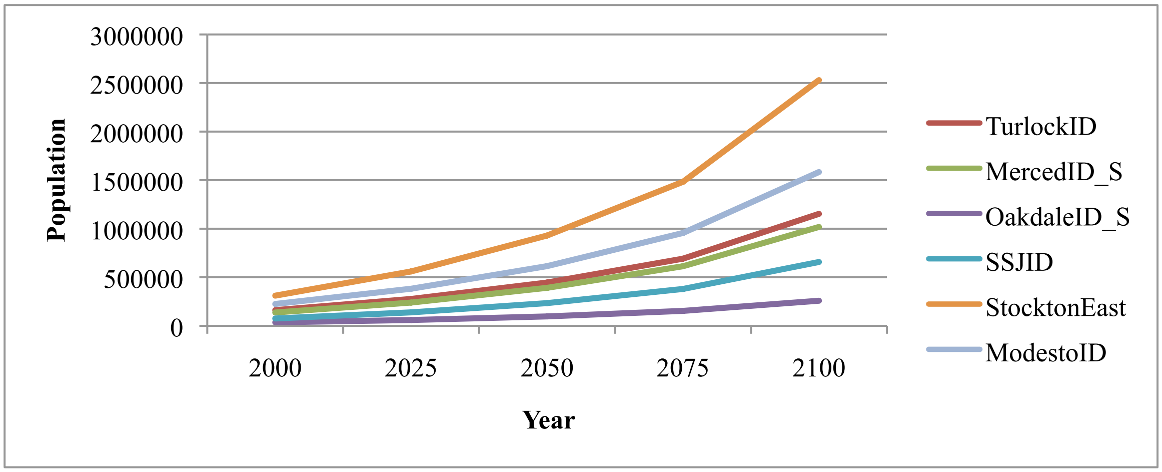


Figure 49: Population projections for areas corresponding to the relevant nodes in the WEAP model. Data are based on GIS analysis of the a) “Low”, b) “Mid” and c) “High” scenarios from the spatially explicit population projections produced by Sanstad et al. (Sanstad et al. 2009).

Figure 50: Digital information transfer and its application to this study of water resources.

Congratulations. As one of the few, and possibly the only, person to ever read this dissertation, you join a select group. If you are indeed the first person to come across this figure, you benefit from an age-old tradition, morphed to the digital age. Urban legend has it that students have sometimes squirreled away a twenty-dollar bill in the bound copy of their dissertation, returning years later to either find it remaining in the untouched volume deep in the musty stacks, or to thrill in the knowledge that someone may have found interest in their graduate research. Although I am among the first generation at Berkeley to file my dissertation electronically, you can still partake in the great tradition. Contact me with your thoughts on my dissertation. If you are the first to do so, I will send you twenty dollars. Electronically, of course.

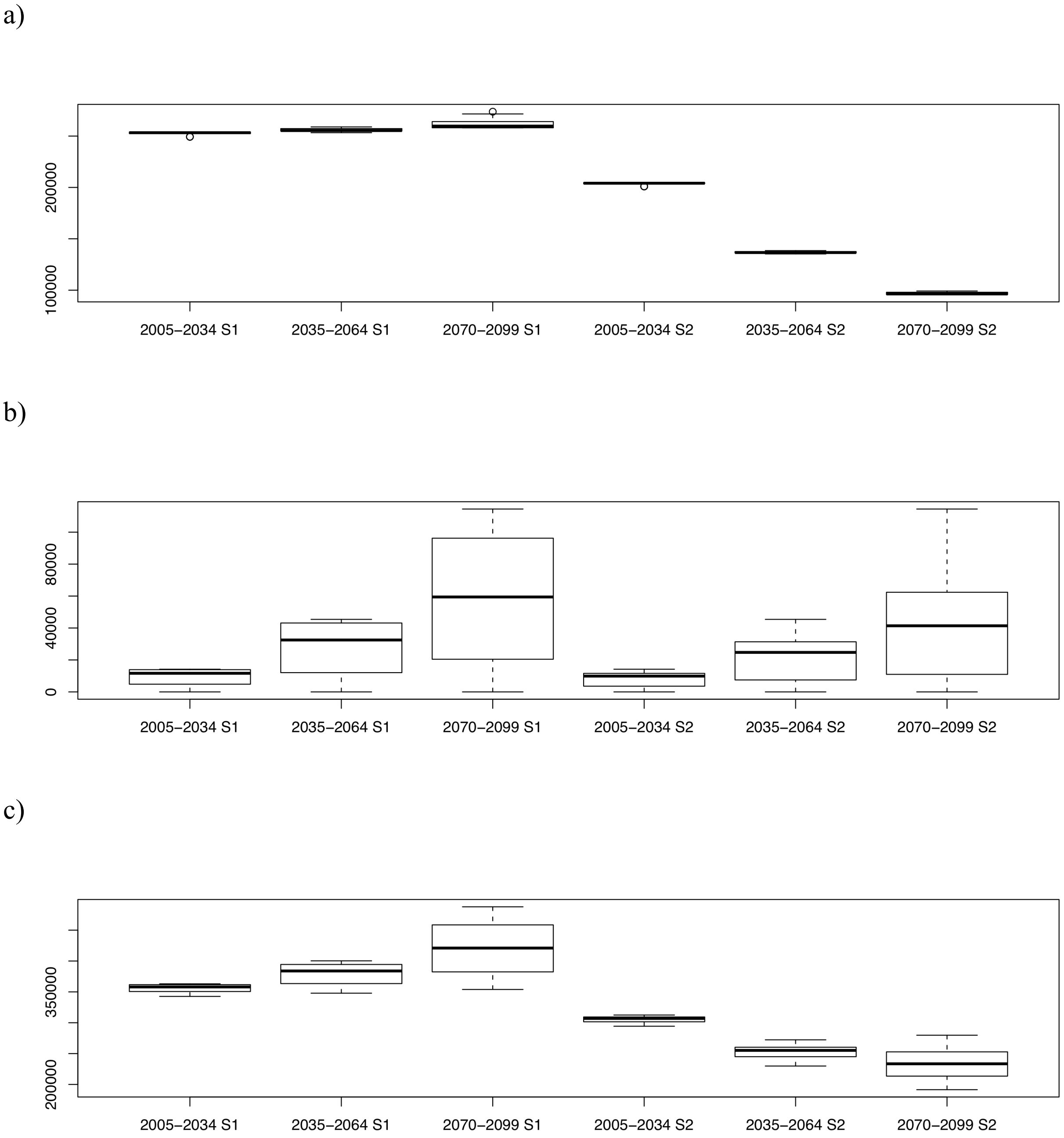


Figure 51: Modeled annual urban and agricultural water demands at SSJID node (in AF); a) agricultural demands under 6 climate change scenarios, with S1 holding urbanization at 1995 levels, and S2 incorporating projected urbanization; b) aggregate urban demands, with S1 incorporating population growth and S2 incorporating population growth and WUE scenarios; c) combined urban and agricultural demands, with S1 incorporating climate change, population growth, WUE, and S2 also incorporating urbanization. See Table 24 for description of scenarios used in this study.

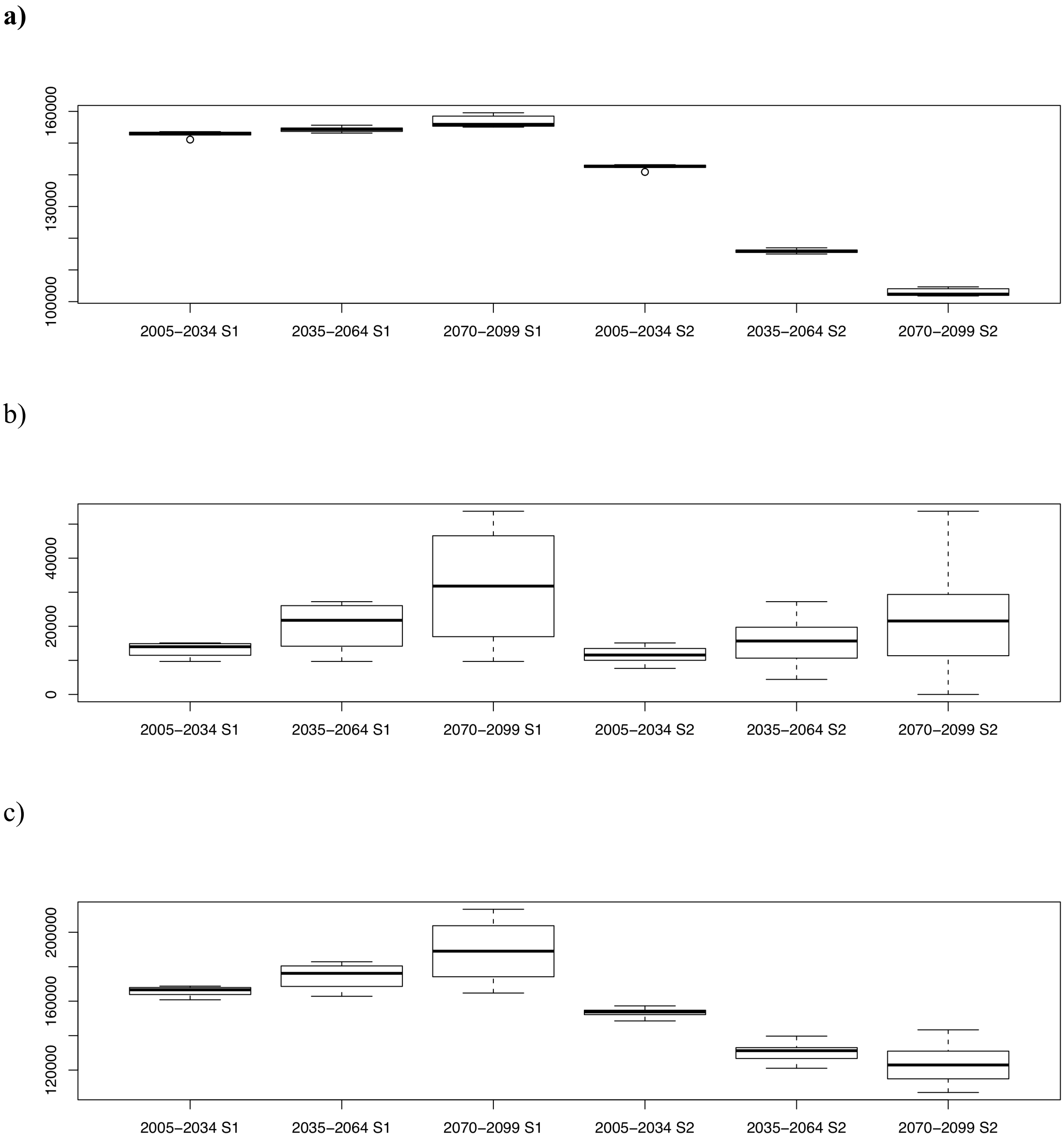


Figure 52: Modeled annual urban and agricultural water demands at OID node; a) agricultural demands, b) aggregate urban demands, c) total urban and agricultural demands. See Figure 51 caption for details.

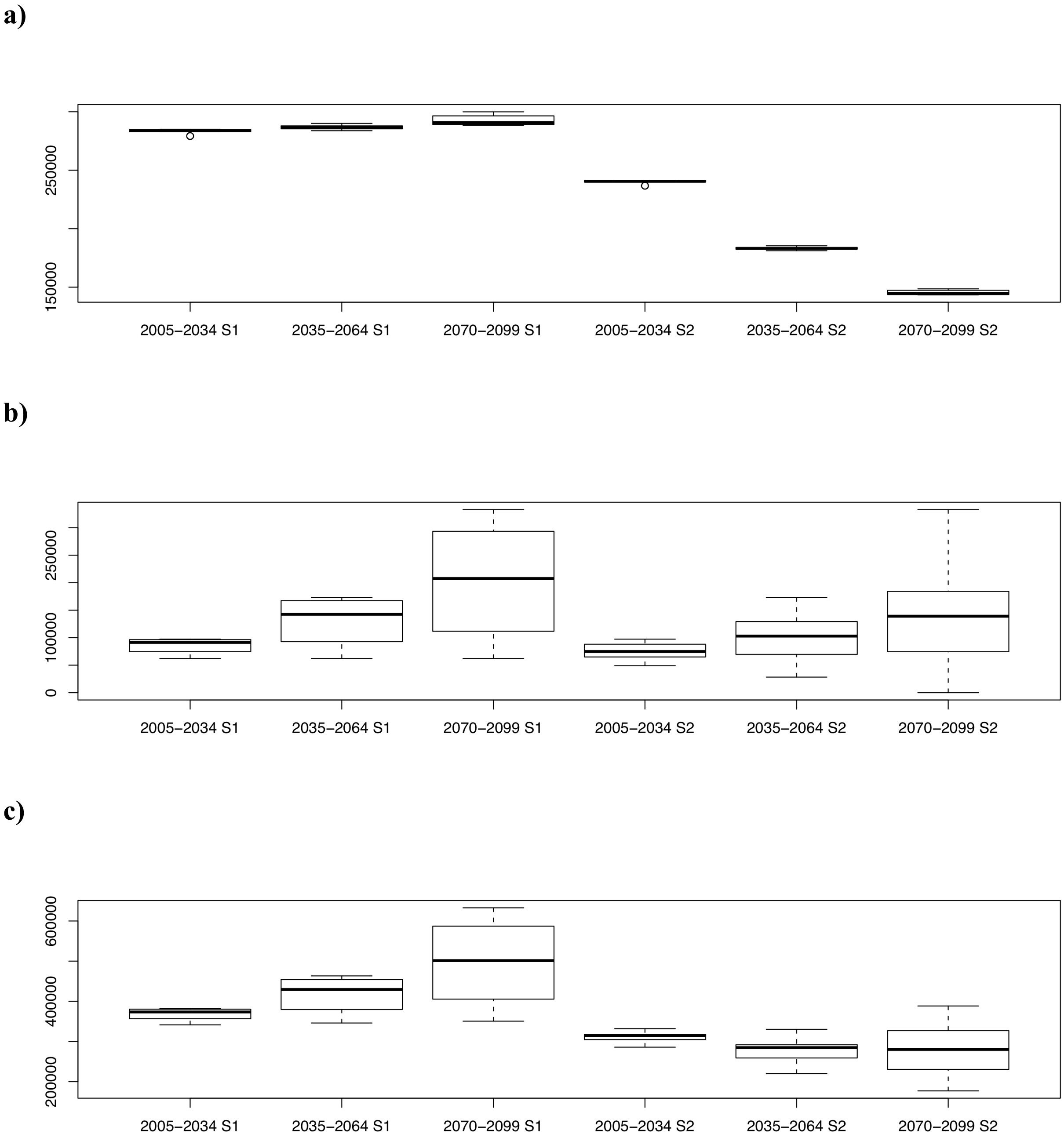


Figure 53: Modeled annual urban and agricultural water demands at Modesto ID node; a) agricultural demands, b) aggregate urban demands, c) total urban and agricultural demands. See Figure 51 caption for details.

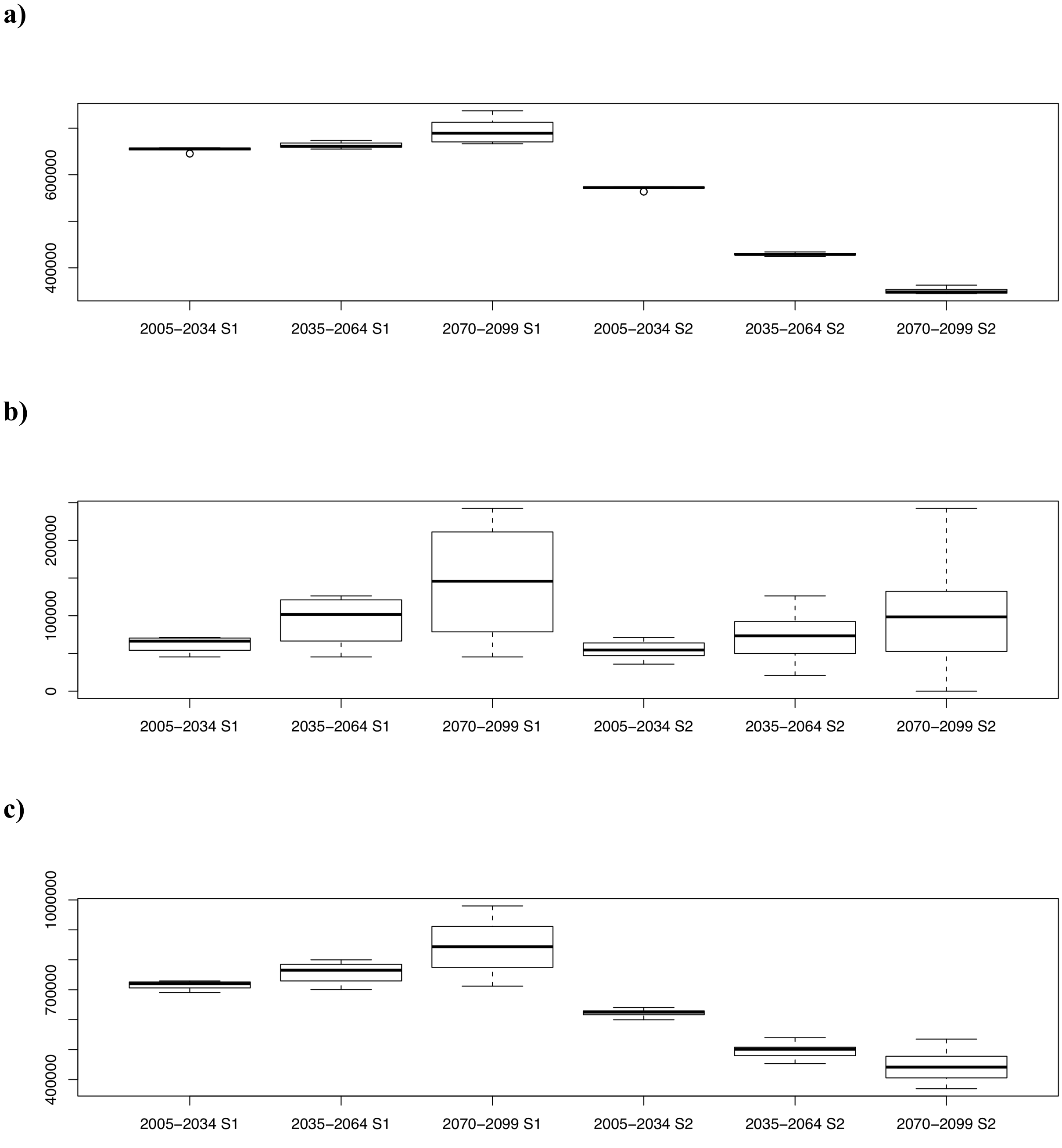


Figure 54: Modeled annual urban and agricultural water demands at Turlock ID node; a) agricultural demands, b) aggregate urban demands, c) total urban and agricultural demands. See Figure 51 caption for details.

