CALFED BAY-DELTA PROGRAM

CALFED SCIENCE FELLOWS PROGRAM

In cooperation with the

California Sea Grant College Program

Sea Grant California

FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE ☐ Postdoctoral Researcher ☒ Ph.D. Graduate Student

PROJECT NUMBER _____

PROJECT TITLE Climate change and in-stream flows: Methods for application of risk analysis to modeling of environmental water supplies

FINANCIAL SUMMARY

First Year CALFED Funds Requested:	49,375.00
Total CALFED Funds Requested:	98,750.00
Duration:	2 years
Proposed Start/Completion Dates:	1-Sep-08 31 August 2010

APPROVAL SIGNATURES

FELLOW:

Name: Michael Kiparsky
Position/Title: Ph.D. Candidate
Department: Energy and Resources Group
Institution: UC Berkeley
Address: 310 Barrows Hall
City, State & Zip: Berkeley, CA 94720-3050
Telephone: 415 806 6656
Fax: (510) 642-1085
E-mail: kiparsky@berkeley.edu

MENTOR/PRINCIPAL INVESTIGATOR:

Name: W. Michael Hanemann
Position/Title: Chancellor's Professor
Department: Agricultural and Resource Economics and Public
Institution: UC Berkeley
Address: 207 Giannini Hall
City, State & Zip: Berkeley, CA 94720-3310
Telephone: 510 642 2670
Fax: 510 643 8911
E-mail: hanemann@are.berkeley.edu

AUTHORIZED INSTITUTIONAL REPRESENTATIVE:

Name: Jyl Baldwin
Position/Title: Asst. Director for Compliance and Special Projects
Department: Sponsored Projects Office
Institution: The Regents of the University of California
Address: 2150 Shattuck Ave., Suite 313
City, State & Zip: Berkeley, CA 94704-5940
Telephone: Phone (510)642-8110
Fax: 510)642-8236
E-mail: jbaldwin@berkeley.edu

Will animal subjects be used? Yes ☒ No

APPROVAL DATE: _____ PROTOCOL #: _____ PENDING: X

Does this application involve any recombinant DNA technology or research? ☐ Yes ☒ No

CALFED Science Fellows Proposal:
Climate change and in-stream flows: Methods for application of risk analysis to modeling of environmental water supplies

1 Introduction and overview

1.1 Background

CALFED agencies have invested heavily in restoration activities in aquatic ecosystems. These investments are contingent on the reliability of the quantity and quality of in-stream flows to assure benefits to species of concern. Water law and water planning in California, including that for in-stream flows, implicitly or explicitly assumes that future hydrologies will resemble, or be identical to, the observed historical record. However, scientific consensus indicates 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 [4, 5]. Adaptation (adjustment of human systems to moderate harm from climatic stimuli) will be a critical component of regional and local responses to climate change, in natural resource management [6-11]. For CALFED agencies, this will involve incorporating uncertainties from climate and other sources into water planning and management decisions [12].

Because of the inherent uncertainties, climate change assessment and adaptation strategies are fundamentally about risk.[1] 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 [15, 16]. Indeed, with the CALFED community, uncertainty and a changing environment are increasingly recognized as critically important, as are acknowledgements that natural resource planning and management processes are not appropriately equipped to manage these uncertainties [17].

While some instream flows are set by regulations that seasonally varying minimum flow requirements, others are more flexible, and thus uncertain. In recent years, schemes have incorporated aspects of market- and gaming-based management (e.g. Environmental Water Account) or negotiated agreements among multiple supplying entities (e.g. Vernalis Adaptive Management Program). All of these methods of providing environmental flows are at risk from climate change and variability.

While management of in-stream flows may not exist in the exact form of EWA and VAMP in the next iteration of California's management of the Delta and its watersheds, , strategies akin to these efforts will certainly be incorporated in future as water management becomes more innovative of necessity [18]. The most effective efforts of this kind will require adaptive, flexible management, bolserted by robust methods to quantify the tradeoffs in decisions under multiple sources of uncertainty.

The proposed dissertation research will develop tools and methods for quantifying the risks in such approaches to instream flow management, and will produce a method to clarify decision-making given risk and risk aversion by decision makers. The questions driving this research include:

- How can we quantify the risks in complex resource management questions like managing in-stream flows for California's aquatic ecosystems?
- How can we craft an acceptable level of risk for environmental flows and ecosystem objectives?

[1] Although definitions of uncertainty and risk vary widely, for the purposes of this proposal, uncertain events are those with unknown probabilities [13], because of error in measurement, natural variability or epistemic uncertainties [14]. Risky events are those for which probabilities can be estimated [13], and risk generically is the product of these probabilities times the consequences of the events. More concrete definitions of economic risk and risk aversion follow in the text.

- Can novel approaches to risk management and risk sharing distribute risks between human and environmental uses for California's water?

1.2 The importance of climate change

Climate change is a global environmental problem, but humans will be most concerned with the local and regional effects. Integrated assessments [19] of climate change can be used to shift both the scale and granularity of analysis from that of coupled Ocean-Atmosphere General Circulation Models (GCMs) to local models [6], and to translate the variables observed from climatic ones (e.g. temperature and precipitation) to those of more direct relevance to human interests (e.g. hydrologic impacts).

Hydrologic systems are among those most vulnerable to climate change [6]. Hydrology is directly influenced by climatic variables, and modeling studies consistently suggest that hydrology will be sensitive to changes in climate [20, 21]. Indeed, these changes are already upon us; observations have revealed climate-driven hydrologic changes at multiple spatial scales [22-25]. Two decades ago, Gleick [26] 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 [23], in the Western U.S. [27], and in California [28, 29]. Such changes in hydrology may impact the ability of California's water system to deliver water during peak demand in the dry summer months for human and environmental needs [30].

Recent studies disagree about the potential difficulty of adapting to climate change in water resources. For example, Tanaka et al. [31] 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. [30] 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.

1.3 Risk and risk aversion

Risk aversion is a central component of human decision-making. 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 [13]. The risk premium is greater the larger the degree of risk aversion and the greater the magnitude of the uncertainty. The importance of risk aversion is only recently beginning to receive attention in the context of climate change.

Risk aversion manifests in instream flow management in California primarily because of the potential for extended dry (or warm) conditions to have profound impacts on the populations of species of concern in California's heavily managed aquatic systems. Thus, management to avoid impacts from such extreme events means that they may need to be given more weight in decision-making. Put in terms of a simplified example, extended dry conditions at particular times have greater impacts on species of concern, and thus are of proportionally greater concern to managers than variability within "normal" years. These differences are not captured by engineering risk analyses that define risk as linear relationships like "probability x consequences".

In spite of the acknowledged ubiquitous importance of risk aversion [13, 32], climate impacts assessments have not explicitly taken the risk aversion of public and private decision-makers into account. Since human decision-makers have risk averse tendencies [13], 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 management analysis could benefit from more sophisticated risk analysis.

1.4 Research objectives

The proposed research will address these issues of climate impacts on instream flow management by integrating climatology, hydrology, and decision analysis. I will incorporate risk aversion into a regional integrated assessment model [19] of water resources in California's Stanislaus, Tuolumne and Merced River Basins (STM Basins). I will build a spatially explicit hydrology and water operations model of these basins, and drive it with downscaled, re-sampled General Circulation Model (GCM) data, generating probabilistic output of instream flow reliability under various climate and management scenarios. I will also elicit risk preferences from decision makers in these basins using economic techniques of utility theory and choice experiments to generate utility functions based on distributions of water deliveries. I will then combine the modeling output with the elicited utility functions to generate clearer estimates of the severity of climate impacts in the water sector and better understanding of potential adaptive responses to climate change.

The expected products of the proposed work will be

- A water resources model that incorporates water operations and hydrology, including snowmelt dynamics, and is able to thus address limitations in existing tools for assessing climate impacts in California. The model will also be more transparent and accessible to managers and stakeholder groups.
- A method for uncertainty analysis in this model, based on Latin Hypercube analysis of 1) resampled downscaled GCM output 2) land use and land cover and 3) population projections. The model output will be probabilistic estimates of instream flows and water deliveries under a variety of scenarios, for use in a risk analysis.
- A generalizable method for empirical application of economic risk analysis techniques to evaluation of management decisions under uncertainty.
- Case studies demonstrating empirically the importance of risk aversion in decision-making under climate change and the potential applicability and implications of this method for negotiated, flexible and adaptive in-stream flow agreements.

2 Literature review

2.1 Probabilistic approaches

To the extent that estimates of water supply reliability [sensu 33, 34, 35] estimate probabilities of water deliveries, these probabilities tend to be derived from historical climate [36]. However, historical data neither accurately represents past [37-39] nor future [28, and refs therein, 29] climatic conditions. This disconnect motivates integration of climatology into water modeling, and the uncertainties inherent in both water systems modeling and climate modeling suggest that formally incorporating risk analysis could improve tools for water planners.

Only recently have scientists begun to incorporate probabilistic methods into sensitivity analyses for describing impacts of climate change [40-43]. Such analyses have mostly been done at a global scale, for example to estimate exceedence probabilities of global average temperature rise [42] or used to evaluate emissions thresholds for 'dangerous climate change' with integrated assessment [40, 41]. Using similar methods in regional and local scale analysis for adaptation is not common [42, but see 44], and suggests a logical next step for impacts analysis.

2.2 Risk-based frameworks

Decision-making without estimates of uncertainty or risk amounts in effect to ignoring the uncertainty present in any model [45, 46], 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 to the real-world implications of uncertainty for human behavior [13, 32], this has scarcely been used in climate change assessments in spite of the inherently uncertain nature of climate change.

The focus of this study is instream flows in California's Central Valley and Delta, determined by decision-makers at CALFED agencies in conjunction with relevant stakeholders. The different agents have different potential responses to disruptions in flows. They face different costs and have different tolerances for risk, and therefore different risk premiums. Managers' risk preference will reflect some weighting of the various components of the ecosystem.

2.3 Institutional context

Water planning and management in the U.S. is primarily a local affair for several reasons. 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 [47]. This is a system that elevates history over rationality, equity or flexibility [48, 49]. The system is also poorly suited to climate non-stationarity [50] because, at least at present, there is no legal precedent in most western states for modifying existing water rights to accommodate different climatic conditions [51].

Against this backdrop of a legal system unlikely to be resilient in the face of climate change, there exists a disconnect between institutional assumptions and scientific understandings of climate. The historical climate in which the institutional system evolved [47] does not capture extreme droughts in the paleoclimate record [37, 39, 52], a projected drying trend in Southewestern North America [53], or the increase in extreme events projected by climate modelers [5, 6]. Water users and the environment alike may thus be more vulnerable to climate risk than managers realize.

The importance of legal and management institutions as drivers of local responses to a global phenomenon, combined with a tendency towards risk aversion by water managers [54-57], suggests that local-scale assessment of climate adaptation with estimates of risk aversion will improve projections of adaptive response to climate change. I propose to build on the theoretical work cited above by quantifying the implications of this risk aversion for decision-making.

2.4 Relationship to other CALFED science efforts

CALFED has funded a large effort to connect climate simulations to ecosystem effects [CASCaDE, 58], along with many other efforts to increase understanding of ecosystem dynamics in relation to hydrology. The research proposed here is complimentary to these efforts. CASCaDE will provide important information of the potential impacts of climate and other scenarios on aquatic ecosystems. However, as was discussed at the May 19, 2008 meeting of the CALFED Independent Science Board, the CASCaDE effort will not provide a framework for using its various modeling inputs in decision making, as its independent outputs and the values placed on them by managers are not comparable in a single analytic framework.

CASCaDE will overlay scenarios of impacts on aquatic assemblages and their dependencies on in-stream flows. Because of uncertainties and complexity of key elements being modeled, and because of the multi-objective nature of decisions about in-stream flows, actually using this model output for decision-making may prove non-trivial. The methods I propose to develop will build on applications in other complex decision-making processes where voluminous and sometimes conflicting information must be processed and integrated. They will explicitly provide probabilistic outputs as opposed to 'bracketing' uncertainties [58], and

provide a framework for decision-makers to combine probabilistic data with the knowledge they gain from other CALFED-funded efforts about ecosystem function in relation to scenarios of instream hydrologic conditions.

3 Research goals and objectives

My goal for this research is to develop an integrated assessment risk and decision analysis method for analyzing instream flow decisions in the face of climatic and other uncertainties. The tools developed in my research will be developed in conjunction with, and made available to, CALFED agencies and stakeholders, and add value to multiple areas of water resources planning and management.

- Stage 1 objective: Produce an integrated hydrology/water operations model that will enable.
- Stage 2 objective: Generate climate input timeseries by resampling method described below; begin probablistic model runs on computer cluster. Begin developing analogues for novel water management instruments.
- Stage 3 objective: Develop method for elicitation of utility functions from resource managers; conduct interviews; generate utility functions for instream flow reliability.
- Stage 4 objective - final synthesis: Combine results from Stage 2 and Stage 3 using Multi-attribute Utility Theory to inform decisions with multiple objectives in the face of uncertainties.