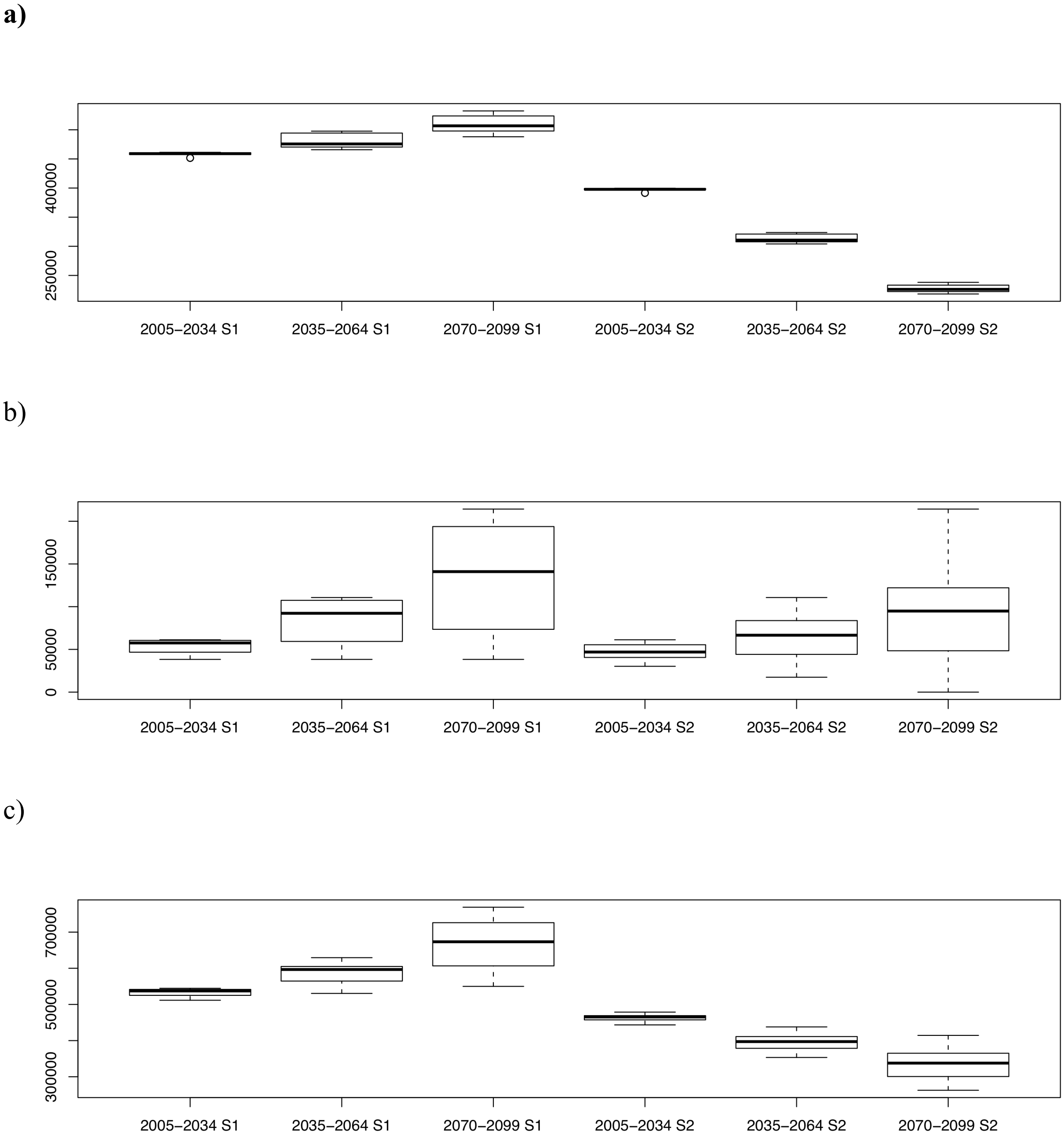


Figure 55: Modeled annual urban and agricultural water demands at Merced ID node; a) agricultural demands, b) aggregate urban demands, c) total urban and agricultural demands. See Figure 51 caption for details.

3.8 **Tables**

		2000	2015	2020	2030	2100
WUE Scenario	Baseline	0	0	0	0	0
	20x2020 - SJR	0	15	30	30	38
	20x2020 - overall	0	10	20	20	25
	CBDA Projection 1	0	Values interpolated between 2000 and 2030 values		10	13
	CBDA Projection 2	0			11	14
	CBDA Projection 3	0			14	18
	CBDA Projection 4	0			15	19
	CBDA Projection 5	0			16	20
	CBDA Projection 6	0			24	30
	Groves - CT	0			9	11
	Groves - LRI	0			15	19
	Groves - MRI	0			0	0
	Groves - LWD	0			15	19
	Pacific Insitute	0			33	41

Table 22: Scenarios of per capita urban water use efficiency increase over baseline (%) for WEAP modeling, based on analysis by the State Water Resources Control Board (State Water Resources Control Board 2009), California Bay-Delta Authority (CALFED Bay-Delta Program 2006), Groves et al. (Groves et al. 2005), and Gleick et al. (Gleick et al. 2003; Gleick et al. 2005). Note that eleven of these scenarios are unique, and for this analysis I chose four to cover the space represented here, as shown in Table 24.

River	**Surface water diversion**	**Ag Nodes Supplied**	**Urban Nodes Supplied**	**Groundwater source**
Stanislaus	SSJID Cn	SSJID	Manteca_Urban	Eastern San Joaquin
		OakdaleID_N	Manteca_SSJID_Growth	Eastern San Joaquin
	OID South Cn	OakdaleID_S	Oakdale_Urban	NA
			Oakdale_Growth	Modesto
	Goodwin Tn	StocktonEastWD	Stockton_Urban	Eastern San Joaquin
			Stockton_Growth	Eastern San Joaquin
Tuolumne	Modesto Main Cn	ModestoID	Modesto_Urban	Modesto
			Modesto_Growth	Modesto
	Turlock Main Cn	TurlockID	Turlock_Urban	Turlock
			Turlock_Growth	Turlock
Merced	Merced ID Main Cn	MercedID_N	Merced_Urban	Merced
			Merced_Growth	Merced
	Merced ID N	MercedID_N	NA	Turlock

Table 23: Grouping of model output based on diversion point.

	Climate	**Urbanization**	**Population**	**WUE**
1	“Historical”	"DWR 1995"	"Low"	"1_Baseline"
2	"2.0_a2_cnrmcm3"	"Sanstad"	"Mid"	"2_20x2020_SJR"
3	"3.0_a2_gfdlcm21"		"High"	"3_CBDA Projection_1"
4	"4.0_a2_miroc32med"		"No_Growth"	"4_Pacific Institute"
5	"5.0_a2_mpiecham5"			
6	"6.0_a2_ncarccsm3"			
7	"7.0_a2_ncarpcm1"			
8	"8.0_b1_cnrmcm3"			
9	“9.0_b1_gfdlcm21”			
10	“10.0_b1_miroc32med”			
11	"11.0_b1_mpiecham5"			
12	"12.0_b1_ncarccsm3”			
13	"13.0_b1_ncarpcm1"			

Table 24: Overview of scenarios used to drive the WEAP model. Scenarios were run in full factorial combination to produce results presented below. Details of the scenarios and their derivation are given in the text. Scenarios are coded based on this array. For example, Scenario 3.2.2.4 represents climate scenario A2 GFDL CM21 with Sanstad et al. urbanization projection, “Mid” population growth, and WUE scenario derived from the Pacific Institute. Note that the data reported in this chapter includes climate scenarios 2-13, run in full factorial combination across the four variables. Results under historical climate are described in Chapter 2.

Irrigation District	Simulation Years	Scenario set	Median (TAF)	% change over 2004-34 value (Median)	N
SSJID	2005-2034	S3	253	-	6
	2035-2064	S3	255	1%	6
	2070-2099	S3	260	3%	6
	2005-2034	S4	204	-	6
	2035-2064	S4	137	-33%	6
	2070-2099	S4	96	-53%	6
Oakdale ID N	2005-2034	S3	94	-	6
	2035-2064	S3	95	1%	6
	2070-2099	S3	96	2%	6
	2005-2034	S4	94	-	6
	2035-2064	S4	95	1%	6
	2070-2099	S4	96	2%	6
Oakdale ID S	2005-2034	S3	153	-	6
	2035-2064	S3	154	1%	6
	2070-2099	S3	156	2%	6
	2005-2034	S4	143	-	6
	2035-2064	S4	116	-19%	6
	2070-2099	S4	102	-28%	6
Turlock ID	2005-2034	S3	656	-	6
	2035-2064	S3	661	1%	6
	2070-2099	S3	689	5%	6
	2005-2034	S4	572	-	6
	2035-2064	S4	429	-25%	6
	2070-2099	S4	348	-39%	6
Modesto ID	2005-2034	S3	284	-	6
	2035-2064	S3	286	1%	6
	2070-2099	S3	291	2%	6
	2005-2034	S4	240	-	6
	2035-2064	S4	183	-24%	6
	2070-2099	S4	144	-40%	6
Merced ID S	2005-2034	S3	459	-	6

	2035-2064	S3	475	3%	6
	2070-2099	S3	506	10%	6
	2005-2034	S4	398	-	6
	2035-2064	S4	311	-22%	6
	2070-2099	S4	226	-43%	6

Table 25: Projected agricultural demands across the study area under two sets of scenarios, corresponding to Figure 51a through Figure 55a. Agricultural demands as modeled are sensitive to climate and urbanization scenarios. S3 includes the response to climate change projections with 1995 land use, and S4 includes the response to climate change with modeled urbanization (Table 24). The values presented are median values across each set of scenarios (e.g. S1, S2), each of which has N members. Each set of scenarios is made up a value of the mean of model output for the indicated 30-year period, for each scenario. Note that these agricultural demands do not account for system inefficiencies, which are modeled separately.

Urban Demand Nodes	Simulation Years	Scenario set	Median (TAF)	% change over 2004-34 value (Median)	N
Manteca	2005-2034	S1	12	-	4
	2035-2064	S1	32	179%	4
	2070-2099	S1	59	410%	4
	2005-2034	S2	10	-	16
	2035-2064	S2	25	150%	16
	2070-2099	S2	41	319%	16
Oakdale	2005-2034	S1	14	-	4
	2035-2064	S1	22	55%	4
	2070-2099	S1	32	127%	4
	2005-2034	S2	12	-	16
	2035-2064	S2	16	36%	16
	2070-2099	S2	22	86%	16
Turlock	2005-2034	S1	66	-	4
	2035-2064	S1	102	53%	4
	2070-2099	S1	146	120%	4
	2005-2034	S2	55	-	16
	2035-2064	S2	73	34%	16
	2070-2099	S2	98	80%	16
Modesto	2005-2034	S1	91	-	4
	2035-2064	S1	143	56%	4
	2070-2099	S1	208	127%	4
	2005-2034	S2	75	-	16
	2035-2064	S2	103	37%	16
	2070-2099	S2	139	86%	16
Merced	2005-2034	S1	58	-	4
	2035-2064	S1	92	60%	4
	2070-2099	S1	141	145%	4
	2005-2034	S2	47	-	16
	2035-2064	S2	67	42%	16
	2070-2099	S2	95	102%	16

Table 26: Projected urban demands across the study area under two sets of scenarios, corresponding to Figure 51b through Figure 55b. Urban demands as modeled are sensitive to population and water use efficiency. S1 includes the response to population growth scenarios 1-4 alone with baseline WUE, and S2 incorporates both population growth scenarios 1-4 and WUE scenarios 1-4 (Table 24).

Demand Area Ag + Urban Total	**Simluation Years**	**Scenario set**	**Median (TAF)**	**% change over 2004-34 value (Median)**	**N**
SSJID Area	2005-2034	S5	357	-	96
	2035-2064	S5	375	5%	96
	2070-2099	S5	397	11%	96
	2005-2034	S6	308	-	95
	2035-2064	S6	257	-17%	95
	2070-2099	S6	234	-24%	95
OID Area	2005-2034	S5	164	-	96
	2035-2064	S5	170	3%	96
	2070-2099	S5	177	8%	96
	2005-2034	S6	154	-	95
	2035-2064	S6	132	-14%	95
	2070-2099	S6	124	-20%	95
Turlock Area	2005-2034	S5	710	-	96
	2035-2064	S5	735	4%	96
	2070-2099	S5	788	11%	96
	2005-2034	S6	627	-	95
	2035-2064	S6	503	-20%	95
	2070-2099	S6	446	-29%	95
Modesto Area	2005-2034	S5	359	-	96
	2035-2064	S5	390	9%	96
	2070-2099	S5	431	20%	96
	2005-2034	S6	315	-	95
	2035-2064	S6	286	-9%	95
	2070-2099	S6	285	-10%	95
Merced Area	2005-2034	S5	528	-	96
	2035-2064	S5	566	7%	96
	2070-2099	S5	625	18%	96
	2005-2034	S6	467	-	95
	2035-2064	S6	399	-15%	95

	2070-2099	S6	345	-26%	95

Table 27: Combined urban and agricultural demands across the study area under two sets of scenarios, corresponding to Figure 51c through Figure 55c, representing the combination of sensitivity to climate, population, urbanization, and water use efficiency scenarios. S5 includes the response to climate scenarios, population growth scenarios 1-4, WUE scenarios 1:4, with 1995 urbanization. S6 has the same set of scenarios, except with projected future urbanization (Table 24).

	Simulated COM, 1981-1999	**Simulated shift in COM, days**		
		2 degrees C	**4 degrees C**	**6 degrees C**
STN	30-Apr	7.7	11.6	12.1
TUO	1-Mar	6.4	9.9	10.3
MER	30-Apr	7.2	12.8	15.9

Table 28: Simulated shift in hydrograph center of mass earlier in the water year, with uniform temperature increase applied to historical climate inputs over the reference period from 1981-1999.

Scenario set	**Description**
S10	climate scenarios, all others baseline
S11	climate and population growth scenarios, others baseline
S12	climate, population growth, and WUE scenarios, urbanization baseline
S13	climate, population growth, WUE, and urbanization scenarios

Table 29: Scenario sets used in reliability analysis.

Reservoir	Simluation Years	Scenario set	Carryover storage (A2)
New Melones	2005-2034	S10	1,567,248
	2035-2064	S10	1,481,008
	2070-2099	S10	1,412,459
	2005-2034	S11	1,567,248
	2035-2064	S11	1,254,140
	2070-2099	S11	1,091,082
	2005-2034	S12	1,567,248
	2035-2064	S12	1,304,904
	2070-2099	S12	1,172,266
	2005-2034	S13	1,635,725
	2035-2064	S13	1,527,619
	2070-2099	S13	1,376,809
Don Pedro	2005-2034	S10	1,307,528
	2035-2064	S10	1,202,924
	2070-2099	S10	1,156,823
	2005-2034	S11	1,307,528
	2035-2064	S11	1,159,902
	2070-2099	S11	1,081,727
	2005-2034	S12	1,307,528
	2035-2064	S12	1,170,731
	2070-2099	S12	1,107,319
	2005-2034	S13	1,360,297
	2035-2064	S13	1,322,782
	2070-2099	S13	1,300,571
New Exchequer	2005-2034	S10	542,393
	2035-2064	S10	505,391
	2070-2099	S10	477,682
	2005-2034	S11	542,393
	2035-2064	S11	486,939
	2070-2099	S11	457,215
	2005-2034	S12	542,393
	2035-2064	S12	492,677
	2070-2099	S12	463,661
	2005-2034	S13	562,633
	2035-2064	S13	540,058

	2070-2099	S13	535,964
Overall average			1,052,578
Average 2005-2034			1,150,847
Average 2035-64			1,037,423
Average 2070-99			969,465
Average S10			1,072,606
Average S11			994,242
Average S12			1,014,303
Average S13			1,129,162

Table 30: Simulated carryover storage. Scenario sets are as described in Table 29.

Urban growth nodes	Simluation Years	Scenario set	Simulated Reliability (A2)	Simulated Reliability (B1)
Manteca	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.46	0.50
	2070-2099	S11	0.30	0.33
	2005-2034	S12	NA	NA
	2035-2064	S12	0.51	0.55
	2070-2099	S12	0.38	0.41
	2005-2034	S13	NA	NA
	2035-2064	S13	0.62	0.65
	2070-2099	S13	0.56	0.60
Oakdale	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.46	0.50
	2070-2099	S11	0.30	0.33
	2005-2034	S12	NA	NA
	2035-2064	S12	0.51	0.55
	2070-2099	S12	0.38	0.41
	2005-2034	S13	NA	NA
	2035-2064	S13	0.62	0.65
	2070-2099	S13	0.56	0.60
Turlock	2005-2034	S10	NA	NA
	2035-2064	S10	0.00	0.00
	2070-2099	S10	0.00	0.00
	2005-2034	S11	NA	NA
	2035-2064	S11	0.03	0.04
	2070-2099	S11	0.05	0.05
	2005-2034	S12	NA	NA
	2035-2064	S12	0.03	0.03
	2070-2099	S12	0.04	0.04

	2005-2034	S13	NA	NA
	2035-2064	S13	0.07	0.07
	2070-2099	S13	0.15	0.17
Modesto	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.28	0.34
	2070-2099	S11	0.23	0.25
	2005-2034	S12	NA	NA
	2035-2064	S12	0.29	0.35
	2070-2099	S12	0.25	0.27
	2005-2034	S13	NA	NA
	2035-2064	S13	0.47	0.51
	2070-2099	S13	0.45	0.50
Merced	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.02	0.02
	2070-2099	S11	0.01	0.01
	2005-2034	S12	NA	NA
	2035-2064	S12	0.03	0.03
	2070-2099	S12	0.02	0.02
	2005-2034	S13	NA	NA
	2035-2064	S13	0.03	0.03
	2070-2099	S13	0.02	0.02
Overall average			0.25	0.28
Average 2005-2034			NA	NA
Average 2035-64			0.28	0.30
Average 2070-99			0.23	0.25
Average S10			0.00	0.00
Average S11			0.22	0.24
Average S12			0.24	0.27
Average S13			0.36	0.38

Table 32, Table 33). Each scenario set is run under six GCMs (Table 24), with results for A2 and B1 emissions scenarios presented separately.

Agricultural nodes	Simluation Years	Scenario set	Simulated Reliability (A2)	Simulated Reliability (B1)
SSJID	2005-2034	S10	0.98	0.95
	2035-2064	S10	0.96	0.96
	2070-2099	S10	0.92	0.94
	2005-2034	S11	0.98	0.95
	2035-2064	S11	0.91	0.91
	2070-2099	S11	0.81	0.81
	2005-2034	S12	0.98	0.95
	2035-2064	S12	0.92	0.93
	2070-2099	S12	0.85	0.86
	2005-2034	S13	0.99	0.96
	2035-2064	S13	0.99	0.97
	2070-2099	S13	0.96	0.96
Oakdale ID S	2005-2034	S10	0.98	0.93
	2035-2064	S10	0.96	0.93
	2070-2099	S10	0.93	0.92
	2005-2034	S11	0.98	0.93
	2035-2064	S11	0.92	0.90
	2070-2099	S11	0.82	0.83
	2005-2034	S12	0.98	0.93
	2035-2064	S12	0.94	0.91
	2070-2099	S12	0.86	0.86
	2005-2034	S13	0.99	0.94
	2035-2064	S13	0.99	0.95
	2070-2099	S13	0.96	0.95
Turlock ID	2005-2034	S10	0.82	0.77
	2035-2064	S10	0.76	0.79
	2070-2099	S10	0.72	0.74
	2005-2034	S11	0.82	0.77
	2035-2064	S11	0.74	0.78
	2070-2099	S11	0.69	0.72
	2005-2034	S12	0.82	0.77
	2035-2064	S12	0.75	0.78

	2070-2099	S12	0.70	0.72
	2005-2034	S13	0.86	0.82
	2035-2064	S13	0.90	0.91
	2070-2099	S13	0.91	0.92
Modesto ID	2005-2034	S10	0.89	0.86
	2035-2064	S10	0.87	0.88
	2070-2099	S10	0.80	0.84
	2005-2034	S11	0.89	0.86
	2035-2064	S11	0.85	0.87
	2070-2099	S11	0.79	0.80
	2005-2034	S12	0.89	0.86
	2035-2064	S12	0.86	0.87
	2070-2099	S12	0.79	0.82
	2005-2034	S13	0.92	0.89
	2035-2064	S13	0.95	0.96
	2070-2099	S13	0.95	0.96
Merced ID S	2005-2034	S10	0.90	0.87
	2035-2064	S10	0.85	0.88
	2070-2099	S10	0.77	0.82
	2005-2034	S11	0.90	0.87
	2035-2064	S11	0.82	0.85
	2070-2099	S11	0.71	0.76
	2005-2034	S12	0.90	0.87
	2035-2064	S12	0.83	0.86
	2070-2099	S12	0.74	0.78
	2005-2034	S13	0.93	0.90
	2035-2064	S13	0.92	0.94
	2070-2099	S13	0.91	0.92
Overall average			0.88	0.87
Average 2005-2034			0.92	0.88
Average 2035-64			0.88	0.89
Average 2070-99			0.83	0.85
Average S10			0.87	0.87
Average S11			0.84	0.84
Average S12			0.85	0.85
Average S13			0.94	0.93

Table 31: Simulated water supply reliability at agricultural demand nodes. S10 includes climate change scenarios from the six GCMs listed in Table 24, with other variables in the table at baseline levels. S11 includes climate change and the three population growth projections. S12

includes climate change, population growth, and the three water use efficiency projections. S13 includes climate change, population growth, water use efficiency, and urbanization projections.