4 Research questions and hypotheses

The main challenge for the proposed research is to finish building a generalizable risk analysis method and a modeling tool for the study area. The main output from the model will be time series of water flows at each node in the model under each scenario of climatic and management conditions. Such data can be used to ask a multitude of questions. In this section, I describe my research questions. Following this overview, I will detail my planned methods.

4.1 Research questions

- How will climate-induced changes to California hydrology impact reliabilty of instream flows?
- What are the risks and uncertainties in planning for instream flow regimes in the face of climate-change and other sources of uncertainties?
- How might risk preferences of various decision-makers influence estimates of the severity of climate change on their water supply? How do (or should) their risk preferences influence decisions about water management?

4.2 Hypotheses

Using modeling methods described below, I will evaluate the following primary hypotheses:

- Reliability of instream flows will decrease during spring and summer under projected climate change.
- Projected climatic impacts will be distributed unevenly among water users because of the variation in seniority of water rights. Under current water law in the west, junior rights holders (including those of recent and future efforts like EWA), those with little access to storage or groundwater, and those without opportunities to develop other sources of water will face an increasing likelihood of shortfall in their water supply under climate change.
- Projected impacts of climate change will be greater when incorporating risk aversion than under assumptions of risk neutrality.
- Utility function for resource managers will exhibit characteristics different from standard theoretical models based on financial markets.

- Water management strategies that formally take risk into account (e.g. formal quantification of water portfolios, dry year options, weather derivatives, inter-basin coordination) could be used to manage climate-induced risk.
- Evaluating climate adaptation options with a formal risk analysis will increase the attractiveness of inter-basin coordination to individual decision-makers as well as from a system-wide perspective.

5 Study area: Stanislaus, Tuolumne, and Merced River Basins, California

The Stanislaus, Tuolumne, and Merced River Basins (STM) in California's Central Valley together form an ideal area for integrating risk assessment into a study of climate adaptation.[2] The three basins are on the western slope of the Sierra Nevada Mountains, where hydrology will be sensitive to climate change [e.g. 26, 27, 59, 60]. Constraints below (water quality regulations at Vernalis) and above (diversions at Friant Dam deplete flows above the Merced River in all but the wettest years)[3] the three basins allow for modeling local dynamics within a large and complex system using some reasonable assumptions. Thus, modeling these basins will allow me to ask meso-scale questions on a dissertation time scale in order to produce a generalizable model for extension to other areas.

The three basins also have physical and management characteristics that will allow me to investigate the geographical determination of climate-induced water supply risk, as well as geographical diversification as a risk reduction strategy. In spite of their physical proximity and similar characteristics when viewed at large extent and coarse grain[4], the basins may differ significantly. Knowles and Cayan [61] suggest that the elevation band from approximately 1300 to 2700 meters will be the most sensitive to projected climate warming, and each basin has a different proportion of its upper watershed within this band (Stanislaus, 62%; Tuolumne, 47%; Merced, 43%), and a different ratio of total area in this band to available water storage (Stanislaus, 2.05; Tuolumne, 1.34; Merced, 1.28). These observation, bolstered by anecdotal evidence from a recent water year [62], suggests that the basins may have different hydrologic response to climate warming, with the Stanislaus potentially the most vulnerable. These geophysical characteristics, combine to make the STM basins a potentially rich arena for analysis relevant to climate change impacts and adaptation.

I propose to conduct several case studies to develop my methods for settings of concern to CALFED: instream flows, urban, and agricultural water supply. First, I will focus on the risks and reliability of a negotiated flow augmentation program, the Vernalis Adaptive Management Program (VAMP), which combines pulse flows from the STM basins with export modifications to adaptively understand the relationship between flows and juvenile salmon survival. One interesting aspect of VAMP is that augmentations diminish after multiple dry years, which may be when fisheries managers want them the most. Given the projected increases in occurrence of extreme events of this type, this case may prove illustrative of the risks perceived and faced by the aquatic ecosystem and its managers.

---

[2] To the question, "why make another model?" I am working with the WEAP framework for a several reasons. 1) Using WEAP will allow me to improve on existing modeling tools such as CALSIM and CALVIN that have limited ability to represent the most important first- and second-order hydrologic impacts of climate change, since they do not endogenously represent mountain hydrology. 2) The WEAP platform provides a more transparent and user-friendly interface that will ultimately be accessible to a broader range of agency and stakeholder users, and thus will be a major contribution to the environmental and water resources community that currently may lack the resources to conduct sensitivity analysis with existing models. 3) Note that the WEAP modeling proposed as part of this dissertation research proposed here will link with other WEAP modeling efforts in California, eventually resulting in a state-wide implementation of this model that will complement existing tools. This modeling approach is being taken seriously by decision-makers: DWR will include results from these efforts in its California Water Plan Update for 2009.

[3] Proposed settlement of pending lawsuits on San Joaquin River flows would be easily integrated into model scenarios.

[4] The basins each are on the Western Slope of the Southern Sierra Nevada Mountains, have large dams contributing significant storage capacity in the foothills, and have heavy agricultural water use in the lowlands, managed by Irrigation Districts and punctuated by urban centers using a combination of groundwater and surface water.

In the water supply arena, a compelling example to investigate will be the San Francisco Public Utilities Commission (SFPUC, gets water from the Tuolumne Basin) and the Oakdale Irrigation District (OID, gets water from the Stanislaus Basin), who are negotiating a water transfer [63]. Investigating *a priori* expectations that the risk aversion of the two agencies (a more risk-averse residential purveyor and a less-risk averse agricultural supplier) should differ based on the sensitivity of their constituencies to water supply reductions could allow for a directly informative application of these techniques.

6 Methods

The proposed research will use an integrated assessment model to translate climate change impacts from global-scale models to a regional and watershed scale water model, with the added innovation of 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 will proceed in several stages. First, I am implementing an integrated hydrology and water operations simulation model of the STM Basins using the Water Evaluation and Planning [WEAP, 64] modeling framework. Second, re-sampling synthetic historical weather time series (and perturbing them based on downscaled GCM data) over many model runs will allow me to generate probability distributions for water supply at each demand node in the model. Third, risk preferences for water organizations in the study basins will be described using an application of economic techniques for utility function elicitation. Combined with probabilistic output from the hydrology model, these utility functions will allow estimation of expected utility. Finally, scenarios of management options for adapting to projected changes will be 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 evaluate the utility to each decision maker of each climate and adaptation scenario to generate both positive and normative evaluations of decision-making and provide a framework for clarifying complex decisions.

6.1 Integrated Assessment overview

Integrated Assessments [19] quantitatively describe potential impacts and adaptation options 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. The Conceptual Model for this proposal gives an overview of the structure of the proposed integrated assessment. The following sections describe its component parts.