Urban growth nodes	**Simluation Years**	**Scenario set**	**Simulated Reliability (A2)**	**Simulated Reliability (B1)**
Manteca	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.46	0.50
	2070-2099	S11	0.30	0.33
	2005-2034	S12	NA	NA
	2035-2064	S12	0.51	0.55
	2070-2099	S12	0.38	0.41
	2005-2034	S13	NA	NA
	2035-2064	S13	0.62	0.65
	2070-2099	S13	0.56	0.60
Oakdale	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.46	0.50
	2070-2099	S11	0.30	0.33
	2005-2034	S12	NA	NA
	2035-2064	S12	0.51	0.55
	2070-2099	S12	0.38	0.41
	2005-2034	S13	NA	NA
	2035-2064	S13	0.62	0.65
	2070-2099	S13	0.56	0.60
Turlock	2005-2034	S10	NA	NA
	2035-2064	S10	0.00	0.00
	2070-2099	S10	0.00	0.00
	2005-2034	S11	NA	NA
	2035-2064	S11	0.03	0.04
	2070-2099	S11	0.05	0.05
	2005-2034	S12	NA	NA
	2035-2064	S12	0.03	0.03

	2070-2099	S12	0.04	0.04
	2005-2034	S13	NA	NA
	2035-2064	S13	0.07	0.07
	2070-2099	S13	0.15	0.17
Modesto	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.28	0.34
	2070-2099	S11	0.23	0.25
	2005-2034	S12	NA	NA
	2035-2064	S12	0.29	0.35
	2070-2099	S12	0.25	0.27
	2005-2034	S13	NA	NA
	2035-2064	S13	0.47	0.51
	2070-2099	S13	0.45	0.50
Merced	2005-2034	S10	NA	NA
	2035-2064	S10	NA	NA
	2070-2099	S10	NA	NA
	2005-2034	S11	NA	NA
	2035-2064	S11	0.02	0.02
	2070-2099	S11	0.01	0.01
	2005-2034	S12	NA	NA
	2035-2064	S12	0.03	0.03
	2070-2099	S12	0.02	0.02
	2005-2034	S13	NA	NA
	2035-2064	S13	0.03	0.03
	2070-2099	S13	0.02	0.02
Overall average			0.25	0.28
Average 2005-2034			NA	NA
Average 2035-64			0.28	0.30
Average 2070-99			0.23	0.25
Average S10			0.00	0.00
Average S11			0.22	0.24
Average S12			0.24	0.27
Average S13			0.36	0.38

Table 32: Simulated water supply reliability at urban demand nodes. Scenario sets are as in Table 31.

NOTE: Results for Merced and Turlock urban demands seem spurious to me. I need to sort through some layers of code to troubleshoot this. Note that the results here are for urban *growth* above baseline 2000 levels only. The assumption is that water supply for baseline demands will continue to be met with groundwater in the area. For this reason, with no additional population-generated demands in S10 reliability results are undefined.

	Climate	Urb.	Pop.	WUE	
Climate	+	-	+		WUE
Urb.	-	-	-		Climate
Pop.	+	-	+	-	Urb.
WUE	---	-		-	

Table 33: Overview of parameter interactions on total water demands in the study areas. Each cell indicates the sign or signs (+, -, ---, or +/-; for net increase, decrease, balance, or mixed effects, respectively) of the combined effects of the indicated parameters on total water demand. Cells on the diagonal indicate single effects (e.g. top left is climate change with baseline urbanization, population, and WUE); darkly shaded cells below the diagonal indicate two effects (e.g. lower left cell is climate change and WUE, with baseline, urbanization and population); cells above the diagonal indicate the combination of three of the four inputs. Impacts of all four combined are represented in Figure 51c through Figure 55c and discussed in the text.

3.9 **References**

Ajami, N. K., Q. Duan and S. Sorooshian (2007). "An integrated hydrologic Bayesian multimodel combination framework: Confronting input, parameter, and model structural uncertainty in hydrologic prediction." Water Resources Research **43**: W01403, doi:01410.01029/02005WR004745.

Arnold, C. A., Ed. (2005a). Wet Growth: Should Water Law Control Land Use. Washington DC, Environmental Law Institute.

Arnold, C. A. T. (2005b). "Is Wet Growth Smarter Than Smart Growth?: The Fragmentation and Integration of Land Use and Water." 35 ELR 10152 3-2005.

Beven, K. (2000). "On model uncertainty, risk and decision making." Hydrological Processes **14**(14): 2605-2606.

Brekke, L., M. Dettinger, E. Maurer and M. Anderson (2008). "Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments." Climatic Change **89**(3): 371-394.

CALFED Bay-Delta Program (2006). Water Use Efficiency Comprehensive Evaluation. Sacramento, CA, CBDA Water Use Efficiency Element

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, NicholasGraham and R. Flick (2009). Climate Change Scenarios And Sea Level Rise Estimates For The California 2009 Climate Change Scenarios Assessment. Sacramento, CA, California Energy Commission, California Climate Change Center.

Claessens, L., C. Hopkinson, E. Rastetter and J. Vallino (2006). "Effect of historical changes in land use and climate on the water budget of an urbanizing watershed." Water Resources Research **42**(3): W03426.

Cooley, H., J. Christian-Smith and P. H. Gleick (2008). More with Less: Agricultural Water Conservation and Efficiency in California: A Special Focus on the Delta. Oakland, CA, Pacific Institute**:** 69.

DeWalle, D. R., B. R. Swistock, T. E. Johnson and K. J. McGuire (2000). "Potential effects of climate change and urbanization on mean annual streamflow in the United States." Water Resources Research **36**(9): 2655–2664.

Dracup, J. A., S. Vicuna, R. Leonardson, L. Dale and M. Hanneman (2005). Climate Change and Water Supply Reliability. Sacramento, CA, California Energy Commission, PIER Energy- Related Environmental Research. CEC-500-2005-053.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund and R. E. Howitt (2003). "Economic-Engineering Optimization for California Water Management." Journal of Water Resources Planning and Management **129**(3): 155-164.

Duane, T. P. (1999). Shaping the Sierra: Nature, Culture, and Conflict in the Changing West. Berkeley, University of California Press.

DWR (2004). Bulletin 118 Update, California's Groundwater, San Joaquin Valley Groundwater Basin, Merced Subbasin. Sacramento, CA, Department of Water Resources, California Resources Agency.

Gleick, P. H., H. Cooley and D. Groves (2005). California Water 2030: An Efficient Future. Oakland, CA, Pacific Institute**:** 48.

Gleick, P. H., D. Haasz, C. Henges-Jeck, V. Srinivasan, G. Wolff, K. K. Cushing and A. Mann (2003). Waste Not, Want Not: The Potential for Urban Water Conservation in California. Oakland, CA, Pacific Institute**:** 176.

Groves, D. G. and R. J. Lempert (2007). "A new analytic method for finding policy-relevant scenarios." Global Environmental Change **17**(1): 73-85.

Groves, D. G., S. Matyac and T. Hawkins (2005). Quantified Scenarios of 2030 California Water Demand. Bulletin 160 California Water Plan Update 2005. Sacramento, CA, Department of Water Resources, California Resources Agency.

Hall, J., G. Fu and J. Lawry (2007). "Imprecise probabilities of climate change: aggregation of fuzzy scenarios and model uncertainties." Climatic Change **81**(3): 265-281.

Hashimoto, T., J. R. Stedinger and D. P. Loucks (1982). "Reliability, Resiliency, and Vulnerability Criteria for Water-Resource System Performance Evaluation." Water Resources Research **18**(1): 14-20.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan and J. H. Verville (2004). "Emissions pathways, climate change, and impacts on California." PNAS: 0404500101.

IPCC (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Joyce, B., S. Vicuna, L. Dale, J. Dracup, M. Hanemann and D. Purkey (2006). Climate Change Impacts on Water for Agriculture in California: A Case Study in the Sacramento Valley - FINAL REPORT. Sacramento, CA, CEC PIER.

Kallis, G., M. Kiparsky and R. Norgaard (2009). "Collaborative governance and adaptive management: Lessons from California's CALFED Water Program." Environmental Science & Policy **12**(6): 631-643.

Lach, D., H. Ingram and S. Rayner (2005). "Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations " Texas Law Review **83**: 2027-2053.

Landis, J. D. and M. Reilly (2003). How We Will Grow: Baseline Projections of the Growth of California's Urban Footprint through the Year 2100, Institute of Urban & Regional Development. IURD Working Paper Series.

Loucks, D. P. and E. Van Beek (2005). Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Paris, UNESCO.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier and B. Nijssen (2002). "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." Journal of Climate **15**(22): 3237-3251.

Norgaard, R. B., G. Kallis and M. Kiparsky (2009). "Collectively engaging complex socio-ecological systems: re-envisioning science, governance, and the California Delta " Environmental Science and Policy(This issue).

Pielke Sr., R., K. Beven, G. Brasseur, J. Calvert, M. Chahine, R. R. Dickerson, D. Entekhabi, E. Foufoula-Georgiou, Hoshin Gupta, V. Gupta, W. Krajewski, E. P. Krider, W. K. M. Lau, J. M.-. Nell, W. Rossow, J. Schaake, J. Smith, S. Sorooshian and E. Wood (2009). "Climate Change: The Need to Consider Human Forcings Besides Greenhouse Gases." Eos, Transactions of the AGU **90**(45).

Purkey, D., B. Joyce, S. Vicuna, M. Hanemann, L. Dale, D. Yates and J. Dracup (2008). "Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley." Climatic Change **87**(0): 109-122.

Rayner, S., D. Lach and H. Ingram (2005). "Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts." Climatic Change **69**(2 - 3): 197-227.

Sanstad, A. H., H. Johnson, N. Goldstein and G. Franco (2009). Long-run socioeconomic and demographic scenarios for California, Draft Report. Sacramento, CA, California Climate Change Center

Sax, J. L. (2002). "We Don't Do Groundwater: A Morsel of California Legal History." U. Denv. Water L. Rev. **6**: 269.

Seager, R., A. Tzanova and J. Nakamura (2009). "Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change&#42." Journal of Climate **22**(19): 5021-5045.

State Water Resources Control Board (2009). 20x2020 Water Conservation Plan Draft Final Report. Sacramento, CA, California Environmental Protection Agency.

Vicuna, S. and J. Dracup (2007). "The evolution of climate change impact studies on hydrology and water resources in California." Climatic Change **82**(3): 327-350.

Vicuna, S., E. P. Maurer, B. Joyce, J. A. Dracup and D. Purkey (2007). "The Sensitivity of California Water Resources to Climate Change Scenarios." Journal of the American Water Resources Association (JAWRA) **43**(2): 482-498. DOI: 410.1111/j.1752-1688.2007.00038.x.

Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers (2000). "Global water resources: Vulnerability from climate change acid population growth." Science **289**(5477): 284-288.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee (2005). "WEAP21 - A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics." Water International **30**(4): 487-500.

Young, C. A., M. I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J. F. Mount, V. K. Mehta, D. Purkey, J. H. Viers and D. Yates (2009). "Modeling the Hydrology of Climate Change in California's Sierra Nevada for Subwatershed Scale Adaptation." JAWRA Journal of the American Water Resources Association **45**(6): 1409-1423.

4 Chapter 4 - Quantifying risk preferences of water managers for an integrated assessment of future impacts on water supply

4.1 Overview of risk concepts

Because of the inherent uncertainties, climate change assessment and adaptation strategies are fundamentally about risk. As methods advance for incorporating probabilistic information into climate models, it is becoming increasingly clear that climate change impacts assessments need to move from deterministic approaches towards incorporating uncertainty and risk (Jones 2000; Dessai et al. 2007).

The importance of risk preferences, in particular risk aversion, is only recently beginning to receive attention in the context of climate change. Recently, the Stern Review employed an integrated assessment model which explicitly incorporated risk aversion for the global-scale economic assessment of climate impacts (Stern 2007), fueling an active debate about the importance of risk aversion (a preference for certainty in potential outcomes and the desire to manage events so as to reduce risk) (Nordhaus 2007; Stern and Taylor 2007; Anthoff et al. 2009).

The central notion is that a risk averse decision maker will evaluate uncertain quantities not on the basis of their expected value but rather by adding a risk factor (a risk premium) that serves to discount expected gains (raise expected losses) associated with the uncertainty (Chavas 2004). The risk premium is greater the larger the degree of risk aversion and the greater the magnitude of the uncertainty.

However, risk aversion alone does not adequately explain decision-making behavior. Another important feature of decision-making is loss aversion, the tendency for people to strongly prefer avoiding losses to acquiring gains, which has been described theoretically and empirically as different behavior above and below a defined threshold value (Fishburn 1977; Bawa 1978; Kahneman and Tversky 1979; Tversky and Kahneman 1992). Loss aversion, when combined with notions from expected utility theory, leads to the notion of downside risk: the potentially different treatment of risk above and below a threshold between perceived losses and perceived gains (Markowitz 1959; Fishburn 1977).

In spite of the acknowledged importance of risk aversion and loss aversion in decision making (Chavas 2004; Eeckhoudt et al. 2005), climate impacts assessments have not explicitly taken the risk preferences of public and private decision-makers into account in analysis of vulnerability and adaptation on regional and local scales. Assessments of impacts on water supply could benefit from more sophisticated risk analysis. Since human decision-makers have risk averse tendencies (Chavas 2004), incorporating risk preferences into models of impacts and responses may be a critical next step in understanding responses to a changing geophysical setting, both in terms of decision-making, as well as from the perspective of assessing broader social impacts and policies.

I describe here methods for incorporating risk into an integrated assessment of climate change impacts on water resources. In particular, I adapt methods based on expected utility theory and loss aversion (Abdellaoui et al. 2008), which have features salient for an initial investigation of risk in water resources under future uncertainties.

4.2 **Conceptual overview of the risk analysis**

4.2.1 Integrated Assessment modeling

Just as decision-making without estimates of uncertainty or risk amounts in effect to ignoring the uncertainty present in any model (Beven 2000; Oreskes 2003), impacts assessment that ignores the risk preferences of the decision-maker may misestimate the importance of an impact by producing biased impacts estimates. Since climate change and other future system-wide changes are inherently uncertain, and therefore inherently risky, risk preference, and in particular the risk aversion and loss aversion typical in most human decisions, needs to play a part in the estimates of the importance of future impacts.

The current chapter describes an effort to develop an empirically calibrated measure of risk aversion and loss aversion for an integrated assessment model of impacts on water supply in California's Central Valley. For context, Figure 2 and Figure 3 give a conceptual overview of the modeling in the entire integrated assessment, including work presented in other chapters. In brief, I built an integrated hydrology and water operations model of three basins in California's San Joaquin Valley, calibrated to available historical data on streamflow and water deliveries. I then examined the sensitivity of the model to downscaled GCM data, projections of population growth and land use change, and projections of urban water use efficiency. Each of these drivers of system behavior has a range of uncertainty derived individually and separately by running the model under multiple published scenarios. Please refer to previous chapters for details. The results of the modeling analyses described earlier are aggregated into probability distributions for water supplied to irrigation districts, and used in conjunction with methods described in the current chapter to estimate risk from climate and other uncertain drivers of system change.

4.2.2 Expected utility theory and risk aversion

4.2.2.1 Overview

The research described here focuses on a subset of risk analysis termed downside risk aversion or loss aversion, described in detail later in this paper. This section provides background on utility theory in general to contextualize the methods presented in this chapter (Chavas 2004; Eeckhoudt et al. 2005).

Expected utility theory provides a foundation for integrating decision-maker preferences into risk analysis. In essence, univariate expected utility takes the form

$$Eu(w) = \int u(w)p(w)dw \qquad \text{Equation 9}$$

with $u(w)$ the utility function over the random variable $\tilde{w}$ of interest, and $p(w)$ the probability distribution function of that random variable. Combining a utility function with the probability distribution of water supply and integrating gives the expected utility for a given agent under a given modeling scenario.

4.2.2.2 Characteristics of risk averse utility functions

An agent is risk-averse if he dislikes every lottery with an expected payoff of zero. That is, a risk-averse agent prefers receiving a given payout with certainty, rather than risking a lottery with a mean value of the same payout. Note that a risk-averse decision maker may choose to participate in a gamble if the expected payoff is high enough.

The degree of risk aversion is reflected by the concavity of the utility function,

$$A(w) = -u''(w)/u'(w), \qquad \text{Equation 10}$$

an approximation of the rate of decreasing marginal utility. Risk aversion is modeled by concave utility functions, where $A > 0$. Agents with a larger $A(w)$ will be less willing to accept small risks. $A(w)$ is also a measure of the degree of concavity of the utility function, or the speed at which marginal utility declines for the agent.

Note that modeling utility using this approximation requires a twice-differentiable utility function.

Conceptually, with decreasing marginal utility and a zero-mean lottery, a monetary gain at a given level of wealth has less value to an agent than an equivalent loss, when compared to the mean value received with certainty. The potential loss outweighs the potential gain, in spite of the fact that they have the same absolute value. By how much the potential loss outweighs the potential gain depends on the shape of the utility function.

Note that it is also possible for an agent to exhibit risk-loving behavior, that would be represented by a convex utility function, and behavior would be opposite – preference for lotteries, tendency not to diversify, etc. A special case would be a risk-neutral decision-maker, represented by an increasing linear utility function, who would chose lotteries by their expected payoff.

Decreasing Absolute Risk Aversion (DARA) is a way of describing how agents' perceptions of risk differ based on different initial levels of wealth. Intuitively, those with greater wealth stand to suffer fewer consequences from a given risk than those with less wealth, and thus could be expected to pay less to avoid the same risk. This is the concept of decreasing absolute risk aversion, which states that a risk premium is decreasing in wealth for agents with concave utility functions. Formally, it can be defined by comparing prudence

$$P(w) = -u'''(w)/u''(w) \qquad \text{Equation 11}$$

with risk aversion, such that DARA exists if

$$P(w) \geq A(w). \qquad \text{Equation 12}$$

Relative Risk Aversion is a unitless measure, defined as the rate of decreasing marginal utility with one percent increase in wealth. Relative risk aversion is simply the product of wealth and absolute risk aversion,

$$R(w) = wA(w). \qquad \text{Equation 13}$$

Analogous to the Arrow-Pratt risk premium discussed below, relative risk premium measures the share of initial wealth an agent is willing to give up to avoid a given risk,

$$\hat{\Pi}(z_l) = \frac{\Pi(wz_l)}{w} \cong \tfrac{1}{2}\sigma^2 R(w). \qquad \text{Equation 14}$$

This models the idea that if two agents have the same initial wealth, the more risk averse of the two would pay more to avoid a given *proportional* risk (proportional to the total wealth of each agent, respectively). This is a less clearly defensible or intuitive proposition than DARA, and experiments offer conflicting conclusions. Also, intuitively there are two conflicting ideas at play. Under DARA, as one becomes wealthier, one becomes less risk averse. However, as one becomes wealthier, a given proportional risk becomes a greater absolute risk, wz_l, thus increasing absolute risk aversion, Π. It is not clear theoretically or empirically which of these two effects will dominate.

4.2.2.3 Motivation for incorporating risk

Many risk analyses do not include decision maker risk preferences. When a probability distribution is collapsed to an expected value without invoking an explicit utility function, it is equivalent to invoking a linear utility function. Doing so implicitly assigns a 'risk neutral' preference to the decision maker, an assumption that does not jibe with empirical studies of human decisions under uncertainty.

The overarching goal of this research is a comparison of the sensitivity of expected utility to multiple future scenarios of system change, which will enable me to bring a measure of risk aversion into an impacts analysis. To do so I invoke expected utility with risk aversion and loss aversion as described below.

4.3 **Theory of loss aversion**

Although the definitions of risk in classical expected utility measures described above encompass uncertainty across the entire domain of the distribution of possible outcomes, in practice, decision-makers often view risk differently on the domain of negative outcomes (Fishburn 1977; Laughhunn et al. 1980; Laughhunn et al. 1983). Theories to account for this non-uniform behavior invoke the concepts of loss aversion and downside risk.

In this section, I describe theories of loss aversion that have been developed to account for different behavior above and below given 'thresholds' of returns, and then describe the elicitation method that I used to estimate risk preferences for water managers.

Much of the theory for decision-making under risk has been developed in the literature on finance (Bernstein 1996), although techniques have been developed to apply and extend these concepts in evaluating a broad range of decisions (Keeny and Raiffa 1993). I describe some of the concepts below in terms of its original applications to give context to my efforts to adapt downside risk aversion for water resources under climate change.

As reviewed by Nawrocki (1999), portfolio theory essentially began with Markowitz's (Markowitz 1952) groundbreaking framework to quantify risk in financial portfolio management. Markowitz's initial method used historical mean returns, variances, and covariances to develop an "efficient frontier," the set of asset combinations that maximize return for a given variance, or minimize variance for a given return.

This was later extended based on two seminal ideas. First, 'safety first' describes the idea that investors would want to protect principal at a target return in their investing (Roy 1952). Second, variance measures of risk apply only when returns are normally distributed, a special condition not often applicable in financial markets (nor in hydrologic systems). Markowitz (1959) developed a method for estimating downside risk that takes both into account by using only part of the variance (the partial variance or semivariance).

Markowitz (1959) described two metrics for downside risk. First, below-mean semivariance uses the mean of the expected return as the reference point for downside risk.

$$R_{SVm}(x) = \int_{-\infty}^{t} (\bar{x} - x)^2 \, dF(x) \qquad \text{Equation 15}$$

Second, the mean-target semivariance model allows comparison of investments based on the conception of risk as exposure to losses below a specified level.

$$R_{SVt}(x) = \int_{-\infty}^{t} (t - x)^2 \, dF(x) \qquad \text{Equation 16}$$

Both measures reflect the concept of downside risk, or loss aversion. Although strictly speaking risk involves the chances of both desirable and undesirable outcomes, investors frequently equate the concept of risk not only with the consequences of low returns, but with the consequences of failing to achieve a target return. If this is the case (and *a priori* one would expect so in water resources), then using measures such as the mean that change from distribution to distribution is questionable for representing actual decision-maker preferences.

Fishburn (1977) generalized this concept of loss aversion to include different risk preferences by describing a more general theory, termed the $\alpha - t$ model.

$$R_{\alpha}(x) = \int_{-\infty}^{t} (t - x)^{\alpha} \, dF(x), \alpha > 0 \qquad \text{Equation 17}$$

with *F(x)* the cumulative distribution function for the probability of getting a return not exceeding *x*. Fishburn's formulation requires specification of two parameters. *t* is the target return level below which the decision-maker exhibits a risk preference specified by α. Conceptually, Fishburn recognized that Markowitz's mean-target semivariance model implies a specific level of risk aversion with α= 2. Varying α from this special case enables representation of either risk neutral (α= 1; linear utility function), risk seeking (α< 1; convex utility function) or risk averse ($\alpha > 1$; concave utility function) preferences on uncertain returns below *t*, based on its weighting of returns below the target return. Empirical studies have demonstrated discontinuities in utility functions (e.g. Laughhunn et al. 1980; Payne et al. 1980; Laughhunn et al. 1983). Such discontinuity in utility function has been described as an important feature of decision-making (Kahneman and Tversky 1979; Tversky and Kahneman 1992), and I argue below that it applies to this water resources case study.

4.4 **Units of analysis**

4.4.1 Local vs. global risk analysis

The importance of risk aversion in climate impacts assessment has recently been recognized, and researchers have begun to incorporate risk into global-scale climate impacts analysis using estimated risk parameters (Stern 2007; Anthoff et al. 2009). In contrast to such aggregated economic damage estimates, the present study focuses at the granularity of the actual decision-maker, effectively introducing risk into an integrated impacts analysis at a level to the far right in the conceptual model in Figure 2.

It is important to note that I conceptualize the present risk analysis similarly to such global analyses. Risk analysis techniques were developed in part for a normative framework, that is, to aid in an actual decisions (e.g. what investment mix to choose, or what infrastructure to invest in). While the techniques I present here could (and will in future work) be used in decision-making for water systems (Figure 56, left side), this dissertation uses them in the spirit of the integrated assessments cited above (Figure 56, right side) (Stern 2007; Anthoff et al. 2009). However, this dissertation integrates across scales, as conceptualized in Figure 57.

In essence, risk preferences are used here to weight uncertain potential impacts resulting from changes exogenous to the systems considered, in order to inform larger questions about the impacts of environmental stressors. While the water managers I interviewed do not themselves make decisions materially pertinent to climate change or population growth, they will live with and work with the future consequences of these changes. Thus, their attitudes towards risk should be reflected in state, national and global politics that will influence of future social and environmental conditions, regardless of whether they have agency over the probability distributions of the eventual outcomes. The present research is an attempt to formalize this integration of the decision maker risk preferences into analysis of climate impacts.

4.4.2 Institutions

Social scientists have observed that U.S. water organizations are conservative and risk averse (Haddad 1999; Lach et al. 2005). Such organizations tend to make marginal and incremental change even in situations where more fundamental legal, technical, and behavioral innovation are warranted because of institutional conservatism (Rayner et al. 2005), although perceptions of acute risk can motivate action such as the use of weather forecasts (O'Connor et al. 2005). However, these observations and their implications have not been empirically demonstrated in a formal risk analysis setting.

Risk assessment combines probabilistic estimates of impacts with the consequences to given agents, but the definition of ‘risk’ depends on the context. The focus of this study is water users in the southern Central Valley of California, in particular a selection of Irrigation Districts and urban areas within the case study basins.[17] The different water users have different potential responses to disruptions in water supply. They face different economic costs and have different tolerances for risk, and therefore different risk premiums.

For initial case studies, I have chosen Irrigation Districts (IDs), as they play a large role in allocation of water in California and other regions of the world (Thompson Jr. 1993). Water organizations are increasingly important decision-making bodies in California, and studying their responses to future risk will allow representation of institutionally meaningful adaptive mechanisms such as interbasin transfers and coordination.

Within these IDs, I interviewed representatives responsible for substantial decision-making and operations, and used their responses to generate risk preferences reflective of overall decision-making by each organization. The IDs' own risk preference will reflect (perhaps with some weighting) the interests of the various users within the service area. Note that while individual farmers and water users are ultimately the ones exposed to the consequences of water supply shortfalls, organizations are still a logical unit of analysis because they are responsible for making management decisions, their decision makers are accountable to poor performance, and the performance of an ID as a whole aggregates the individual risk to farmers within that district.

4.4.3 What water when and where?

I use total annual diversions from the river as the base unit on which utility is calculated. However, there exist spatial and temporal considerations in a choice of a metric for water supply in the present system, as well as important considerations of tractability.

The choice of river diversions as a metric for surface water is congruent with the unit of analysis (the Irrigation District) and the primary metric (water deliveries) for the decision makers (District water managers). Temporally, annual data were used for simplicity and to keep the length of elicitations reasonable to avoid potential fatigue of informants. In terms of tractability, historical data are important for model calibration as well as developing the historical or prior distributions for water supply reliability. Such data are available for most of the Irrigation Districts in this study only at the diversion points on the river where water is diverted into district canal(s) for delivery to water users. It is at this point where each district's surface water diversion right is measured, lending coherence with the legal constraints on and definition of water supply in this system, and providing a coherent legal upper bound on water diversions, both in terms of historical distribution and future expectation. In keeping with the data limitations mentioned above, model calibration was also anchored by the available data, and thus may be more accurate than intra-district metrics for deliveries (see the Chapter 2 for details).

In future, the methods described in this dissertation could be scaled spatially for use on individual farms, with farmers rather than water managers as the relevant decision makers, although much more detailed modeling would be required.

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[17] These include both agricultural and urban water users, users of hydropower, and environmental stakeholders, as well as the management of the water districts supplying these uses that face strong incentives to be responsive to the districts' customer base and regulations.

Developing monthly or seasonal utility functions for water deliveries could be investigated in future work. It would be logical to do this as a second stage of research, with motivated decision makers who were primed for lengthy, detailed elicitations.

4.4.4 Some key differences in water

As mentioned above, much of the theoretical and empirical literature on risk has been developed in the context of finance. Decisions involving money, whether they are for personal or managerial purposes, may differ from decisions about water supply.

One way to conceptualize this is that the relationships between ‘stocks’ and ‘flows’ of money and water are different. Flows by necessity dominate the water problem, while in some cases accumulation of stocks of money can be the goal for utility. While money can be ‘stored’ without practical limit in time or amount in investments or bank accounts, storage for water is limited to the available space in surface water (and sometimes groundwater banks), and each form of storage may involve ‘depreciation’ of the water asset (e.g. through evaporation or groundwater seepage). The annual flows of water ‘through’ a system, and in particular the reliability of these flows, are necessarily the concern of water managers, rather than any potential for long-term accumulation. Water is also less fungible than money, because of its physical limitations. In many water systems, conveyance capacity is a limiting factor in water management, related to the dominance of flows over stocks. Even where this is not the case, institutional constraints on water transfers can limit the use of water spatially and temporally.

One of the ways in which these aspects of water might affect the utility functions for water is in their non-monotonicity. In particular, at some point, more water delivered during a year stops having more value to a water manager, either because their demands are satisfied, their water right has been filled, or even because too much water can lead to flooding.

4.4.5 Characteristics of water

I invoke expected utility theory for the purpose of evaluating water supply risk. Water managers are the relevant decision makers, and probability distributions for water supply are derived from modeling of exogenous impacts including climate change. To generate utility functions for managers, I adapt the method of Abdellaoui et al. (2008), which enables estimation of a discontinuous utility function and loss aversion. Related methods have been used in decision analysis in a wide variety of contexts (Keeny and Raiffa 1993), including natural resources (Stewart and Scott 1995; Hobbs et al. 1997; McDaniels et al. 2006; Mendoza and Martins 2006), but to my knowledge downside risk has not been applied to water resources problems, and the economic conception of risk has not yet been commonly integrated into local scale climate change impacts analysis.

I focus on loss aversion, the desire to avoid returns below a target threshold. However, it is worth noting some interesting aspects of water resources for future exploration. If one were to construct a representative utility function for water supplied, it would ideally be multivariate. For example, even water managers focused on water supply for irrigation will consider at a minimum the carryover storage available for next year’s crops in their decisions, and many will also take into account differing priorities such as urban uses, managing groundwater levels, seasonal timing of water demands, possibilities for short-term water transfers, and so forth. Such a utility function would also be non-monotonic. For example, above a certain capacity defined by conveyance and storage capacity, soil water absorption capacities, hydrology, geomorphology, development, and so on, additional water ‘deliveries’ result in flooding, which would not be preferred by a decision maker. Thus, a utility function might have a break point at some threshold where full deliveries with full carryover storage turn into flood damage, resulting in sharply decreased utility. Other discontinuities might occur during drought conditions.

My study focuses on water supply risk, and does not address flood risk. In water resources modeling, flood risk and water supply risk are often most effectively treated with separate approaches, given the fundamentally different nature of the problems in terms of spatial and temporal granularity of the relevant physical processes. While I acknowledge that both the utility functions for damage, and the probability distributions for potential flood events will likely change for California as a result of both climate change (Dettinger et al. 2009) and land use change, a study involving different types of modeling and a different set of decision-makers would be better suited to estimating flood risk with the present framework.

4.5 **Representing the utility of water**

I treat the non-monotonicity, discontinuity, and possible context-dependence of managers’ utility functions described above by developing a three-part, conditional utility function.

Utility functions were elicited using a method modified from Abdelaoui et al. (2008). The essential characteristics of the method are well suited for my purposes. It includes the ability to describe a discontinuity in a utility function based on a threshold value, and thus to reflect and measure loss aversion. The utility functions can be fitted in any functional form above and below the threshold, and can reflect risk aversion, risk neutrality, or risk seeking behavior. The method is relatively efficient, requiring fewer elicitations of certainty equivalents than other methods. And the method enables congruence with either expected utility or with prospect theory, of which I invoke the former.

4.5.1 Conditionality and context dependence of utility function

In elicitations of utility functions, context matters (Hershey and Schoemaker 1980; Hershey et al. 1982; Yaqub et al. 2009). Common formulations of expected utility for monetary wealth can be framed as questions of final wealth (which can be thought of as a stock quantity) or in terms of the results of discrete gambles (which can be thought of as flow quantities).

Water supply differs from monetary wealth in part because there is an upper limit on the total amount attainable at any one time, set by the physical and operational limits on surface water storage plus any groundwater storage. In California’s Mediterranean climate, with its annual cycle of wet winters followed by dry summers and high demand periods, any annual maximum water storage state, is inevitably followed by a decline in storage as water is released to meet demands.

Decision maker risk preferences for surface water supplies may also be sensitive to other opportunities for supply (e.g. groundwater) as well as other uses for supply (e.g. carryover storage). While such tradeoffs can be incorporated using multi-attribute risk in future work, I used a conditional approach using the main driver of change for a suite of such other attributes, namely the preceding year types.

One of they key elements of the context-dependence of water is the embeddedness of the irrigation districts modeled here within larger economic, social, climatic and hydrologic systems. In particular, managers may value water differently under drought. A central reason for this is the existence of groundwater as an additional water supply. However, in addition to long-term overdraft (Faunt 2009; Ho et al. 2009) groundwater supply can be impacted by drought on shorter time scales. Increased pumping in response to decreased surface water availability can case declines in water tables, increasing pumping costs and impacting the productivity of wells.

Managers may have a different view of their surface water sources during long droughts, and that this may be reflected in their utility functions. While I do not address this in this dissertation, I acknowledge this important aspect of situational context in water resources and incorporate potential changes in manager behavior. Future work will incorporate conditional utility functions

$$u(x; c_i)$$

with x the annual water diversions, and c_i a water year class metric incorporating previous years' conditions, with $i = 1,\dots,n$ for n year classes defined based on conversations with managers. I have not tested this method in the first round of elicitations, and thus $i=1$ for a normal year in the results that follow.

In future elicitations, I will define $i=1,2$ separate year type scenarios based on a combination of historical data analysis and conversation with managers. The first year type will be described to the respondent as a "Normal" year condition, following a string of five normal years. The intent is to evoke conditions in which surface water has been plentiful, with attendant implications for better groundwater availability after a period with low pressure on local groundwater use and conditions with groundwater recharge. The second year type comes after a multi-year drought, with the attendant impacts on groundwater as an alternative water source. The length of the drought used for each scenario is defined in conversation with the manager before either elicitation begins. The goal will be to determine a level of drought beyond which managers would typically expect to see substantial changes in aspects of their water system such as carryover storage, groundwater pumping, and declining aquifers. The *a priori* expectation is that protracted drought conditions would change the context within for surface water diversions such that managers' utility functions for surface water $u(x)$ will differ from normal years. I will repeated the elicitation protocol once for each scenario to explore the sensitivity of elicited utility functions to antecedent water system conditions. Expected utility can then calculated based on a conditional representation of year class in historical or modeled output. The present iteration of this method does not include such conditionality.

4.5.2 Utility and loss aversion

Below, I use the notation $(x, p; y)$, which refers to a gamble between outcome x with probability p, and outcome y with probability $1-p$. A 50-50 gamble between x and y is abbreviated as (x, y). A preference comparison between gamble (x,p,y) and sure outcome w is signified as $(x,p,y)\underline{R}\, w$. The decision maker is presented with the choice, and asked to specify their preference relation R as $\succ$, $\prec$, or $\sim$. For example, $a \succ b$ symbolized "a is preferred to b", and $a \sim b$ symbolizes 'decision maker is indifferent in a choice between a and b'.

Loss aversion can be defined in reduced form as the difference in slope between the utility functions above and below a threshold value representing a break-even point. One way to represent this is by the difference in the change in utility a given distance above and below the threshold value, which can be expressed as a loss aversion coefficient $-U(-x)/U(x) \geq 1$ over the relevant range of x (Kahneman and Tversky 1979).

Describing loss aversion requires defining a target or threshold level t below which the decision maker perceives a loss. Fishburn (1977) notes that, "Depending on context and the circumstances of the decision maker or his firm, t might be formulated as a ruinous return, as the zero profit return, as the return available from an insured safe investment, or as a target which reflects a general attitude towards acceptable performance in the firm." In a system dominated by flows, as described above, there may be no 'natural' threshold value that defines losses. This contrasts to a situation in which a monetary gamble is presented with possibilities for gains and losses, with the subject's pre-existing wealth set as the implicit threshold (Payne et al. 1980; Payne et al. 1981; Abdellaoui et al. 2008).

In one of a seminal series of experimental demonstrations of loss aversion and downside risk Payne et al. (1981) defined target values *for* their respondents, by telling them that in the hypothetical exercise they would be judged by their superiors on their success at returns above a given threshold level, and eliciting a downside risk aversion parameter (Fishburn 1977) given this scenario.

The present method adds an elicitation of the respondent's threshold value to the elicitation itself. While there may be uncertainty in this subjective value, setting a threshold value based on the user preferences is not without precedent, and allows the opportunity for the decision maker to express a discontinuity in their utility function consistent with loss aversion.

Three elicitations are then conducted to characterize the user's utility function over water; one on the domain above a 'threshold' value, one on the domain below it, and one across the threshold.

In the terminology of Abellaoui et al. (2008), loss aversion is represented in the current method as a composition of a loss aversion coefficient λ and a basic utility u that reflects the decision maker's preferences for outcomes. I normalize the utility function given the non-zero threshold value, as described below.

$$U(x) = \left\{ \begin{array}{l} u(x)\ if\ \ x \geq 0 \\ \lambda u(x)\ if\ \ x < 0 \end{array} \right\}.$$

Equation 18

For the component utility functions, I chose to use a commonly invoked power function such that

$$u(x) = (x - t)^{\alpha},\ for\ r \geq x > t\ (gains)$$

Equation 19

$$u(x) = -(-(t - x)^{\beta},\ for\ x < t\ (losses)$$

Equation 20

$$u(x) = (r - t)^{\alpha},\ for\ x > r\ (above\ water\ right)\cdot$$

Equation 21

For $x \leq r$, the utility function was elicited from district representatives as outlined below. As a district cannot legally divert additional water above its water right *r* in a given year, I modeled their utility as having a zero slope above this value. As discussed elsewhere in this chapter, I leave examination of the potential disutility of flood risk for future work.