6.2 Hydrology and water operations modeling

To understand impacts of climate change and possible adaptive responses in my study area, I am building a spatially explicit hydrology and water operations model of the STM Basins using a Geographic Information System (GIS) and the WEAP modeling platform. WEAP adopts a semi-distributed water balance approach to representing hydrology [64], enabling integration of both water operations and physical hydrology. WEAP has the capacity to represent hydrological processes including snowmelt dynamics, groundwater and groundwater-surfacewater interactions, and water quality constituents including temperature and dissolved oxygen.

Within each weekly time step, the physical hydrology module first routes water through the watershed using a series of quasi-physical parameterized equations. The results of these calculations provide constants that are used to drive a linear program to simulate allocation of water in the managed part of the watershed in the same time step. Preliminary data in Figure 2 shows temperature sensitivity of the hydrograph in the Merced River Basins, based on initial modeling of the hydrology above Lake McClure. Similar results are available for the Stanislaus and Tuolumne Rivers.

I have developed a spatially explicit GIS of the case study basins using ArcGIS [65]. The GIS incorporates the information in Figure 1: elevation [66], vegetation and landcover including cropping patterns [67], a stream network derived from 30 meter Digital Elevation Models [66] using ArcHydro [68], soils [69], water district areas [70-72], population centers and projections, dams [73], canals and other conveyance, and streamflow gage data and locations [74]. These data are being used to develop 1) quasi-physical lumped parameter representation of the hydrology for each sub-catchment within the basins, and 2) a representation of the built infrastructure and demand points to model water allocation to human and environmental demands based on institutional boundaries and water rights. These data are being used to parameterize a WEAP model of these basins (Figure 1).

6.3 Climate inputs

To drive my hydrology model, I will use data from ensembles of coupled ocean-atmosphere GCMs [5, 75]. I will use statistical downscaling to translate GCM data to a scale relevant to my research. Statistical downscaling compares historical GCM results to historical results at a given location, and via regression analysis determines a bias correction factor that can correct the GCM output to have the same statistical distribution as the historical data [76]. This bias correction factor is then applied to GCM projections of future climate scenarios at a regional level.

Multi-model ensembles can estimate the overall spread of GCM projections [75, 77, 78], and I will use them as inputs for stochastic modeling [44]. Studies are beginning to appear in the literature that use ensembles of GCM data to estimate hydrologic uncertainty [79, 80]. I will use philosophically similar methods, but extend the available data by using re-sampling methods to generate many synthetic weather time series. I will use Markov Chain-Monte Carlo methods developed by Yates et al. [81] to re-sample from a daily time-step model designed to represent weather patterns in complex terrain (DAYMET, www.daymet.org) [82]. This method will allow me to generate new time series with the same statistical properties to historical and GCM-derived scenarios, allowing for multiple model runs and generation of probabilistic output from deterministic models.

6.4 Uncertainty and reliability analysis

The uncertainty analysis will be conducted using a Latin Hypercube approach [14, 83], a re-sampling scheme that allows for efficient stratified sampling of input parameter space. This will allow me to maximize my representation of extreme events of greatest interest to risk averse managers, and most efficiently utilize my computational resources (see Budget for more details). I will use the Computer Assisted Reasoning software (CARS, www.evolvinglogic.com) to manage the input and output data for these Latin Hypercube analyses.

Reliability statistics will be modified slightly from standard event or time-based approaches [33-35] to take seasonality into account. I will also employ the xQy statistic [84] (a metric of the lowest (or highest) x-day, y-year flow), using it to generate projected distributions of extended low flows over specific seasonal windows, a metric that may be particularly useful to managers concerned with instream flow regimes.

6.5 Utility theory and risk aversion

Unlike many engineering risk analyses commonly applied in water resources, economic risk describes decisions with assumptions like risk aversion made explicit, which can lead to very different results from standard expected value modeling. I will use multiple attribute utility theory (MAUT) as the theoretical basis for my risk analysis [85-87]. Operationalizing MAUT in this system will require eliciting utility functions for resource managers concerned with in-stream flows (and/or of water managers concerned with water deliveries at the level of water organizations). These functions will be combined with probabilistic flow reliability statistics to get the expected utility for each decision-making organization under each scenario.

In essence, univariate expected utility takes the form $Eu(w) = \int u(w)p(w)dw$ (Eq. 1), 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 will give the expected utility for a given agent under a given modeling scenario. *Comparison of the sensitivity of expected utility of each decision-making organization to each scenario will be the main result of the risk analysis.*

Expected utility theory was initially developed to model univariate decision-making, which is essentially isomorphic to financial decision with a single (monetary) outcome. Using water as the random variable of interest will be conceptually similar, but since there are multiple uses of water with different interests behind them, it will require a multi-attribute approach to do justice to the complexity of water allocation decision-making. In very brief terms, MAUT is an approach that permits the elicitation of multi-attribute utility functions. For example, if amount of water delivered to an organization in a given time period, $\tilde{w}$, is the random variable of interest, and $i = 1,...,n$ index a series of values related to water deliveries (e.g. crop production, fish stocks, urban development potential, etc.), then $\tilde{w}$ will be transformed by a series of functions into a vector for use in the multi-criteria utility function, $U(x_1, x_2, ..., x_n)$.

I will begin with a pilot study that will follow the same general steps as the final case studies. First, I will develop *a priori* schema for water resources decision-making, linking objectives to goals to attributes [sensu 85]. Second, I will work with representative decision-makers to finalize these schema to reflect their priorities. Third, and most crucially, I will use choice experiments [88] to elicit multi-attribute preferences [89] from the decision makers based on hypothetical choices between sets of alternative scenarios involving different combinations of attributes.[5] Fourth, using data from these choice experiments, econometric techniques will be used to estimate the multi-attribute utility function [85]. Finally, these utility functions will be combined with probabilistic output from my modeling as in equation (1) above. Final output will be a comparison of expected utility for each decision-maker under each climate/management scenario, which will in essence 1) represent the sensitivity of complex decision-making to climate and other uncertainty, and 2) provide a framework to clarify decisions by managers faced with competing objectives.

6.6 Scenarios

The above methods will be used to compare a variety of modeling 'experiments' based on climate change impacts and adaptation options. I will develop a set of scenarios based on a) climate model output under multiple emissions scenarios and b) informal institutional analysis of legal, social, and organizational aspects of the case study. The goal will be to compare 1) climate impacts on instream flow regimes under risk neutrality with those incorporating risk preferences, and 2) the potential for operational and institutional changes to reduce these impacts in the water sector.

I will use interviews [90, 91] with decision-makers to understand their institutional constraints and opportunities for adaptation and develop these scenarios. These data will be gathered in the spirit of formal institutional analysis [92, 93], but the focus of my qualitative data collection will be to prepare for the choice experiments that will enable quantification of risk and climate-change impacts.