Although the method of Abdelloaui et al. (2008) allows for estimation of probability weighting functions above ($\delta^{+} = w^{+}(p_g)$) and below ($\delta^{-} = w^{-}(p_l)$) the threshold value to enable representation of decision maker preferences under prospect theory, I choose to follow the special case of congruence with expected utility, and use a single probability for the elicitation, such that

$$w(p_g) = w(p_l) = p_g = 1 - p_l = 0.5. \qquad \text{Equation 22}$$

Expected utility for the domain above and below the threshold is

$$u(G_i) = \delta^{+}(u(x_i) - u(y_i)) + u(y_i),\ for\ x > t \qquad \text{Equation 23}$$

$$u(L_i) = \delta^{-}(u(x_i) - u(y_i)) + u(y_i),\ for\ x < t \qquad \text{Equation 24}$$

Accordingly,

$$G_i = u^{-1}(\delta^{+}(u(x_i) - u(y_i)) + u(y_i)) \qquad \text{Equation 25}$$

$$L_i = u^{-1}(\delta^{-}(u(x_i) - u(y_i)) + u(y_i)). \qquad \text{Equation 26}$$

I choose to represent the utility function above and below the threshold with a commonly used power function $u(x) = (x)^{\alpha}$ (Abdellaoui et al. 2008), adjusted to take into account the threshold value,

$$u(x) = (x - t)^{\alpha}\ \ for\ x > t \qquad \text{Equation 27}$$

$$u(x) = -(t - x)^{\beta}\ \ for\ x < t. \qquad \text{Equation 28}$$

Thus, the α and β parameters can be estimated using nonlinear least squares with

$$G_i = (\delta^{+}((x_i - t)^{\alpha} - (y_i - t)^{\alpha}) + (y_i - t)^{\alpha})^{1/\alpha} \qquad \text{Equation 29}$$

$$L_i = (\delta^{-}((t - y_i)^{\beta} - (t - x_i)^{\beta}) - (t - y_i)^{\beta})^{1/\beta}. \qquad \text{Equation 30}$$

The above equations can be used to estimate utility separately above and below *t*. To connect the utility above and below the threshold and find the loss aversion coefficient, a value G^* from $(t,r]$ is selected, enabling determination of the value $L^* < t$ for which $t \sim (G^*, p_g; L^*)$ through an additional elicitation. Then,

$$\delta^{+}u(G^{*}) + \delta^{-}\lambda u(L^{*}) = u(t) = 0 \qquad \text{Equation 31}$$

can be used to determine the loss aversion coefficient λ, with $\lambda > 1$ indicating loss aversion, and $\lambda < 1$ indicating gain seeking.

4.6 **Elicitation method**

To elicit the utility functions described above, I further adapted the method of Abdellaoui et al. (2008). My procedure uses a semi-structured interview coupled with a computer-based choice experiment, and follows a four-step procedure to elicit values necessary to estimate the following: 1) the domain of perceived potential deliveries bounded by *l* and *r*, and a threshold value, *t*, and, using the equations described above, 2) *u(x)* above the threshold, 3) *u(x)* below the threshold, and 4) a loss aversion coefficient across the threshold. Elicitations were carried out in this order, with questions ordered semi-randomly within each group, and a random subset repeated for consistency.

For the elicitation, I assumed that risk can be expressed as a univariate function on annual surface water diversions *x* (in acre-feet) to a decision maker's district. This simplifying assumption could be explored in future work through multi-attribute decision analysis techniques, as discussed above.

The method provides for estimation of several parameters relevant to prospect theory (Kahneman and Tversky 1979). I assume congruence with expected utility theory, and thus estimate only a single parameter for the utility function above and below the threshold, thus setting the probability weighting functions $w^{+}(p)=w^{-}(p) = p$.

The following elicitations were carried out using an interactive computer program that enabled collection of data using the bisection method described below. Each elicitation took < 1 hour, including background discussion. Additional discussions with managers about details of their systems were carried out afterwards or at other times.

4.6.1 Boundaries of the domains

I elicited a threshold value *t* from decision-makers, below which the decision-maker feels they are 'behind the game' and above which they feel they are fulfilling their mission. Given the nature of water management as described above, this value is necessarily heuristic and subjective, and will involve some uncertainty. The upper support for the distribution of water deliveries is the maximum annual diversion *r* based on the Irrigation District's water right. The lower support for the distribution, *l*, is defined as the smallest amount of deliveries a manager views as within the realm of possibilities. These judgments are typically made given a discussion of historical records and other information they possess. While acknowledging that an assumption of stationarity has been challenged in the literature, I chose to set the lower support for the distribution to ensure that only values that 'make sense' to the mangers are presented in the elicitations.

I elicited *t, r,* and *l* from decision makers in a semi-structured conversation, with the *a priori* expectation that the value for *t* will be at or near the average 'normal' year delivery of surface water for each case study.

4.6.2 Elicitation of utility above the threshold value

The basic utility function above the threshold value was elicited using six certainty equivalents with a bisection scheme (Abdellaoui et al. 2008). The values presented to the decision-maker were calculated using a computer program, with initial parameters set through elicitation and assignment of *t* and *r* during semi-structured interviews. The set of questions defined in Table 34 enables coverage of preferences covering the range of *(r,t]*.

Each certainty equivalent is found using a bisection method described by Abdellaoui et al. (2008), again modified for the non-zero threshold. For each of the certainty equivalents, five choices are posed to the respondent. The first certain choice is equal to the expected value of the lottery (e.g. for G_1, the first choice for *G* is calculated as $(t+(r-t)*.2)*p_g + t*p_g)$. Values for the subsequent three choices decrease in a given step if the previous certain choice was selected, and decrease in a given step if the previous lottery was selected, thus narrowing towards a range within which lies the elicited certainty equivalent. Each step changes the value by ½ the absolute value of the previous change. The result is a range bracketing the CE, and the midpoint of this range is selected as the final G_i. I selected the number of choices based on diminishing benefits of apparent precision, as smaller changes in certainty equivalents become progressively less meaningful for managers.

G_i, $i=1,..,6$ were elicited in semi-random order; I biased the initial loss elicitations towards smaller deviations from the threshold (e.g., L_1) , as the larger deviations (e.g., L_6) were perceived as more difficult by respondents. I selected $p_g = 0.5$ for all interviews. All numbers presented are rounded off to the nearest thousand AF.

4.6.3 Elicitation of utility below the threshold value

Utility of water below t was estimated with a similar bisection method, using the six elicitations shows in Table 35 to find the certainty equivalents L_i, $i=1,...,6$. The method mirrors the generation of elicitations above *t*, but takes into account the lower support of the distribution as described in section 4.6.1.

4.6.4 Elicitation of loss aversion coefficient

Loss aversion is estimated by an elicitation linking utility above and below the threshold. I select three values G* on (t,r], and determine $L^*<t$ for which $(G^*,P_g;\, L^*)\sim t$. Then,

$$\delta^{+}u(G^{*}) + \delta^{-}\lambda u(L^{*}) = u(t) = 0 \qquad \text{Equation 32}$$

Previous estimates for all values save λ result from the previous elicitations, and thus the loss aversion coefficient results from this single elicitation. Three values are compared for consistency. Both loss aversion ($\lambda > 1$) and gain seeking ($\lambda < 1$) can result.

4.6.5 Maximum utility of water supply

For each Irrigation District, the maximum annual water right forms the upper boundary r on the domain of x, capping the maximum utility in a given year. Water rights were obtained through the State Water Resources Control Board (State Water Resources Control Board 2009) and in conversation with managers.

4.6.6 Analysis

Each interview yielded, for each year type, six certainty equivalents above the threshold, six below the threshold, and three estimates of the loss aversion coefficient. Nonlinear least squares were used to fit utility functions from the power family to the equations described in Section 4.5.2. The resulting data enable estimation of risk preferences above and below the threshold value, as well as a coefficient of loss aversion.

I assume consistency with expected utility, and thus that $w^{+}(p)=w^{-}(p) = p$. I justify this assumption based on the population surveyed. Water managers are generally quantitatively able as trained civil engineers with hydrology backgrounds. Moreover, their years of experience taking a probabilistic view of hydrology and water supply gives them greater comfort with probabilities in their system, and with the elicitation procedure. These factors likely differentiate the population in this study from either student or business managers commonly the subjects of elicitations in the financial literature.

4.7 **Elicitation protocol**

The elicitation began with a semi-structured interview. Topics included the respondent's current responsibilities and relevant experience; details about the water system(s) in question; and a discussion designed to elicit l, t, and r.

I then presented the elicitations described above to respondents, using an interactive computer program to generate choices and collect response data. I first verbally described the concept of elicitations, and discussed the procedure with each respondent, including an example.

4.8 **Elicitation results**

For this dissertation, I invoked the methods described above on two water managers in the basins of interest.[18] The goals for the exercise were to verify that my translation of these decision-analysis techniques from a financial to a water resources context functioned reasonably and functioned well within the world-view of water managers, and to elicit utility functions for use in the integrated assessment described in the next chapter of this dissertation.

Below, the method is shown to produce results qualitatively in line with a priori expectations. Further work can increase the sample size, move to comparative questions, and extend the work to classes of water resources managers with primary concerns different from water supply.

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[18] Manger A in this study was chosen for participation based on his broad familiarity with the study area. His unique experience in decision-making roles in both the Stanislaus and Merced Basins provided an excellent opportunity to pilot the method. However, results presented here should not be taken as directly indicative of current decision makers risk preferences. Future work will attempt to elicit a complete suite of utility functions from relevant current decision makers in all basins of interest.

4.8.1 *Qualitative results: Decision-maker reactions*

In this initial use of the method, I conducted both passive observation and active questioning at several stages of the process, to gage whether any strongly negative reactions existed either to the semi-structured interviews or to the computer-based elicitations.

The elicitations were straightforward. Background discussion yielded useful context, and seemed to establish a common framework for discussion. Values for r and l emerged readily from discussion, as expected. A value for t required a longer exchange. In some cases, the initial value for t was agreed on, and then revised after experience with the first few computer elicitation questions, and subsequent discussion, helped clarify the manager's preferences. Managers seemed to more readily grasp, internalize, and embrace the concept of the threshold value after seeing one to several elicitation examples. In these cases, the computer elicitation parameters were reset at this point and the elicitation re-started.

I gauged managers' understanding and willingness to continue at each point. They indicated that the choices were interesting, meaningful to them, and that their experience thinking about these metrics for water supply made the elicitation questions interesting, challenging, and relevant. Both were very willing to continue on to a second elicitation, and indicated no undue cognitive burden when given the opportunity to move on to other questions instead.

Managers reported that the elicitation procedure itself made sense to them, and that they were comfortable with the questions posed. They reported between elicitations that the procedure was reasonable and not taxing, indicating also that the sorts of questions posed were very familiar to them in their professional life. As experts intimately familiar with how the tradeoffs in different water levels might affect their jobs, and used to thinking about such questions on a regular basis, they may have less cognitive burden from these elicitations than laypeople exposed to such methods for the first time.

Managers comments and asides during the quantitative part were illustrative as well, suggesting that they realized they were making risk averse choices. Language such as "Yep, I'd take the water," indicated awareness or self-consciousness about making such risk averse choices. Spontaneous discussion of the substantial pressure from water users and board members ("…they expect you to make it rain") validated the conceptual model of managers as integrating risk preferences of water users.

4.8.2 *Quantified results: loss aversion and risk aversion*

Data from elicitations for water supply (Table 36) reveals strong risk aversion above ($\alpha < 1$) and below ($\beta > 1$) the threshold, although within the range reported by others using similar methods (Abdellaoui et al. 2008). This is in keeping with *a priori* expectations as described elsewhere in this dissertation. Results for loss aversion, as estimated by elicitations bridging the domains of gains and losses to produce the loss aversion coefficient lambda, are many orders of magnitude higher than previous work using related methods (Abdellaoui et al. 2008). This result stems directly from greater downside risk aversion relative to the risk aversion on the domain of gains. Figure 58 and Figure 59 illustrate this point dramatically: the risk aversion estimates above and below the threshold are so dissimilar that they cannot be compared visually on a single figure.

In the single elicitation conducted for carryover storage, interestingly, the results are reversed (Table 37). This result could be interpreted in light of the fact that carryover storage, while desirable and important for mangers, is ultimately of secondary importance when compared to the primary goal of deliveries. Thus, managers may feel more comfortable with the potential for 'losses' in the form of lower storage going in to the next water year, since the next year's deliveries will be only partly a function of this attribute. Importantly, the difference in results for water supply and carryover storage suggests that future work taking into account a multi-attribute risk framework could produce a more robust framework for decision analytics. This result will need to be explored with a larger sample.

4.9 **Conclusion**

I have presented a concept and method for estimating the impacts of decision-maker risk preferences, and combining those data with modeled output to determine risk-adjusted estimates of climate change impacts on water supply reliability.

The method draws on the concepts of expected utility and loss aversion, adapting Abdellaoui et al.'s (2008) method for elicitation of utility functions to a water resources context. The additional features of this method are estimates of utility conditional on drought conditions, a cap on utility based on maximum diversions allowed by water rights, and a non-zero threshold value.

Utility functions defined by this method include strong tendencies for risk aversion both above and below the threshold as well as downside loss aversion. In the small sample presented, the results are qualitatively in line with *a priori* expectations for water managers, but of greater magnitude than those described in empirical studies.

In Chapter 5, I will describe the use of these data in an impacts analysis integrating decision-maker preferences, using probability distributions of both historical and modeled future water deliveries to get comparative estimates of water supply risk.

4.10 **Figures**

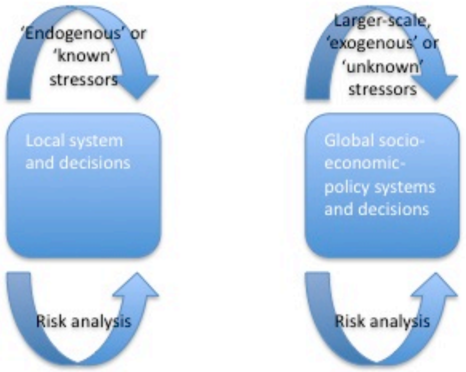

Figure 56: Conceptual model of the distinction between two types of local risk analysis (left) and global aggregated risk analysis (right), describing scale-distinct risk analysis, such as those described in the literature review, each of which considers familiar stressors defined at the local or global scale, respectively, and with risk analysis information feeding into decisions at the same scale.

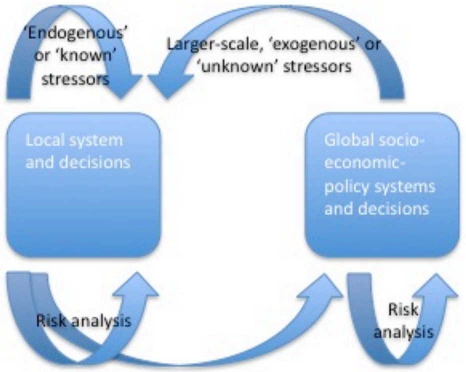

Figure 57: Conceptual model of an integrated risk analysis such as the one in this dissertation, which draws from global and local sources of uncertainty, and provides information to decisions on both local and global scales.

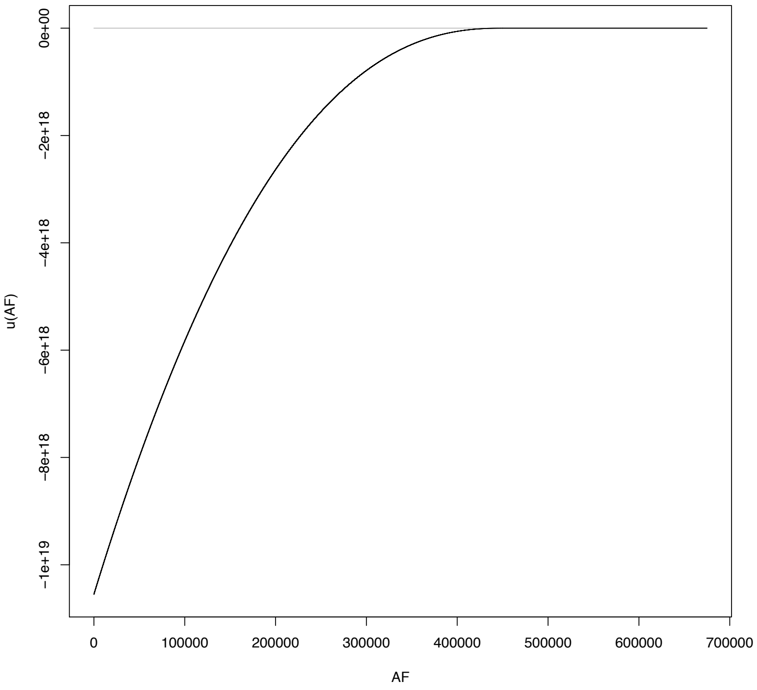

Figure 58: Utility function on the entire domain of annual deliveries for Manager A. Plot reflects high levels of downside risk aversion and loss aversion.

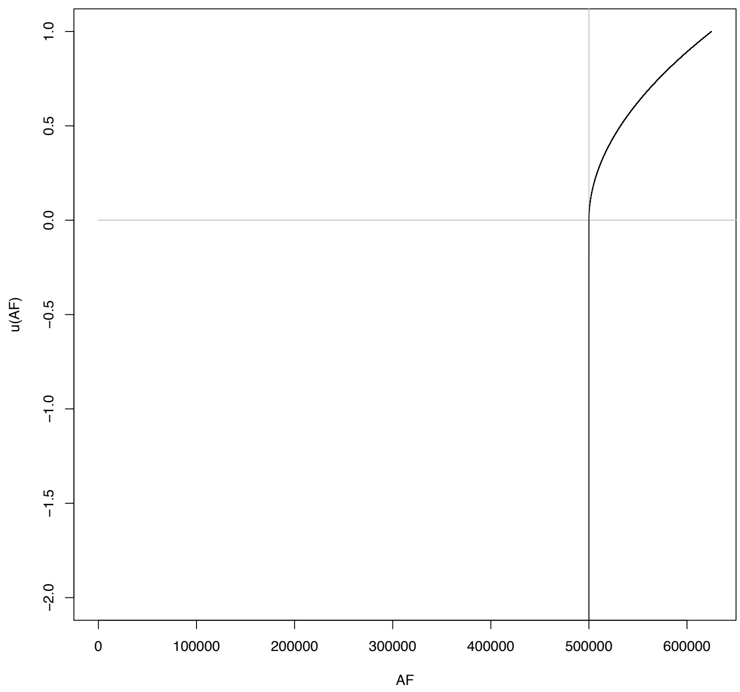

Figure 59: Utility function for Manger A over annual water deliveries, truncated to show the utility function above the threshold value. The manager's elicitation, as reflected in the coefficients for the exponential utility functions above and below the threshold, indicates a risk averse utility function between *t* and *r*, and loss aversion strong enough that it makes the utility functions visually incomparable.

4.11 **Tables**

$G_1 \sim (t+(r-t)*.2, p_g, t)$
$G_2 \sim (t+(r-t)*.4, p_g, t)$
$G_3 \sim (t+(r-t)*.6, p_g, t)$
$G_4 \sim (r, p_g, t)$
$G_5 \sim (r, p_g, t+(r-t)*.6)$
$G_6 \sim (r, p_g, t+(r-t)*.8)$

Table 34: Certainty equivalents elicited for the domain between the threshold value *t* and the water right maximum *r*.

$L_1 \sim (t-(t-l)*.2, 0.5, t)$
$L_2 \sim (t-(t-l)*.4, 0.5, t)$
$L_3 \sim (t-(t-l)*.6, 0.5, t)$
$L_4 \sim (t-(t-l), 0.5, t)$
$L_5 \sim (t-(t-l), 0.5, t-(t-l)*.6)$
$L_6 \sim (t-(t-l), 0.5, t-(t-l)*.8)$

Table 35: Certainty equivalents elicited for the domain below *t*.

Manager	**Subject**	***r (AF)***	***l (AF)***	***t (AF)***	**Alpha (±SE)**	**Beta (±SE)**	**Lambda (3 estimates)**
A	Merced ID Annual Supply	625,000	200,000	500,000	0.51 (0.08)	2.36 (0.48)	0.0000001225, 0.0000000178, 0.0000000035

B	Tri-Dam Projectm NNL Annual Inflows	1,500,000	450,000	600,000	0.26 (0.10)	3.14 (0.85)	0.0000000031, NaN, NaN

Table 36: Results from elicitations of risk preferences for annual water supply. These results should be treated as a proof of concept, with a full suite of elicitations planned for future research.

Manager	**Subject**	***r (AF)***	***l (AF)***	***t (AF)***	**Alpha (±SE)**	**Beta (±SE)**	**Lambda (3 estimates)**
A	Merced ID Carryover Storage	675,000	115,000	450,000	1.58 (0.39)	1.26 (0.11)	255, 42, 46

Table 37: Results from elicitation of risk preference for carryover storage at New Melones Reservoir. These results should be treated as a proof of concept, with a full suite of elicitations planned for future research.

4.12 **References**

Abdellaoui, M., H. Bleichrodt and O. L'Haridon (2008). "A tractable method to measure utility and loss aversion under prospect theory." Journal of Risk and Uncertainty **36**(3): 245-266.

Anthoff, D., R. S. J. Tol and G. W. Yohe (2009). "Risk aversion, time preference, and the social cost of carbon." Environmental Research Letters(2): 024002.

Bawa, V. S. (1978). "Safety-first, stochastic dominance, and optimal portfolio choice." Journal of Financial and Quantitative Analysis: 255-271.

Bernstein, P. L. (1996). Against the Gods: The Remarkable Story of Risk. New York, Wiley and Sons.

Beven, K. (2000). "On model uncertainty, risk and decision making." Hydrological Processes **14**(14): 2605-2606.

Chavas, J.-P. (2004). Risk Analysis in Theory and Practice. San Diego and London, Elsevier Academic Press.

Dessai, S., K. O'Brien and M. Hulme (2007). "Editorial: On uncertainty and climate change." Global Environmental Change **17**(1): 1-3.

Dettinger, M., H. Hidalgo, T. Das, D. Cayan and N. Knowles (2009). PROJECTIONS OF POTENTIAL FLOOD REGIME CHANGES IN CALIFORNIA California Climate Change Center

Eeckhoudt, L., C. Gollier and H. Schlesinger (2005). Economic and Financial Decisions under Risk. Princeton, Princeton University Press.

Faunt, C. C., ed., (2009). Groundwater Availability of the Central Valley Aquifer, California, U.S. Geological Survey Professional Paper 1766**:** 225 p.

Fishburn, P. C. (1977). "Mean-Risk Analysis with Risk Associated with Below-Target Returns." The American Economic Review **67**(2): 116-126.

Haddad, B. M. (1999). Rivers of Gold: Designing Markets to Allocate Water in California. Washington, D.C., Island Press.

Hershey, J. C., H. C. Kunreuther and P. J. H. Schoemaker (1982). "Sources of Bias in Assessment Procedures for Utility Functions." Management Science **28**(8): 936-954.

Hershey, J. C. and P. J. H. Schoemaker (1980). "Risk Taking and Problem Context in the Domain of Losses: An Expected Utility Analysis." The Journal of Risk and Insurance **47**(1): 111-132.

Ho, S., M. Lo, J. M. Famiglietti and e. al. (2009). Total water storage over the San Joaquin and Sacramento River Basins comparing GRACE and observational data (Presentation H11D-0837). American Geophysical Union meeting, San Francisco.

Hobbs, B. F., P. T. Chao and B. N. Venkatesh (1997). "Using Decision Analysis to Include Climate Change in Water Resources Decision Making." Climatic Change **37**(1): 177-202.

Jones, R. N. (2000). "Managing uncertainty in climate change projections - Issues for impact assessment - An editorial comment." Climatic Change **45**(3-4): 403-419.

Kahneman, D. and A. Tversky (1979). "Prospect Theory - Analysis of Decision under Risk." Econometrica **47**(2): 263-291.

Keeny, R. and H. Raiffa (1993). Decision Making with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge, UK, Cambridge University Press.

Lach, D., H. Ingram and S. Rayner (2005). "Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations " Texas Law Review **83**: 2027-2053.

Laughhunn, D. J., R. L. Crum and J. W. Payne (1983). "Risk Attitudes in the Telecommunications Industry." The Bell Journal of Economics **14**(2): 517-521.

Laughhunn, D. J., J. W. Payne and R. Crum (1980). "Managerial Risk Preferences for Below-Target Returns." Management Science **26**(12): 1238-1249.

Markowitz, H. (1952). "Portfolio Selection." The Journal of Finance **7**(1): 77-91.

Markowitz, H. (1959). Portfolio selection: efficient diversification of investments. New York, Wiley.

McDaniels, T., H. Longstaff and H. Dowlatabadi (2006). "A value-based framework for risk management decisions involving multiple scales: a salmon aquaculture example." Environmental Science & Policy **9**(5): 423-438.

Mendoza, G. A. and H. Martins (2006). "Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms." Forest Ecology and Management **230**(1-3): 1-22.

Nawrocki, D. N. (1999). "A brief history of downside risk measures." The Journal of Investing **8**(3): 9-25.

Nordhaus, W. (2007). "Critical Assumptions in the Stern Review on Climate Change." Science **317**(5835): 201.

O'Connor, R. E., B. Yarnal, K. Dow, C. L. Jocoy and G. J. Carbone (2005). "Feeling at risk matters: Water managers and the decision to use forecasts." Risk Analysis **25**(5): 1265-1275.

Oreskes, N. (2003). The role of quantitative models in science. Models in Ecosystem Science. C. D. Canham, J. J. Cole and W. K. Lauenroth. Princeton, Princeton University Press**:** 13-31.

Payne, J. W., D. J. Laughhunn and R. Crum (1980). "Translation of Gambles and Aspiration Level Effects in Risky Choice Behavior." Management Science **26**(10): 1039-1060.

Payne, J. W., D. J. Laughhunn and R. Crum (1981). "Further Tests of Aspiration Level Effects in Risky Choice Behavior." Management Science **27**(8): 953-958.

Rayner, S., D. Lach and H. Ingram (2005). "Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts." Climatic Change **69**(2 - 3): 197-227.

Roy, A. D. (1952). "Safety First and the Holding of Assets." Econometrica **20**(3): 431-449.

State Water Resources Control Board (2009). eWRIMS (Electronic Water Rights Information Management System), California Environmental Protection Agency.

Stern, N. (2007). The Economics of Climate Change: The Stern Review, Cambridge University Press.

Stern, N. and C. Taylor (2007). "ECONOMICS: Climate Change: Risk, Ethics, and the Stern Review." Science **317**(5835): 203-204.

Stewart, T. J. and L. Scott (1995). "A Scenario-Based Framework for Multicriteria Decision Analysis in Water Resources Planning." Water Resources Research **31**(11): 2835–2844.

Thompson Jr., B. H. (1993). "Institutional Perspectives on Water Policy and Markets." California Law Review **81**: 671-764.

Tversky, A. and D. Kahneman (1992). "Advances in Prospect-Theory - Cumulative Representation of Uncertainty." Journal of Risk and Uncertainty **5**(4): 297-323.

Yaqub, M. Z., G. Saz and D. Hussain (2009). "A Meta Analysis of the Empirical Evidence on Expected Utility Theory." European Journal of Economics, Finance and Administrative Sciences **15**: 117-133.

5 Chapter 5 - Integrated risk assessment modeling: Expected utility of water supply under climate change

5.1 Introduction

Economic theory points to risk preferences (e.g., risk aversion, risk neutrality, and risk seeking behavior) as important theoretical and empirically demonstrated components of human decision-making (Chavas 2004; Eeckhoudt et al. 2005). While risk aversion has begun to be discussed in global scale modeling of economic impacts of climate change (Stern 2007; Anthoff et al. 2009) it has not been integrated into climate impacts assessments at the level of local decision-making. It also integrates economic risk analysis, and in particular risk aversion and loss aversion, into an impacts assessment focused on local decision-maker risk preferences.

Previous chapters in this dissertation have described the component parts of an Integrated Assessment modeling exercise for translation of ensembles of future scenarios including climate change into a risk analysis for water resources systems. These parts include a hydrology/water operations model of three basins in California’s Central Valley; impacts assessment under scenario ensembles of climate change and other stressors; and a method for estimating risk preferences of water managers.

The goal of this chapter is to combine results from the previous dissertation chapters into a demonstration of the overarching whole of the research: the combination of Integrated Assessment modeling with economic risk analysis, and in particular risk aversion and loss aversion, to make an “integrated risk assessment” for impacts on water resources under future climate change. I focus this chapter on climate-inducted impacts because that is the context for the conversation to which these results are intended to contribute (Nordhaus 2007; Stern 2007; Stern and Taylor 2007; Anthoff et al. 2009).

The primary contribution of this chapter is quantifying risk to water supply from climate change, from the perspective of water managers, at the geographic scale and institutional level most central to water management in the case study basins. Combining projection distribution functions for water supply under climate change with utility functions for water managers provides insights into the role of risk aversion in impacts assessment, amplifies previous conversations about the potential drawbacks of reliance on historical conditions in planning tools (Milly et al. 2008), and may lay groundwork to inform global-scale integrated assessment modeling.

5.2 Methods

5.2.1 Overview

The present chapter describes the results of an Integrated Risk Assessment of climate change impacts on water resources in California’s Central Valley. The essential elements for estimating expected utility of water supplied to Irrigation Districts are 1) estimates of projection distribution functions for future water supply to each district under scenarios of interest and 2) estimates of utility functions for water for each district. Methods for each part of the modeling are described in previous chapters. In brief, Chapters 2 and 3 describe the hydrology/operations modeling, driven by downscaled General Circulation Model (GCM) data, used to generate distribution functions for water supply. Chapter 4 details the method used to elicit measures of managers' risk preferences, and the resulting utility functions for each irrigation district. Below I describe the results from empirical elicitations of utility functions for decision makers at an Irrigation District in the study region, and the integration of these utility functions with projection distribution functions for water supply to calculate expected utility under an ensemble of climate scenarios.

5.2.2 Water supply metric

The overarching unit of analysis for the purposes of this dissertation is the Irrigation District, as described earlier. For each case considered within the study area, I use the metric of annual diversions to the canal(s) supplying each district as the unit of water supply. I use distributions of scenario-driven model output, or "projection density functions" (Dettinger 2005; Dettinger 2006; Brekke et al. 2009), of annual water deliveries as a framework for describing variability in historical and projected water supply. Reliability metrics such as those used in Chapter 3 are useful for compactly illustrating the interplay between demands and supply. The key difference between the metric presented in this chapter and such reliability measures is that they describe water deliveries relative to time-varying demands. However, for the purposes of this analysis, distributions for water deliveries are more appropriate.

Projection density functions used here are a useful proxy for the probability distribution functions required of expected utility theory, as discussed below, whereas reliability metrics contain embedded probabilistic information and are thus less suitable for risk elicitations. Additionally, the diversions metric is congruent with both legal definitions of appropriative water rights, and with the views expressed by managers themselves during discussions and elicitations. Note that the metric used here includes system losses and water transfers. The diversions metric used in this chapter also enables comparison between historical and future conditions. Historical data are available in the study area for water supply with some precision (Table 38), but I do not have access to equivalent historical data for demands.

5.2.3 Water supply

Records of historical diversions were available for each district as summarized in Table 38. I aggregated daily and monthly records of diversions by water year (Oct-Sept). These data are plotted in Figure 60 through Figure 69, and descriptive statistics are shown in Table 39.

I generated an ensemble of time series of projections of water supply under climate change using the integrated hydrology and water operations model described in detail in Chapter 2. I drove the model with climate scenarios described in Chapter 2. Briefly, an ensemble of climate inputs from 6 GCMs was used, each run under two SRES emissions scenarios, A2 and B1 (Cayan et al. 2009). This ensemble enables representation of both inter-model variability in climate parameters and variability introduced by different emissions trajectories. Each model was downscaled using bias corrected statistical downscaling at 1/8-degree spatial resolution (Wood et al. 2004). For the work described in this chapter, the climate change parameter provides model input variability, while other variables such as land use are held constant at 1995 levels.

5.2.4 Measures of risk preferences

Chapter 4 describes methods for elicitation of risk preferences from water managers on the domain of annual water deliveries. In brief, I first used semi-structured interviews to define the domain of likely annual water deliveries and a threshold value below which a year's water supply would be perceived as loss and above which they would be perceived as gains. Then, I used choice experiments to elicit risk preferences above and below the threshold value, as well as an estimate of loss aversion spanning the threshold value. Details of method and results for the elicitations can be found in Chapter 4.

5.2.5 Use of risk analysis

I use expected utility theory somewhat differently than it has traditionally been employed. Schoemacker (1982) defines four ways in which expected utility (EU) theory has traditionally be used.

- *Descriptive* use of EU theory attempts to model decision processes behind risky choice, to understand the methods and mechanisms by which people decide in uncertain situations.
- *Predictive* or *positivistic* use values the ability of EU models to predict behavior over whether their assumptions describe aspects of decision-making.
- *Postdictive* use assumes that human decisions are optimal, and seeks to iteratively refine models to better describe observed behavior.
- *Prescriptive* or *normative* approaches assume that human choices under risk are generally suboptimal, and seek to improve decisions by packaging and providing information in a 'rational' framework to aid decision-makers.

In the research presented in this dissertation, I use EU in two ways. First, when adapted for use as in the left side of Figure 56, the method will provide a prescriptive aid to decision making. Second, and more central to the thrust of this chapter and dissertation, I use the spirit of a positivistic view of EU, but from a different perspective. Rather than attempting to use it to predict behavior, I use EU theory to develop value functions that enable its integration into an analysis of climate change impacts on water supply. In essence, it allows for weighting of model outputs so as to incorporate risk preferences of decision makers. The next section describes in more detail the different orientations in my application of EU as a tool for local decision support and to inform policymakers' understanding of climate change impacts.

5.2.6 Global vs. local risk analysis

The importance of risk aversion in climate impacts assessment has recently been recognized, and researchers have begun to incorporate risk into global-scale climate impacts analysis using estimated aggregate parameters for risk aversion (Stern 2007; Anthoff et al. 2009). In contrast to such aggregated economic damage estimates, the present study focuses at the granularity of the actual decision-maker, effectively introducing risk into an integrated impacts analysis at a level to the far right in the conceptual model in Figure 2.

It is important to note that I conceptualize the present risk analysis in the spirit of such global analyses. Risk analysis techniques were developed in part for the uses described above, such as a normative framework to aid in actual decisions (e.g. what investment mix to choose, or what infrastructure to invest in). While the techniques I present here could (and will in future work) be used in decision-making for water systems (Figure 56 left side), this dissertation focuses on the spirit of global-scale integrated assessments (Figure 56, right side) (Stern 2007; Anthoff et al. 2009), while integrating across scales as conceptualized in Figure 57.

In essence, risk preferences are used here to weight uncertain impacts resulting from changes exogenous to the systems considered, in order to inform larger questions about the impacts of environmental stressors. While the water managers I interviewed do not make decisions materially pertinent to greenhouse gas emissions, they will live with and work with the future consequences of these changes. In addition, they serve as synthesizers or amalgamators (Keeny and Raiffa 1993) of the preferences of water users in their districts . Thus, their attitudes towards risk could be reflected in state, national and global politics that will influence of future social and environmental conditions, regardless of whether they have agency over the probability distributions of the eventual outcomes. The research in this dissertation is an attempt to formalize integration of decision maker risk preferences into analysis of climate impacts.

5.3 **Results**

Below I describe historical and modeled distributions for annual water supply for several districts in the study area, to illustrate sensitivity to climate change. I carried out the complete risk analysis for the Merced ID, and present those results below as well.

5.3.1 Water supply under historical conditions and climate change

Table 39 and Figure 70 and Figure 71 describe the historical distribution of water deliveries, and those projected under climate change. The historical distribution is negatively skewed, but the climate change distribution is more so, with a longer left tail clearly visible in Figure 71 as compared to Figure 70. The longer right tail is a property of two aspects of climate change expected *a priori* based on properties of GCM outputs. It results from an increase in occurrence of dry events leading to more years with low deliveries, as well as from the combination of increased overall variability in the climate projections coupled with the cap on deliveries that prevents increasing weight in the right tail of the modeled distribution (see Chapter 3 for more details).

The higher kurtosis of the climate change distribution reflects more extreme and infrequent events responsible for the variance in the climate change distribution than historically, again in keeping with *a priori* expectations. Again, since the distribution is capped on the right by the water right maximum, this suggests that more extreme dry years are present, as is visible in Figure 71. Given the weighting of extreme events under loss aversion and downside risk aversion, these characteristics of the distribution are important for calculation of expected utility.

5.3.2 Loss aversion and risk aversion

Chapter 4 describes in detail the methods used to elicit utility functions for water managers. I review these methods briefly here. Document review, semi-structured interviews and choice experiments were used to define the upper (*r*) and lower (*l*) supports for the distributions of water deliveries to a given Irrigation District, as well as a threshold value (*t*) above which the manager feels like he or she is delivering on the mission of their organization, and below which they feel consequences such as pressure from their board of directors or constituents. The aim is to map water supply onto a schema under which decision-makers view risk as pertaining primarily to returns below a given level (Fishburn 1977; Bawa 1978; Abdellaoui et al. 2008). The threshold concept enables representation of a Von Neumann-Morganstern utility function with a ‘kink’ at the threshold point such that different preferences above are possible, and the concepts of loss aversion and/or downside risk aversion can be quantified. *t*, *r* and *l* were used to parameterize a computerized choice experiment by which certainty equivalents elicited above and below *t* enable estimation of parameters describing the characteristics of a utility function for each water manager, using commonly invoked exponential utility functions above and below *t*.

The elicited parameters, as well as others used for comparison, are shown in Table 40.

It should be noted again that the present sample was elicited from a water manager with deep familiarity and long experience with Merced ID operations, but who is not presently responsible for those operational decisions. His depth of knowledge suggests that his responses constitute a valid data point and proof of concept, but will need to be interpreted in light of future elicitations from current managers.

5.3.3 Risk under historical conditions and under climate change

Values calculated for EU under historical and climate change scenarios are presented in Table 41. EU under different assumptions for utility function parameters is also included for comparison. EU is calculated using modeled and historical empirical distribution for water deliveries. A range of utility parameters is also explored as a demonstration of the sensitivity to risk parameters. EU is calculated as

$$Eu(x) = \sum_{i=1}^{n} p_i u_j(x_i) \qquad \text{Equation 33}$$

with $i=1 \ldots n$ data points in the empirical distribution p_i for water supply, and $j=1 \ldots m$

parameterized utility functions $u_j(x)$.

Von Neumann-Morganstern utility theory, while cardinal in its measurement, is ordinal in its results (Schoemaker 1982). Thus, if $u(x_1) > u(x_2)$, we can infer that outcome x_1 is preferred to outcome x_2. However, if $u(x_1) - u(x_2) > u(x_3) - u(x_4)$, we cannot infer that a change from x_2 to x_1 would be preferred to a change from x_4 to x_3. For the purposes of this research, the EU calculated for each climate/utility scenario can be ranked, but comparisons based on relative magnitude of EU are not strictly valid.

The implications of the values presented in Table 4 are discussed below.

5.4 **Discussion**

5.4.1 Risk and reliability

The irrigation districts in the study area have enjoyed high water supply reliability, both before and after increasing the size of the dam on their respective main stem rivers (Table 39). This is unsurprising, given that the districts each are the senior water rights holder in the basin, and that three of the five also own and control large reservoirs.

However, as these districts were founded approximately a century ago, the historical record can be considered brief. The premise motivating studies of climate change and water resources rests on the concept of non-stationarity (Milly et al. 2008), or the idea that the future is unlikely to resemble the historical record.

Within the range of values for climate and risk parameters considered here, resulting values for EU are most sensitive to the downside risk parameter (beta). Of note are the large negative values for downside risk using the elicited utility function, as compared to either previously elicited values or under risk neutrality. In particular, the difference in EU within each scenario set (e.g. the three values calculated for *A2 climate*) is much greater than the difference in utility across estimates of future water supply for a given utility function.

Comparisons of EU under climate change are also revealing. The scenarios considered here rank in terms of favorability to water managers, from highest to lowest, 1) *Historical*, 2) *B1 Climate*, 3) *All Climate*, 4) *A2 Climate*. This ranking holds across all the utility functions. All climate scenarios in Table 41 have greater downside risk, and smaller upside risk, than historical conditions, reflecting the more negatively skewed distribution of modeled water deliveries. Further, variability in EU among climate scenarios for a given utility function is smaller than the difference between EU under climate change and under historical conditions. This suggests that while SRES are determinants of water supply risk, the difference between historical and future climate has a greater effect.

The historical climate in which the institutional system evolved (Sax et al. 2006) does not capture extreme droughts in the paleoclimate record (Stine 1994; Meko and Woodhouse 2005; Woodhouse and Lukas 2006) or the increase in extreme events projected by climate modelers (IPCC 2007b; IPCC 2007a; Seager et al. 2007). Our historical past, and the one on which we base our planning for water resources, is not representative of likely future conditions, all of which may hold greater downside risks. Water users may thus be more vulnerable to climate risk than they realize.