6.7 Modular approach

My research design is a modular approach that will increase the generalizability of this work and its application in other contexts. Rather than internalizing the hydrology/operations modeling, probabilistic methods, and decision analysis into a single modeling software, I will keep each separate. The main advantage of this modular approach is that I will be able to apply each part in different areas. For example, if other

[5] To illustrate, decision-makers could be offered a series of hypothetical choices that varied the attributes, and levels of each attribute. For example, 10,000 acre-feet of irrigation water in May, versus 8,000 acre-feet of municipal water in October, versus 900 megawatt-hours peak hydropower in August. Similar examples will be developed depending on the specific goals of a given in-stream flow program. Note that these choices will actually be presented based on reliability statistics, but are represented here volumetrically for simplicity.

water models produce different probabilistic results [44], those results would be compatible with my decision analysis framework, or my re-sampling efforts could apply to different hydrological model structures.

7 Tractability and Timeline

I have proposed a broadly integrative modeling effort necessary for moving between global and local scales in a climate impacts assessment. I developed skills and knowledge plus a strong network for support and collaboration to ensure that I am able to complete this research (please see Personal Statement).

7.1 Timeline

	Spring 2008	Summer 2008
		Complete integrated hydrology/water operations model
		Begin developing re-sampling methods
Fall 2008	**Spring 2009**	**Summer 2009**
Begin model runs on computer cluster	Conduct final elicitations for risk analysis, develop econometric methods	Conduct final elicitations for risk analysis, develop econometric methods
Begin defining adaptation scenarios	Begin pilot study	
Re-sampling methods completed		
Fall 2008	**Spring 2009**	**Summer 2009**
Data analysis and writing: Differential impacts on water supply reliability	Complete model runs: adaptation scenarios	Complete dissertation writing including policy relevance
Data analysis and writing: Adaptation options under climate-induced risk	Data analysis and writing: Importance of risk aversion in climate impacts estimates	

8 Contributions to the literature

The proposed research will contribute to the fields of physical geography and risk analysis, by linking multi-scale climatology and hydrology with impacts and adaptation using decision analysis tools.

Physical hydrology The proposed hydrology and water operations model will take up theoretical challenges to the widespread assumption of climate stationarity in water resources planning models [50]. By incorporating probability distributions derived from re-sampled climate models to water operations modeling, it will produce a method to more clearly articulate the hydrologic risks faced by resource managers under climatic non-stationarity. In addition, this case study will address issues of scale [94] 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 [94].

Risk aversion The proposed work will challenge an implicit assumption of risk neutrality in the water resources and climate change literatures by demonstrating its importance in decision-making in these contexts. It will also develop a method for using MAUT to reveal preferences and integrate risk aversion into models of water resources decision-making. An interesting feature of this work will likely be the shape of the utility functions.

In the finance literature from which utility theory originated, an assumption is that utility functions will be increasing and concave [32]. Water presents an interesting case for several reasons. First, low levels of water delivery may have a *negative* utility, given scale economies necessary to operate urban and agricultural water systems. Second, high levels of water delivery may also have a negative utility, as they will represent flooding or crop damage. Third, intermediate levels of delivery may take the form of a step function, as threshold levels of delivery allow in turn for more expensive cropping patterns, increased urbanization, and so forth.

Integrated assessment The most significant contribution of the proposed work lies in its integrative nature. Previous integrated assessments have looked at deterministic sensitivity of hydrology to given climate change scenarios, or have integrated Monte Carlo methods to global scale macro-economic general equilibrium models [41]. To my knowledge, very few [42, 95, 96] have assessed impacts to a specific sector of human concern at scales relevant to local decision-making in a probabilistic manner, and none at this scale have integrated risk aversion. By applying both risk and risk aversion to regional scale climate impacts assessment, this work will produce a set of products that are greater than the sum of the individual parts. Comparison between impacts with and without risk aversion at the scale of this research could contribute to an international debate [2, 3] on the importance of various characteristics in climate impacts assessment.

9 Contributions to CALFED

This research will have direct practical applications and societal significance. As noted above, regional and local human adaptation to global climate change will form a critical part of human response to global climate change. New tools such as those proposed here for understanding the positive and normative implications of this need to adapt will be needed in coming decades by human societies.

The tools produced by this research will have direct application in the study system and other water resource systems. The integrated hydrology/water operations model will be a more transparent, accessible tool than those that currently exist for modeling water operations in California [97, 98]. In the short term, the model will be useful for sensitivity analysis by stakeholders who currently lack access to opaque and complex planning tools [36]. In the longer term, the model will be connected with others to form a statewide representation that integrates functionality not available in current tools.

A quantification of climate impacts on in-stream, urban, and agricultural water users would be a novel and fundamental applied contribution that would directly challenge reluctance in the legal community [51] to accept and act on the need for anticipatory climate change adaptation.

Most fundamentally, but elucidating the risks faced by ecosystems and managers, and by providing structure for decision-making with multiple objectives, the proposed research will provide tools and methods to further more able management of California's threatened ecosystems.

10 Conclusion

In conclusion, the proposed research forms a coherent line of inquiry on climate change impacts and adaptation in water resources. The proposed set of questions and approach to answering them is informed by and will contribute to theory from disparate disciplines. Combining climate, hydrology and water operations modeling with risk analysis will produce a set of products that are greater than the sum of the individual parts, and will contribute directly to improving CALFED agency and stakeholder abilities to meet their goals and objectives in a changing, uncertain environment.