Among all the scenarios in Table 41, EU is lowest under climate change with risk. For elicited values, the EU is driven by loss aversion and the long lower tails of each distribution.

Under risk neutrality, downside and upside risk are of similar magnitude in each case given the elicited threshold value. However, given the inclusion of any amount of risk aversion and/or loss aversion, downside risk overwhelms upside gains, even in the historical system. This is a function of the degree of loss aversion, the values chosen for t and r, and the distribution of deliveries above and below t. For comparison, under the normalized utility scale used here, a situation in which every year delivered the threshold amount of water, t, would result in an EU of zero under all cases; a situation in which full deliveries r resulted each year would result in an EU of 1. All climate change scenarios result in lower EU than such a constant threshold value, suggesting that the risk-weighted impacts of climate change are worse even than what managers consider the baseline acceptable performance of their water system (t).

5.4.2 Limitations

Implementing EU theory requires two ingredients: a utility function with values over a given range of some variable (here, water), and a probability density function for amounts of the variable over the same range (see Chapter 4 and Section 5.3.3 below). Chapter 4 details a method to estimate the first. Generating rigorous probability density functions for water supply arguably lies at the cutting edge of multiple disciplines, and is beyond the scope of this dissertation. I review the issues below, and describe our efforts to generate a credible proxy in the form of “projection distribution functions” of water supply.

Generating probability distributions via a cascade of modeling such as the present exercise has a number of dependencies, rooted in the difficulty of assigning probability distributions to input variables and propagating these uncertainties can be propagated through the modeling. This problem is particularly pronounced in a scenarios based modeling exercise such as the one described here.

The scenarios used in this research are narrative descriptions of plausible futures, each focused on certain quantified element(s) of interest. For example, SRES are internally consistent socio-economic storylines that result in trajectories of future emissions. The resulting emissions trajectories are used as inputs to General Circulation Models, on which I rely for regional climate projections, and which are used in downscaled form as inputs to the integrated hydrology/water operations model that in turn generates output for water supply, the model structure and parameters of which are themselves subject to uncertainty (including those variables addressed in Chapter 3 but not in the present chapter). Of note is the fact that the SRES are explicitly not probabilistic scenarios, but rather are referred to as ‘storylines’ without attached likelihoods. In fact, given global economic developments since the SRES were defined, even the high emissions A2 scenario is currently very conservative, and B1 looks increasingly unrealistic.

Thus, each step of the modeling chaing has uncertainty embedded within it, some of which is not explicitly propagated in this modeling method. In short, the relative weight of the uncertainties that are represented in the model is itself uncertain, and there are multiple sources of uncertainty that are not represented at all.

I acknowledge that including a thorough uncertainty analysis of this type is far beyond the scope of a single dissertation. Instead, I use a proxy for uncertainty integration by 1) focusing on one of the dominant sources of uncertainty about water supply that is of particular concern to decision makers at multiple policy levels, and 2) relying on previous work for an approach to representing uncertainty in the climate variable.

Brekke et al. (2008) test the concept of generating weights for climate ensemble members based on their post-diction of historical climate. Their results suggest limited value for such exercises, and that ensemble ‘completeness’ is more important that ensemble weighting. (Brekke et al. 2008). Based on this effort, we choose to generate our distributions using an ensemble of downscaled GCM data, with a uniform prior distribution.

Methods for refining output distributions are at the cutting edge of many disciplines, and beyond the scope of this disseration. As such methods mature, they can be integrated into future versions of the upstream modeling presented in earlier chapters, in order to refine the output from such downstream analysis as is presented here.

5.5 **Conclusion**

The work presented in this chapter brings together two key ingredients of a decision analysis method using EU theory. The first, generating probability distributions over the quantity of interest, was presented in Chapter 2 and 3. The second, eliciting utility functions for relevant decision makers, was presented in Chapter 4. This chapter pulls together the results from each of these efforts to demonstrate the importance of risk preferences, particularly risk aversion and loss aversion, in weighting results of climate impacts assessments in water resources.

The work presented here builds on previous studies that have worked to quantify climate impacts. It builds in finer granularity than previous reports for the region (e.g. Miller et al. 2003; Brekke et al. 2004; Vicuna et al. 2007), generating impacts estimates at the level of the Irrigation District, the most important management unit in the region. Combining this increased granularity with an ensemble of downscaled GCM inputs (Brekke et al. 2008; Brekke et al. 2009) enables projection distribution functions for water supply for the case study areas at the level necessary for EU theory. The novel contribution of empirical utility functions for water managers enables me to invoke EU theory to generate an end-to-end risk analysis at the level of actual decision makers in climate and water resources. This "integrated risk assessment modeling" pushes the analysis of climate impacts to the right of the conceptual model in Figure 2.

The strong risk aversion and loss aversion exhibited by public decision-makers responsible for provision of a basic service like water supply may be reflected in other, related sectors such as energy and food provision or management of ecosystem services. If it is, it may have implications for broader estimates of cross-sector vulnerability, and for necessary adaptation and coping mechanisms given future global change.

The analysis reported in this dissertation supports the notion that managers' risk preferences may be underutilized variables in impacts assessment, and in particular that ignoring them may understate estimates of climate change impacts. As discussed in Chapter 4, the values elicited here for loss aversion and downside risk aversion are substantially greater than those elicited from laboratory experiments, with corresponding results for EU under all scenarios. However, these elicitations were carried out on experts, in the sphere of tradeoffs they consider daily, in systems they are intimately familiar with. In addition, water managers are notably conservative and risk averse (Lach et al. 2005; Rayner et al. 2005) for a variety of reasons (Hanemann 2006). If results using this and other methods on water managers stand to scrutiny and repeated application, and particularly if variants produce congruent results in other sectors of resource management, they may indeed indicate that loss aversion on the local scale could drive consideration of the use of risk analysis in global scale integrated assessment (Nordhaus 2007; Stern 2007; Stern and Taylor 2007). In particular, the Stern Review (Stern 2007) used prescriptive arguments in selecting related parameters for their global-scale economic Integrated Assessment modeling, and the sensitivity analysis of Anthoff et al. (2009) suggests that such parameters can strongly influence estimates of the Social Cost of Carbon emissions (SCC). The present analysis and related analyses could help quantify such risk aversion parameters for global determinations of SCC, as well as contributing to local impact assessments. On a local scale, the method described here may open the door to more nuanced evaluation of policy scenarios, and for valuation of water under uncertainty as water systems managers move to embrace risk management tools such as options and insurance.

5.6 **Figures**

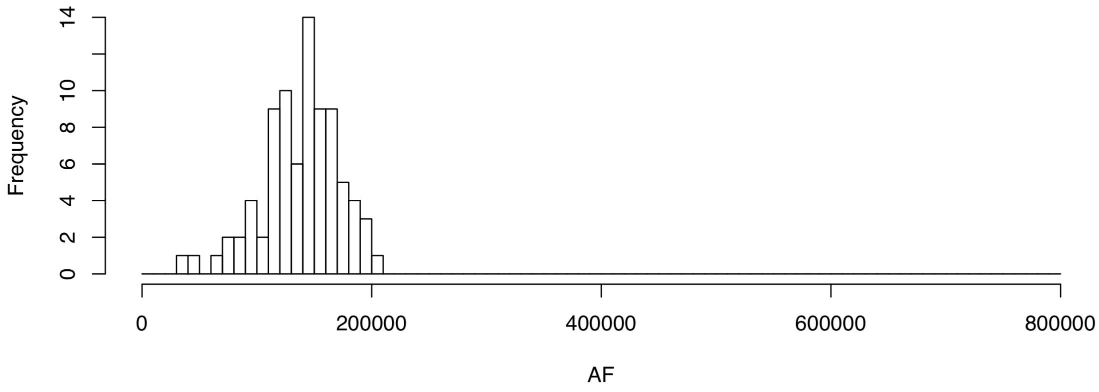

Figure 60: Oakdale ID historical diversions, WY 1926-2008.

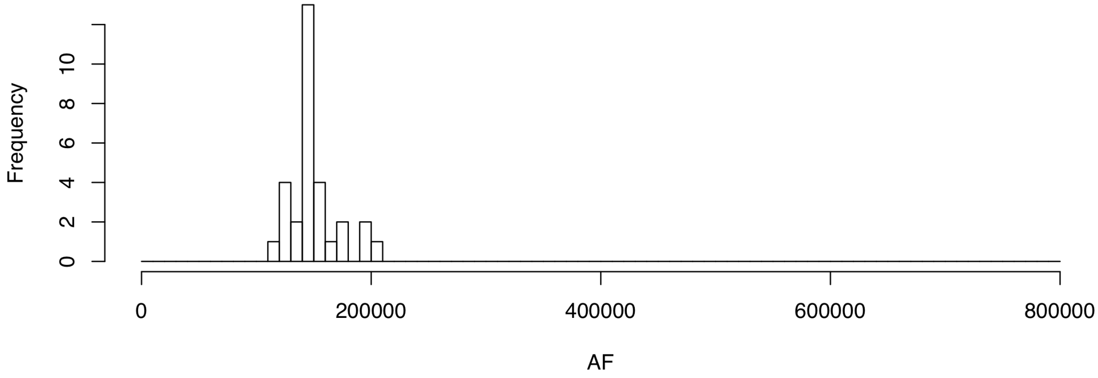

Figure 61: Oakdale ID historical diversions, WY 1979-2008.

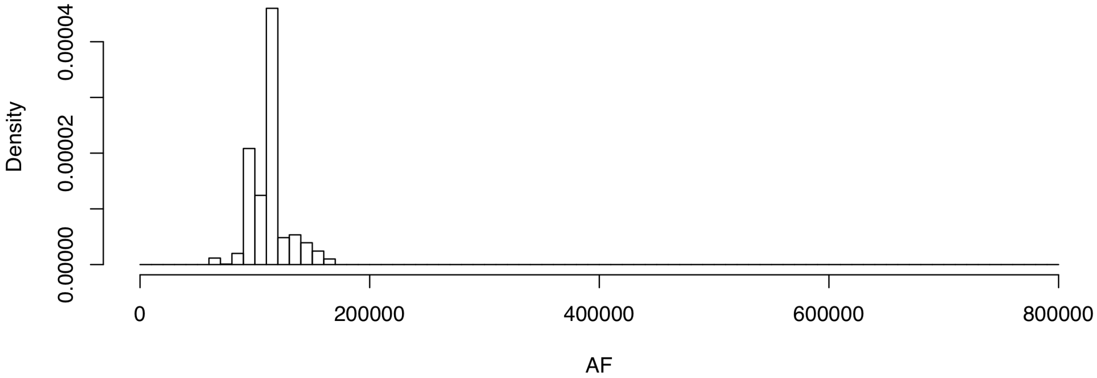

Figure 62: Oakdale ID canal diversions, WY 2000-2099, modeled under 12 climate scenarios with historical land use, population, and water use efficiency.

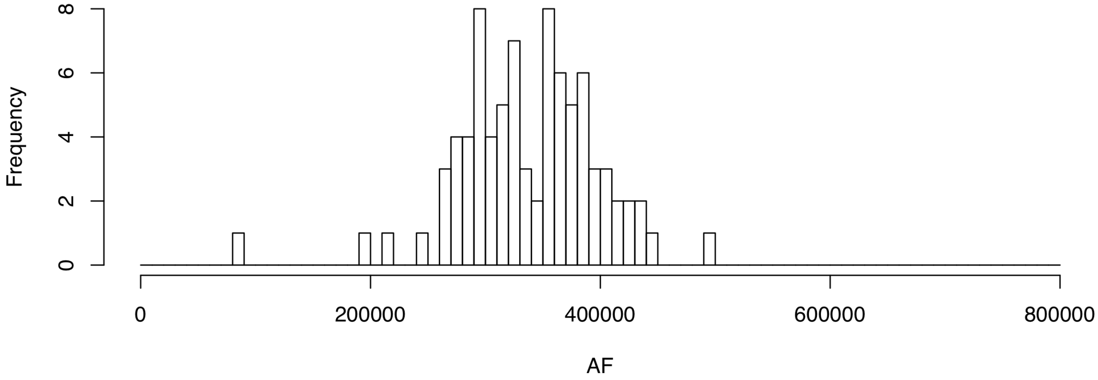

Figure 63: SSJID Main Cn historical diversions, WY 1926-2008.

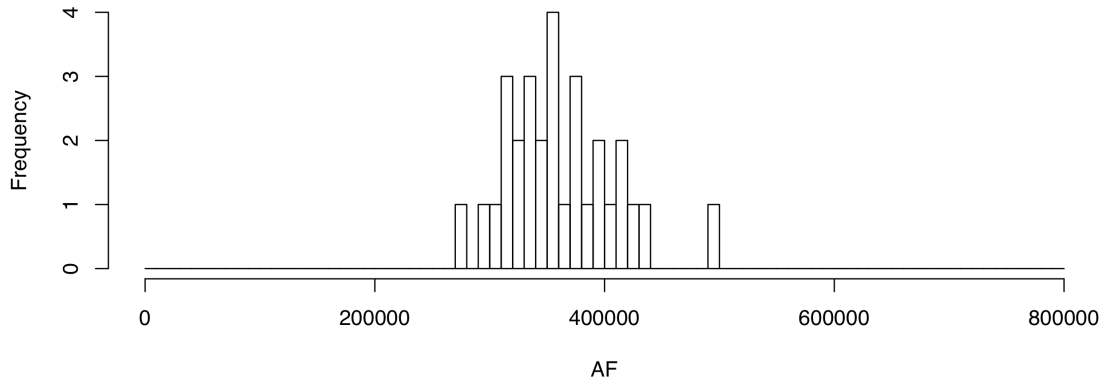

Figure 64: SSJID Main Cn historical diversions, WY 1979-2008.

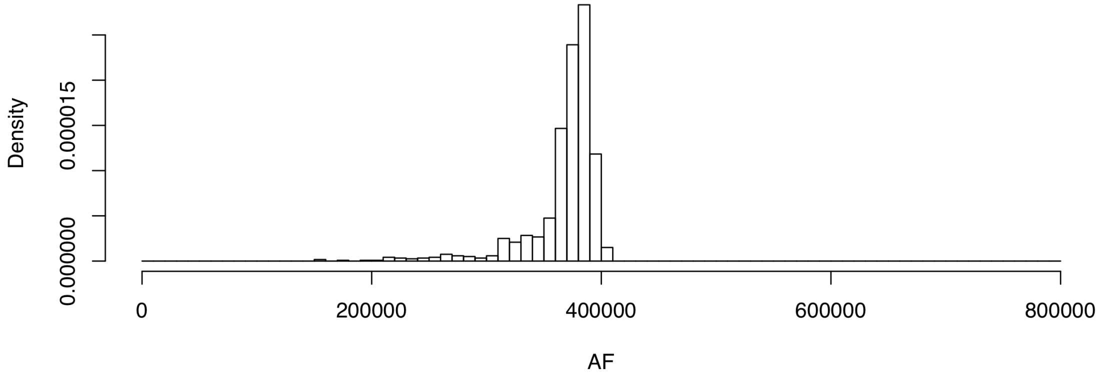

Figure 65: SSJID Main Cn WY 2000-2099, modeled under 12 climate scenarios with historical land use, population, and water use efficiency.

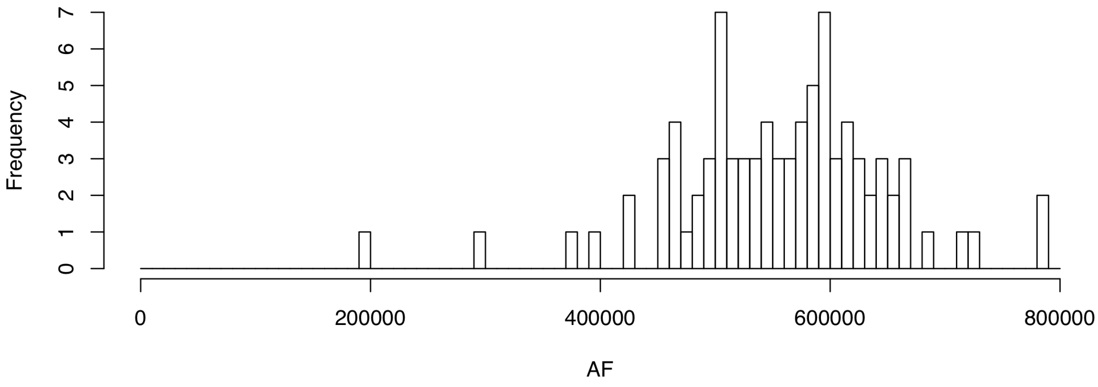

Figure 66: Turlock ID historical diversions, WY 1923-2008.

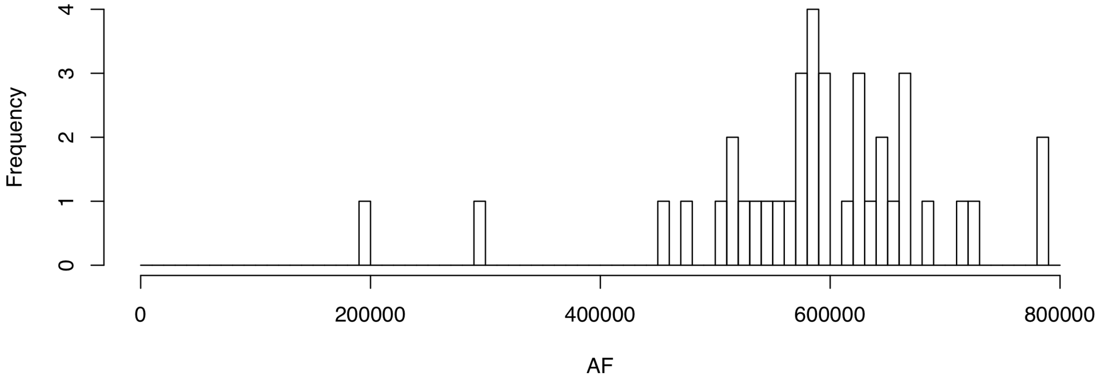

Figure 67: Turlock ID historical diversions, WY 1971-2008.

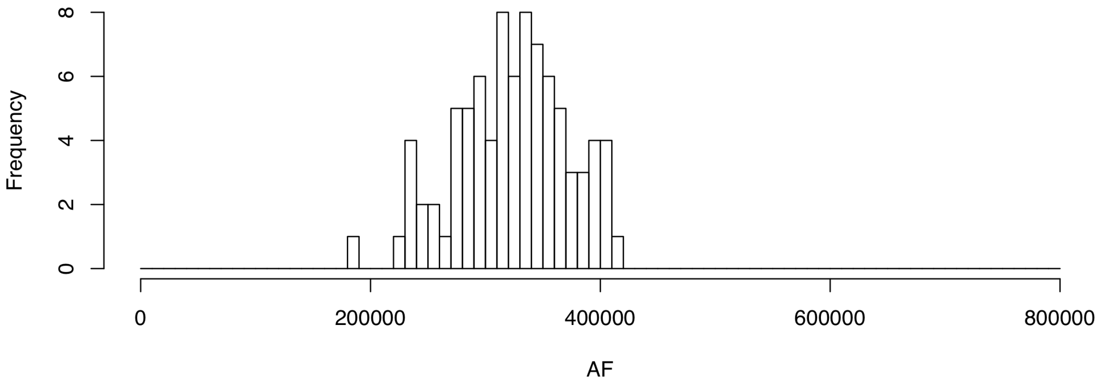

Figure 68: Modesto ID historical diversions, WY 1923-2008.