11 Figures

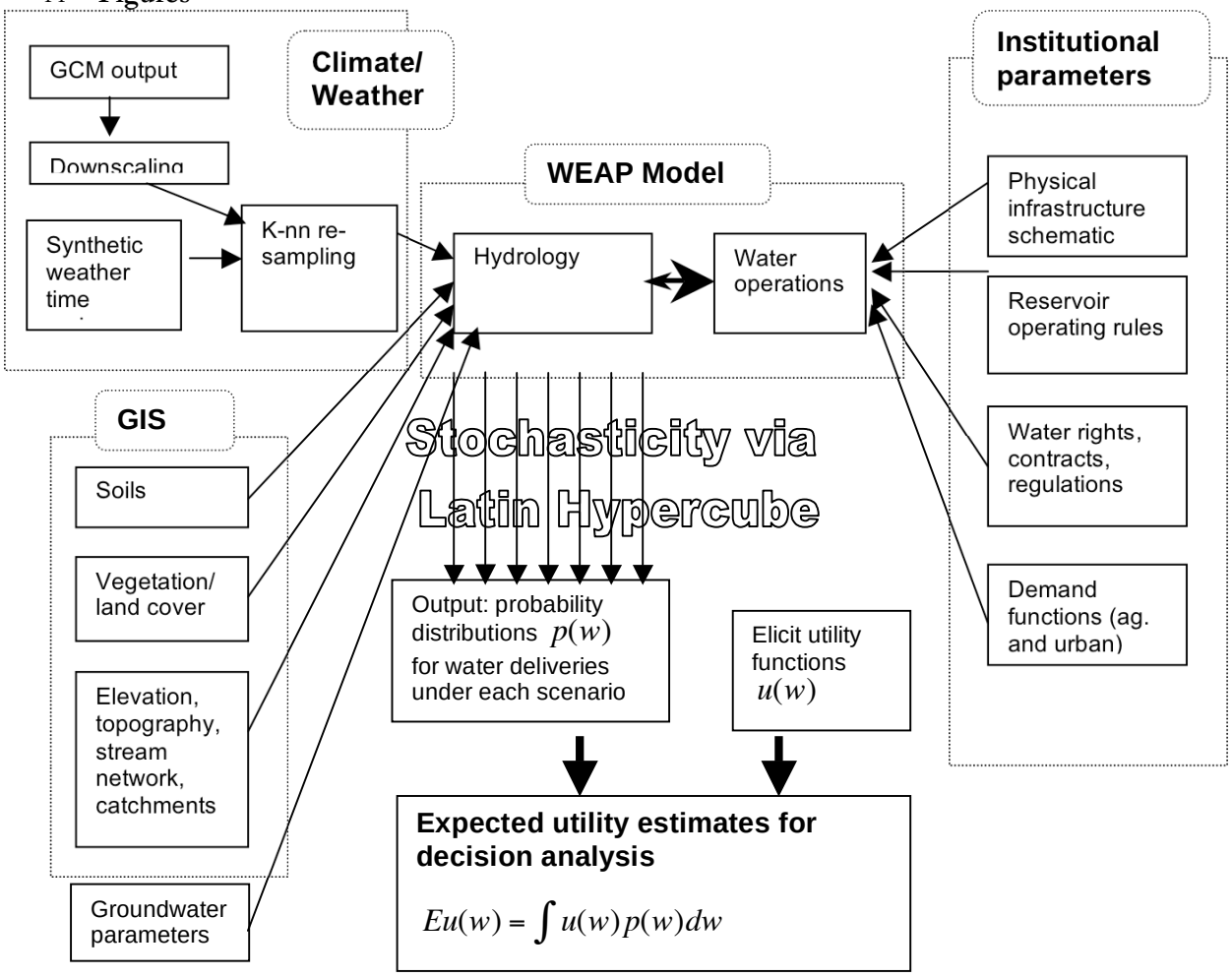

Figure 1: Proposed model structure. Details and citations can be found in the text.

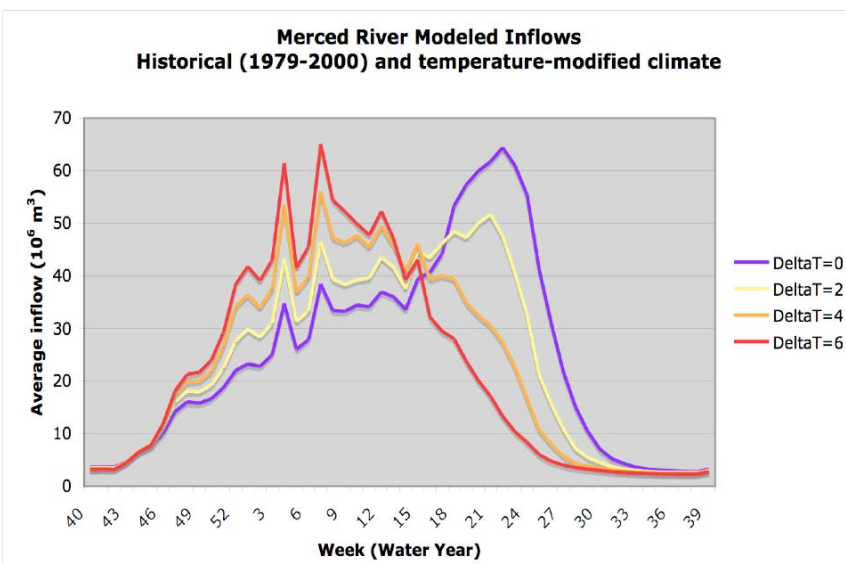

Figure 2: Preliminary hydrology model output, showing temperature sensitivity experiment on the Merced River, with modeled historical climate conditions and temperature perturbations of uniform 2, 4, and 6 degrees C increases.

References

1. Stern N. 2007. *The Economics of Climate Change: The Stern Review*: Cambridge University Press
2. Nordhaus W. 2007. ECONOMICS: Critical Assumptions in the Stern Review on Climate Change. *Science* 317: 201
3. Stern N, Taylor C. 2007. ECONOMICS: Climate Change: Risk, Ethics, and the Stern Review. *Science* 317: 203-4
4. Oreskes N. 2004. Beyond the Ivory Tower: The Scientific Consensus on Climate Change. *Science* 306: 1686-
5. IPCC. 2007. *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. 996 pp. pp.
6. IPCC. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press
7. Pielke R, Prins G, Rayner S, Sarewitz D. 2007. Climate change 2007: Lifting the taboo on adaptation. *Nature* 445: 597-8
8. Dessler AE, Parson EA. 2006. *The Science and Politics of Global Climate Change: A Guide to the Debate*. Cambridge: Cambridge University Press
9. King DA. 2004. Environment - Climate change science: Adapt, mitigate, or ignore? *Science* 303: 176-7
10. California Department of Water Resources. 2006. *Progress on Incorporating Climate Change into Planning and Management of California's Water Resources*, California Department of Water Resources Technical Memorandum Report, Sacramento, CA
11. Luers AL, Moser SC. 2006. *Preparing for the impacts of climate change in California: opportunities and constraints for adaptation. Rep. CEC-500-2005-198-SF*, California Climate Change Center, Berkeley, CA
12. Dettinger MD, Culberson S. 2008. Internalizing Climate Change—Scientific Resource Management and the Climate Change Problem. *San Francisco Estuary and Watershed Science* 6: Article 6, http://repositories.cdlib.org/jmie/sfews/vol/iss2/art6.
13. Chavas J-P. 2004. *Risk Analysis in Theory and Practice*. San Diego and London: Elsevier Academic Press
14. Morgan MG, Henrion M. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge: Cambridge University Press
15. Jones RN. 2000. Managing uncertainty in climate change projections - Issues for impact assessment - An editorial comment. *Climatic Change* 45: 403-19
16. Dessai S, O'Brien K, Hulme M. 2007. Editorial: On uncertainty and climate change. *Global Environmental Change* 17: 1-3
17. Healey M, Dettinger M, Norgaard R. 2008. *2008, State of the science for the Bay-Delta system-Summary for policymakers and the public* CALFED Science Program Report
18. Gleick PH. 2000. The changing water paradigm - A look at twenty-first century water resources development. *Water International* 25: 127-38
19. Parson EA, Fisher-Vanden K. 1997. Integrated Assessment Models of Global Climate Change. *Annual Review of Energy and the Environment* 22: 589-628
20. Arnell N, Liu C. 2001. Hydrology and Water Resources. In *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)*, ed. JJ McCarthy, OF Canziani, NA Leary, DJ Dokken, KS White, pp. 195-233. Cambridge: Cambridge University Press
21. Kundzewicz ZW, Mata LJ, Arnell NW, Do¨ll P, Kabat P, Jime´nez B, Miller KA, Oki T, Sen Z, Shiklomanov IA. 2007. Freshwater resources and their management. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. ML Parry, OF Canziani, JP Palutikof, PJvd Linden, CE Hanson, Eds., pp. 173-210. Cambridge, UK: Cambridge University Press
22. Roos M. 1987. *Possible Changes in California Snowmelt Runoff Patterns*. Presented at Fourth Annual Pacific Climate (PACLIM) Workshop, Pacific Grove, CA
23. Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438: 303-9
24. Zhang X, Zwiers FW, Hegerl GC, Lambert FH, Gillett NP, Solomon S, Stott PA, Nozawa T. 2007. Detection of human influence on twentieth-century precipitation trends. *Nature* 448: 461-5

25. Knowles N, Dettinger MD, Cayan DR. 2006. Trends in snowfall versus rainfall in the Western United States. *Journal of Climate* 19: 4545-59
26. Gleick PH. 1987. Regional Hydrologic Consequences of Increases in Atmospheric Carbon Dioxide and Other Trace Gases. *Climatic Change* 10: 137-61
27. Stewart IT, Cayan DR, Dettinger MD. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* 62: 217-32
28. Vicuna S, Dracup J. 2007. The evolution of climate change impact studies on hydrology and water resources in California. *Climatic Change* 82: 327-50
29. Kiparsky M, Gleick PH. 2003. *Climate Change and California Water Resources: A Survey and Summary of the Literature. Rep. CEC-500-2004-073-ED2*, California Energy Commission
30. Vanrheenen NT, Wood AW, Palmer RN, Lettenmaier DP. 2004. Potential implications of PCM climate change scenarios for Sacramento-San Joaquin River Basin hydrology and water resources. *Climatic Change* 62: 257-81
31. Tanaka SK, Zhu TJ, Lund JR, Howitt RE, Jenkins MW, Pulido MA, Tauber M, Ritzema RS, Ferreira IC. 2006. Climate warming and water management adaptation for California. *Climatic Change* 76: 361-87
32. Eeckhoudt L, Gollier C, Schlesinger H. 2005. *Economic and Financial Decisions under Risk*. Princeton: Princeton University Press
33. Hashimoto T, Stedinger JR, Loucks DP. 1982. Reliability, Resiliency, and Vulnerability Criteria for Water-Resource System Performance Evaluation. *Water Resources Research* 18: 14-20
34. Loucks DP, Van Beek E. 2005. *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*. Paris: UNESCO. 680 pp. pp.
35. Vicuna S, Maurer EP, Joyce B, Dracup JA, Purkey D. 2007. The Sensitivity of California Water Resources to Climate Change Scenarios. *Journal of the American Water Resources Association (JAWRA)* 43: 482-98. DOI: 10.1111/j.752-688.2007.00038.x
36. Draper AJ, Munévar A, Arora SK, Reyes E, Parker NL, Chung FI, Peterson LE. 2004. CalSim: Generalized Model for Reservoir System Analysis. *Journal of Water Resources Planning and Management-Asce* 130: 480-9
37. Stine S. 1994. Extreme and Persistent Drought in California and Patagonia During Medieval Time. *Nature* 369: 546-9
38. Stine S. 1990. Past Climate at Mono Lake. *Nature* 345: 391-
39. Meko DM, Woodhouse CA. 2005. Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado river basins, western USA. *Journal of Hydrology* 308: 196-213
40. Schneider SH, Mastrandrea MD. 2005. Inaugural Article: Probabilistic assessment of "dangerous" climate change and emissions pathways. *PNAS* 102: 15728-35
41. Mastrandrea MD, Schneider SH. 2004. Probabilistic Integrated Assessment of "Dangerous" Climate Change. *Science* 304: 571-5
42. Jones RN. 2004. Incorporating agency into climate change risk assessments - An editorial comment. *Climatic Change* 67: 13-36
43. Allen MR. 2003. Possible or probable? *Nature* 425: 242
44. Brekke LD, Field R, Parker N. 2006. *Model Error Analysis of the CalSim II San Joaquin River Representation*. Presented at Operations Management 2006: Operating Reservoirs in Changing Conditions, Sacramento, California, USA
45. Oreskes N. 2003. The role of quantitative models in science. In *Models in Ecosystem Science*, ed. CD Canham, JJ Cole, WK Lauenroth, pp. 13-31. Princeton: Princeton University Press
46. Beven K. 2000. On model uncertainty, risk and decision making. *Hydrological Processes* 14: 2605-6
47. Sax JL, Thompson Jr. BH, Leshy JD, Abrams RH. 2006. *Legal Control of Water Resources: Cases and Materials, Fourth Edition*. St. Paul, MN: Thomson West
48. Walker RA, Williams MJ. 1982. Water from Power - Water Supply and Regional Growth in the Santa-Clara Valley. *Economic Geography* 58: 95-119
49. Worster D. 1985. *Rivers of Empire: Water, Aridity, and the Growth of the American West*. New York: Pantheon Books. 402 pp.
50. Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008. CLIMATE CHANGE: Stationarity Is Dead: Whither Water Management? *Science* 319: 573-4
51. Doremus H, Hanemann M. in press. The Challenges of Dynamic Water Management in the American West. *UCLA Law Review*