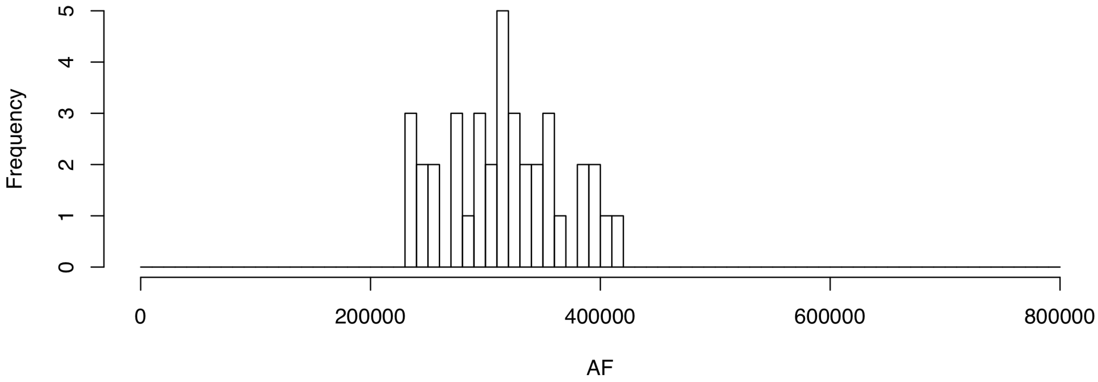

Figure 69: Modesto ID historical diversions, WY 1971-2008.

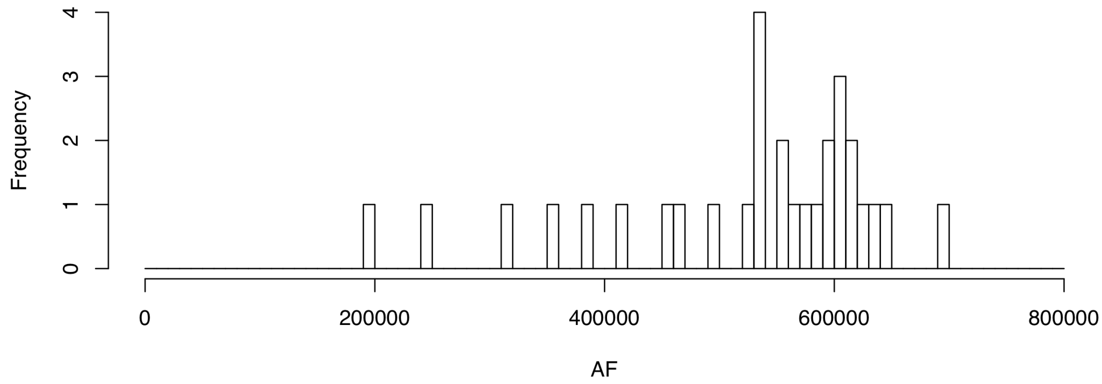

Figure 70: Merced ID combined North and Main Canal diversions, WY 1970-1999.

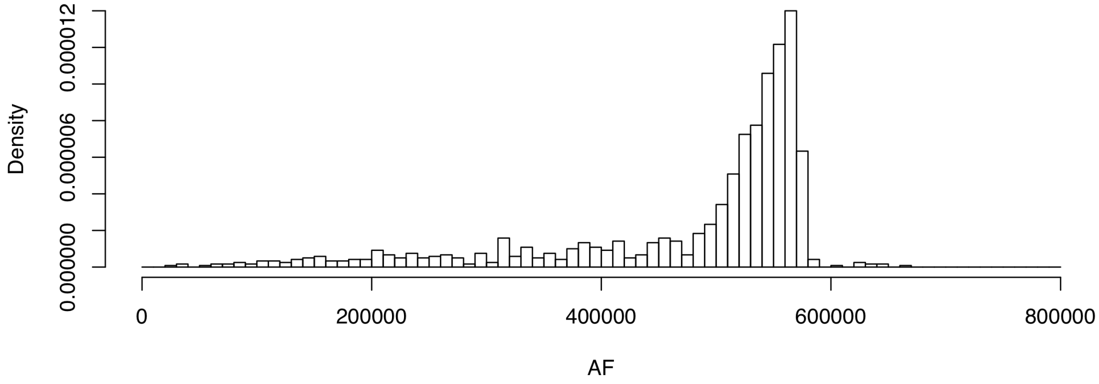

Figure 71: Merced ID combined North and Main canal diversions, WY 2000-2099, modeled under 12 climate scenarios with historical land use, population, and water use efficiency.

5.7 **Tables**

Canal	**Data source**	**Data notes (usgs)**	**Year main dam built**
Oakdale Cn	USGS 11301000 OAKDALE CN NR KNIGHTS FERRY CA	USGS: May 1914 to current year. Records for water years 1933-36 incomplete.	New Melones Dam, 1979; Old Melones Dam 1926
South San Joaquin Cn	USGS 11300500 S SAN JOAQUIN CN NR KNIGHTS FERRY CA	USGS: May 1914 to current year.	New Melones Dam, 1979; Old Melones Dam 1926
Turlock Cn	USGS 11289500 TURLOCK CN NR LA GRANGE CA	USGS: October 1898 to current year.	New Don Pedro Dam, 1971; Old Don Pedro Dam, 1923
Modesto Cn	USGS 11289000 MODESTO CN NR LA GRANGE CA	USGS. Period of Record: April 1903 to current year.	New Don Pedro Dam, 1971; Old Don Pedro Dam, 1923
Merced ID North and Main Cn	Merced Water Supply Plan	Data from Merced ID, 1970-1999	New Exchequer, 1967; Original Exchequer Dam, built between 1924 and 1926

Table 38: Data notes for historical diversions calculations. Note that this and the following tables contain descriptive data for all the irrigation districts in the study area, but the synthesis risk analysis is conducted only for Merced ID. Expansion of the method to the other areas is planned for the next iteration of this research.

Canal	Years	Min	Max	Mean	Std.	Skewness	Kurtosis
Oakdale Cn	1926-2008	39680	200698	137493	33654	-0.54	3.3
	1979-2008	111652	200698	149128	20881	0.9	3.6
	2000-2099	63948	166059	112492	16278	0.56	4.2
SSJID Cn	1926-2008	82879	496395	337464	60880	-0.72	5.7
	1979-2008	272500	496395	361250	47351	0.66	3.6
	2000-2099	150024	406258	367883	32115	-2.8	13
Turlock Cn	1923-2008	199964	785427	555588	92625	-0.61	5.2
	1971-2008	199964	785427	586373	110427	-1.3	6.4
	2000-2099						
Modesto Cn	1923-2008	189439	413744	323310	49072	-0.28	2.6
	1971-2008	231039	413744	316824	50547	0.1	2.2
	2000-2099						
Merced ID North and Main Cn	1970-1999	192900	694500	523047	120365	-1.2	3.8
	2000-2099	24487	660565	480590	120239	-1.7	5

Table 39: Descriptive statistics for historical distributions of water deliveries at each diversion point, before and after construction/expansion of the main dam on each respective river, and under 12 climate change scenarios run from 2000-2099.

Risk parameters	**Alpha**	**Beta**
Elicited values	0.51 (.08)	2.36 (.48)
Abdellaoui et al (2008)	0.86 (0.66-1.08)	1.06 (.92-1.49)
Risk neutral, no loss aversion	1	1

Table 40: Parameters used in calculation of expected utility, as described in Chapter 4. *Alpha* is the coefficient for the exponential utility function for 'gains' on the domain above the threshold value, and *beta* is the coefficient for the exponential utility function for 'losses' on the domain below the threshold value. *Elicited values* are those elicited using the method described in Chapter 4, with parentheses containing the standard error from fitting elicitation data using non-linear least squares. *Abdellaoui et al.* are published values from experiments conducted using similar methods, but with student subjects presented with hypothetical gambles for monetary gains or losses (Abdellaoui et al. 2008), with parentheses containing the interquartile range of elicited values from their sample population. *Risk neutral* parameters describe a linear utility function above and below the threshold value (i.e. risk neutral and with no loss aversion).

Water supply scenario set	**Risk parameters**	**Downside**	**Upside**	**Expected utility**	**Low**	**High**
Historical 1970-1999	Elicited values	-1.67E+09	0.55	-1.67E+09	-1.65E+12	-1.75E+06
	Abdellaoui et al (2008)	-3.31	0.49	-2.82	-6,456	0.41
	Risk neutral	-0.31	0.47	0.16	-	-
All climate, 2000-2099	Elicited values	-3.02E+09	0.40	-3.02E+09	-3.32E+12	-2.84E+06
	Abdellaoui et al (2008)	-4.46	0.29	-4.17	-9,572	0.18
	Risk neutral	-0.41	0.26	-0.16	-	-
A2 climate, 2000-2099	Elicited values	-4.62E+09	0.36	-4.62E+09	-5.07E+12	-4.31E+06
	Abdellaoui et al (2008)	-6.55	0.26	-6.28	-14,373	0.13
	Risk neutral	-0.60	0.23	-0.37	-	-
B1 climate, 2000-2099	Elicited values	-5.17E+09	0.28	-5.17E+09	-5.70E+12	-4.80E+06
	Abdellaoui et al (2008)	-7.26	0.21	-7.05	-15,966	0.08
	Risk neutral	-0.67	0.19	-0.48	-	-

Table 41: Values for expected utility for the Merced ID case study, in utiles. *Water supply scenario sets* refer to distributions of historical and projected annual deliveries to the Merced North and Main Canals. *Risk parameters* are taken from Table 40. *Downside* refers to the expected utility below the threshold value, as described in the text. *Upside* refers to the expected utility above the threshold value. *Expected utility* is the utility function multiplied by the empirical distribution of water supply, in this case the sum of *upside* and *downside*. Expected utility estimates here are normalized to *u(r)=1* and *u(t)=0* as described in the text. *Low* and *high* refer to the range of values for expected utility, taking into account the estimation uncertainty in utility function parameters.

5.8 References

Abdellaoui, M., H. Bleichrodt and O. L'Haridon (2008). "A tractable method to measure utility and loss aversion under prospect theory." Journal of Risk and Uncertainty **36**(3): 245-266.

Anthoff, D., R. S. J. Tol and G. W. Yohe (2009). "Risk aversion, time preference, and the social cost of carbon." Environmental Research Letters(2): 024002.

Bawa, V. S. (1978). "Safety-first, stochastic dominance, and optimal portfolio choice." Journal of Financial and Quantitative Analysis: 255-271.

Brekke, L., M. Dettinger, E. Maurer and M. Anderson (2008). "Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments." Climatic Change **89**(3): 371-394.

Brekke, L. D., E. P. Maurer, J. D. Anderson, M. D. Dettinger, E. S. Townsley, A. Harrison and T. Pruitt (2009). "Assessing reservoir operations risk under climate change." Water Resour. Res. **45**.

Brekke, L. D., N. L. Miller, K. E. Bashford, N. W. T. Quinn and J. A. Dracup (2004). "Climate Change Impacts Uncertainty For Water Resources In The San Joaquin River Basin, California." Journal of the American Water Resources Association **40**(1): 149-164.

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, NicholasGraham and R. Flick (2009). Climate Change Scenarios And Sea Level Rise Estimates For The California 2009 Climate Change Scenarios Assessment. Sacramento, CA, California Energy Commission, California Climate Change Center.

Chavas, J.-P. (2004). Risk Analysis in Theory and Practice. San Diego and London, Elsevier Academic Press.

Dettinger, M. D. (2005). "From Climate-Change Spaghetti to Climate-Change Distributions for 21st Century California." San Francisco Estuary and Watershed Science **3**(1): Article 4, http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4.

Dettinger, M. D. (2006). "A component-resampling approach for estimating probability distributions from small forecast ensembles." Climatic Change **76**(1-2): 149-168.

Eeckhoudt, L., C. Gollier and H. Schlesinger (2005). Economic and Financial Decisions under Risk. Princeton, Princeton University Press.

Fishburn, P. C. (1977). "Mean-Risk Analysis with Risk Associated with Below-Target Returns." The American Economic Review **67**(2): 116-126.

Hanemann, W. M. (2006). The economic conception of water. Water Crisis: Myth or Reality? P. P. Rogers, M. R. Llamas and L. M.-C. (eds.), Taylor & Francis**:** 61-91.

IPCC (2007a). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2007b). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Keeny, R. and H. Raiffa (1993). Decision Making with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge, UK, Cambridge University Press.

Lach, D., H. Ingram and S. Rayner (2005). "Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations " Texas Law Review **83**: 2027-2053.

Meko, D. M. and C. A. Woodhouse (2005). "Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado river basins, western USA." Journal of Hydrology **308**(1-4): 196-213.

Miller, N. L., K. E. Bashford and E. Strem (2003). "Potential Impacts Of Climate Change On California Hydrology." Journal of the American Water Resources Association **39**(4): 771-784.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier and R. J. Stouffer (2008). "CLIMATE CHANGE: Stationarity Is Dead: Whither Water Management?" Science **319**(5863): 573-574.

Nordhaus, W. (2007). "Critical Assumptions in the Stern Review on Climate Change." Science **317**(5835): 201.

Rayner, S., D. Lach and H. Ingram (2005). "Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts." Climatic Change **69**(2 - 3): 197-227.

Sax, J. L., B. H. Thompson Jr., J. D. Leshy and R. H. Abrams (2006). Legal Control of Water Resources: Cases and Materials, Fourth Edition. St. Paul, MN, Thomson West.

Schoemaker, P. J. H. (1982). "The Expected Utility Model: Its Variants, Purposes, Evidence and Limitations." Journal of Economic Literature **20**(2): 529-563.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez and N. Naik (2007). "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America." Science **316**(5828): 1181-1184.

Stern, N. (2007). The Economics of Climate Change: The Stern Review, Cambridge University Press.

Stern, N. and C. Taylor (2007). "ECONOMICS: Climate Change: Risk, Ethics, and the Stern Review." Science **317**(5835): 203-204.

Stine, S. (1994). "Extreme and Persistent Drought in California and Patagonia During Medieval Time." Nature **369**(6481): 546-549.

Vicuna, S., E. P. Maurer, B. Joyce, J. A. Dracup and D. Purkey (2007). "The Sensitivity of California Water Resources to Climate Change Scenarios." Journal of the American Water Resources Association (JAWRA) **43**(2): 482-498. DOI: 410.1111/j.1752-1688.2007.00038.x.

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

Woodhouse, C. A. and J. J. Lukas (2006). "Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning." Climatic Change **78**(2-4): 293-315.

6 Chapter 6 – Conclusion and lay summary

6.1 What I did

This dissertation has posed and answered two overarching questions. First, how do climate change, land use change, and population growth compare and interact as drivers of change to future water demands and supply in a modeled representation of case studies in California's Central Valley? Second, how can we integrate risk into such assessments? How might this risk affect results from the perspective of the decision-makers, and inform results from future global assessments of climate impacts?

Answering these questions took several steps. I first built and calibrated an integrated hydrology and water operations model to simulate the historical water system operations in the Stanislaus, Tuolumne, and Merced river basins in California's Central Valley. I then drove this model over the course of the century using an ensemble of simulations of climate change, population growth, land use change, and water use efficiency, resulting in a comparison of the effects of each of these drivers of change on water demands and water supply reliability, as well as a representation of the variability resulting from each stressor.

The second part of the dissertation brought in risk. I developed a method for quantifying risk preferences of water managers, based on the economic concepts of risk aversion (the desire to avoid and manage risk) and loss aversion (a tendency for people to strongly prefer avoiding losses to acquiring gains). I applied the method through interviews with managers of water supply to irrigations districts in the study area. I then combined the resulting risk preferences with output from the climate-driven hydrology modeling to get 'expected utility' under climate change. In effect, this procedure weights the losses and gains projected under climate change based on the decision makers attitudes towards risk, 'punishing' poor supply years and 'rewarding' ample supply years based on how decision makers feel about each outcome.

6.2 What I found

In comparing the projected effects of climate change, land use change, and population growth on water demands and supply in the case study area, I found that future climate change, urbanization, population growth, and water use efficiency may combine to produce very different projections of future urban and agricultural water demands than with consideration of any of these factors alone. In the study area, the effects of climate change may not dominate changes in future water supply. In this area, with projected low-density urban growth displacing farmland, the impact of population growth (increasing demands) and urbanization (decreasing demands) is each greater than that of climate change alone. However, the net effect is decreasing water demands driven by removal of acreage from agricultural production, and its replacement with low-density urban use. Although climate change considered alone results in decreasing water supply reliability, when population growth and land use change are also taken into account the decreased demands mute the effect on water supply. Thus, climate change, population growth, and land use change each impact the water system in different ways, and result in more complex interplay of effects when analyzed together.

When bringing risk into the analysis, my interviews with managers revealed high levels of both risk aversion and loss aversion when it comes to their duties in water provision for agricultural customers. Model results for water supply under climate change give lower expected utility for managers than given historical conditions, indicating that impacts of climate change will be negative for the water sector in this region regardless of the degree of managers' risk aversion. However, the expected utility for decision makers is strongly influenced by their risk preferences, and in fact these risk preferences are stronger determinants of results for expected utility than are climate conditions.

6.3 **Why it matters**

If the results in this dissertation stand to scrutiny and prove general when these methods are applied in other areas, they can inform science, decision-making, and policy in a number of ways. The implications of these results for water resources institutions are potentially interesting.

The first set of results highlight the importance of considering land use as a driver of water system change, especially when invoking population growth as a driver of change. They also show the limitations of climate impacts assessments that do not incorporate a range of major stressors, complement previous path breaking global-scale efforts (Vörösmarty et al. 2000), and highlight the importance of place-specific, spatially explicit analyses.

In a system of water rights which are prescribed based on historical and ongoing use of specific types, changes of the type and magnitude described here are unlikely to be accommodated by the existing system of allocation. In practical terms, the data highlight the importance of actively considering land use and population directly alongside the considerable progress on incorporating climate change into California water planning. However, the work presented here constitutes only one step in this conversation, rather than any information directly actionable by policy makers. Further work can tackle the essential and difficult tasks of taking these broad ideas into a useable realm, through establishing credible probabilities for these or other scenarios, robust analysis of suites of policy choices, collaborative approaches to science and decision-making, or some combination of these and other methods.

The empirical risk analysis for water managers represents an end-to-end integrated assessment with a risk analysis that brings uncertainty from climate change and other projected stressors to the level of water resources decision makers (Figure 2). This "integrated risk assessment modeling" pushes the analysis of climate impacts to relevant decision makers with direct influence over the end users of water in this system. In the small sample presented, the results are qualitatively in line with *a priori* expectations for water managers, but of greater magnitude than those described in other empirical studies outside water resources. The strong risk aversion and loss aversion exhibited by public decision-makers responsible for provision of a basic service like water supply may be reflected in other, related sectors such as energy and food provision or management of ecosystem services. If it is, it may have implications for broader estimates of cross-sector vulnerability, and for necessary adaptation and coping mechanisms given future global change.

The analysis reported in this dissertation supports the notion that managers' risk preferences may be underutilized variables in impacts assessment, and in particular that ignoring them may understate estimates of climate change impacts. If results using this and other methods with water managers stand to scrutiny and repeated application, and particularly if variants produce congruent results in other sectors of resource management, they may indicate that loss aversion on the local scale should drive the use of risk analysis in global scale integrated assessment (Nordhaus 2007; Stern 2007; Stern and Taylor 2007). The present analysis and related analyses could then help quantify such risk aversion parameters for global determinations of Social Cost of Carbon emissions (Anthoff et al. 2009). On a local scale, the method described here may open the door to more nuanced evaluation of policy scenarios, and for valuation of water under uncertainty as water systems managers move to embrace risk management tools.

6.4 **References**

Anthoff, D., R. S. J. Tol and G. W. Yohe (2009). "Risk aversion, time preference, and the social cost of carbon." Environmental Research Letters(2): 024002.

Nordhaus, W. (2007). "Critical Assumptions in the Stern Review on Climate Change." Science **317**(5835): 201.

Stern, N. (2007). The Economics of Climate Change: The Stern Review, Cambridge University Press.

Stern, N. and C. Taylor (2007). "ECONOMICS: Climate Change: Risk, Ethics, and the Stern Review." Science **317**(5835): 203-204.

Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers (2000). "Global water resources: Vulnerability from climate change acid population growth." Science **289**(5477): 284-288.

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