52. Woodhouse CA, Lukas JJ. 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change* 78: 293-315
53. Seager R, Ting M, Held I, Kushnir Y, Lu J, Vecchi G, Huang H-P, Harnik N, Leetmaa A, Lau N-C, Li C, Velez J, Naik N. 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* 316: 1181-4
54. Lach D, Ingram H, Rayner S. 2005. Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations *Texas Law Review* 83: 2027-53
55. Haddad BM. 1999. *Rivers of Gold: Designing Markets to Allocate Water in California*. Washington, D.C.: Island Press
56. Rayner S, Lach D, Ingram H. 2005. Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts. *Climatic Change* 69: 197-227
57. O'Connor RE, Yarnal B, Dow K, Jocoy CL, Carbone GJ. 2005. Feeling at risk matters: Water managers and the decision to use forecasts. *Risk Analysis* 25: 1265-75
58. Cloern JE, and others. 2004. *CASCADE: Computational Assessments of Scenarios of Change for the Delta Ecosystem, Proposal to CALFED Science Program PSP*, USGS, Menlo Park, CA
59. Dettinger MD, Cayan DR, Meyer M, Jeton AE. 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: 283-317
60. Knowles N, Cayan DR. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters* 29: 1891
61. Knowles N, Cayan DR. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed. *Climatic Change* 62: 319-36
62. Pope D. 2006. Hydroelectric Project Manager, Merced Irrigation District. Personal communication, December 2006.
63. Fischer D. 2007. TUOLUMNE RIVER WATER: Activists call PUC plan an unwise water grab; Two environmental groups say Tuolumne River water would go for suburban landscaping. In *Oakland Tribune*. Oakland, CA
64. Yates D, Sieber J, Purkey D, Huber-Lee A. 2005. WEAP21 - A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics. *Water International* 30: 487-500
65. ESRI. 2007. ArcGIS 9.2. Redlands, CA: ESRI.
66. USGS. 2007. National Elevation Dataset. United States Geological Survey. http://seamless.usgs.gov.
67. CADWR. 2007. California Land and Water Use. California Department of Water Resources. http://www.landwateruse.water.ca.gov/basicdata/landuse/standards.cfm.
68. ESRI. 2007. ArcHydro Toolkit. Redlands, CA: ESRI.
69. USDA. 2006. Soil Survey Geographic (SSURGO) Database. United States Department of Agriculture. http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/.
70. USBR. 2006. Federal Water Districts - Mid-Pacific Region version 4.0. U.S. Bureau of Reclamation http://gis.ca.gov.
71. USBR. 2003. State Water Districts for California version 1.1. U.S. Bureau of Reclamation in coordination with the California Department of Water Resources http://gis.ca.gov.
72. USBR. 2003. 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 http://gis.ca.gov.
73. National Atlas of the United States. 2006. Major Dams of the United States. National Atlas of the United States. http://nationalatlas.gov/atlasftp.html?openChapters=chpwater#chpwater.
74. USGS. 2007. National Water Information System. United States Geological Survey. http://waterdata.usgs.gov/nwis.
75. Dettinger MD. 2006. A component-resampling approach for estimating probability distributions from small forecast ensembles. *Climatic Change* 76: 149-68
76. Wood AW, Leung LR, Sridhar V, Lettenmaier DP. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change* 62: 189-216
77. Dettinger MD. 2004. *From Climate-Change Spaghetti to Climate-Change Distribution*. *Rep*. *500-04-028*, California Energy Commission, Public Interest Energy Research Program Discussion Paper
78. Dettinger MD. 2005. From Climate-Change Spaghetti to Climate-Change Distributions for 21st Century California. *San Francisco Estuary and Watershed Science* 3: Article 4, http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4

79. Maurer EP, Duffy PB. 2005. Uncertainty in projections of streamflow changes due to climate change in California. *Geophysical Research Letters* 32
80. Maurer E. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. *Climatic Change* 82: 309-25
81. Yates D, Gangopadhyay S, Rajagopalan B, Strzepek K. 2003. A technique for generating regional climate scenarios using a nearest-neighbor algorithm. *Water Resources Research* 39
82. Thornton PE, Running SW, White MA. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology* 190: 214-51
83. McKay MD, Beckman RJ, Conover WJ. 1979. Comparison of 3 Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics* 21: 239-45
84. Harte J, El-Gasseir M. 1978. Energy and Water. *Science* 199: 623-34
85. Keeny R, Raiffa H. 1993. *Decision Making with Multiple Objectives: Preferences and Value Tradeoffs*. Cambridge, UK: Cambridge University Press
86. Dyer JS, Fishburn PC, Steuer RE, Wallenius J, Zionts S. 1992. Multiple Criteria Decision Making, Multiattribute Utility Theory: The Next Ten Years. *Management Science* 38: 645-54
87. Dyer J. 2005. Maut — Multiattribute Utility Theory. In *Multiple Criteria Decision Analysis: State of the Art Surveys*, ed. J Figueira, S Greco, M Ehrgott, pp. 265-92. Dordrecht: Springer
88. Louviere JJ, Hensher DA, Swait JD. 2000. *Stated Choice Methods: Analysis and Applications*. Cambridge: Cambridge University Press
89. Brown TC, Adamowicz WL. 2003. Attribute-Based Methods. In *A Primer on Nonmarket Valuation*, ed. TC Brown, KJ Boyle, PA Champ. Dordrecht: Kluwer Academic Publishers
90. Lofland J, Lofland LH. 1984. Analyzing social settings: A guide to qualitative research and analysis. *Belmont, CA: Wadsworth*
91. Weiss RS. 1995. *Learning From Strangers: The Art and Method of Qualitative Interview Studies*: Free Press. 256 pp. pp.
92. Blomquist W, Schlager E, Heikkila T. 2004. *Common Waters, Diverging Streams: Linking Institutions and Water Management in Arizona, California, and Colorado*: Resources for the Future
93. Heikkila T. 2003. Coordination in water resource management: the impact of water rights institutions. *Water Policy* 5
94. Gibson CC, Ostrom E, Ahn TK. 2000. The concept of scale and the human dimensions of global change: a survey. *Ecological Economics* 32: 217-39
95. Jones RN. 2000. Analysing the risk of climate change using an irrigation demand model. *Climate Research* 14: 89-100
96. Luo QY, Jones RN, Williams M, Bryan B, Bellotti W. 2005. Probabilistic distributions of regional climate change and their application in risk analysis of wheat production. *Climate Research* 29: 41-52
97. Close A, Hanneman WM, Labadie JW, Loucks DP, Lund JR, McKinney DC, Stedinger JR. 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
98. Ferreira IC, Tanaka SK, Hollinshead SP, Lund JR. 2005. Musings on a model: CalSim II in California's water community. *San Francisco Estuary and Watershed Science* 3: Article 1 (http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art)
99. Brown TC. 2006. Trends in water market activity and price in the western United States. *Water Resources Research* 42: doi:10.1029/2005WR004180
100. Thompson Jr. BH. 1993. Institutional Perspectives on Water Policy and Markets. *California Law Review* 81: 671-764