DELTA RISK MANAGEMENT STRATEGY

INITIAL TECHNICAL FRAMEWORK PAPER

ASSESSING EFFECTS OF CLIMATE CHANGE ON FLOOD RISK IN THE SACRAMENTO–SAN JOAQUIN DELTA

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Assessing Effects of Climate Change on Flood Risk in the Sacramento–San Joaquin Delta

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Foreword

The purpose of the Delta Risk Management Strategy (DRMS) Initial Technical Framework (ITF) is to guide the analysis of specific technical topics as they relate to assessing potential risks to Delta levees and assets resulting from various potential impacts (e.g., floods, earthquakes, subsidence, and climate change). These ITFs are considered “starting points” for the work that is to proceed on each topic. As the work is developed, improvements or modifications to the methodology presented in this ITF may occur.

Increased flood frequency is a predicted consequence of increased atmospheric greenhouse gases (“global warming”) in California (Dettinger et al. 2004; Hayhoe et al. 2004; Maurer et al. 2006) and elsewhere (e.g., Whetton et at. 1993; Trenberth 1999). Mechanisms whereby increased atmospheric greenhouse gases lead to elevated flood risk include sea level rise, more intense daily precipitation events, and shifts in the seasonal timing of river flows. All of these may be occurring now or may occur in the future in California, and could contribute to increased flood risk and levee failure in the Delta. The key quantities needed to estimate climate-change impacts on the Delta are projections of sea-level rise, daily-timescale flows on rivers feeding the system, and local wind speeds and directions. All these will be handled probabilistically, as a way of accounting for uncertainties in the regional-scale manifestations of climate change.

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1.0 BACKGROUND

Increased flood frequency is a predicted consequence of increased atmospheric greenhouse gases (“global warming”) in California (Dettinger et al. 2004; Hayhoe et al. 2004; Maurer et al. 2006) and elsewhere (e.g., Whetton et al. 1993; Trenberth 1999; Thumerer et al. 2000; Middlekoop et al. 2001). Consistent with this, the frequency of major floods was observed to increase worldwide during the 20th century (Milly et al. 2002).

Mechanisms whereby increased atmospheric greenhouse gases lead to elevated flood risk include sea level rise, more intense daily precipitation events, and shifts in the seasonal timing of river flows. All of these may be occurring now or may occur in the future in California, and could contribute to increased flood risk and levee failure in the Delta. The highest observed water levels in the Delta have resulted to a large extent from short-term increases in river flows, rather than sea level variations (Cayan et al. 2006).

Increases in mean sea level result from thermal expansion of seawater, as well as from increased ocean mass resulting from melting of land ice sheets and glaciers. Imperfect understanding of both these mechanisms contributes to uncertainties in projections of future rise in mean sea levels; however, Overpeck et al. (2006) suggest that the latter factor contributes more uncertainty, and that previous projections may have severely underestimated future sea level rise.

The immediate flood risk associated with sea level rise results from short-term fluctuations in sea level; these are due to several factors, including astronomical tides, storm surge, changes in regional water temperature (due to e.g., El Nino). All of these factors except tides are likely to be affected by climate change; therefore, it may not be accurate to assume that that short-term fluctuations in sea level about the mean will be the same in the future as today. Furthermore, many of the factors that drive short-term sea level fluctuations also affect river flows. For example, a strong storm can result in higher-than-normal sea levels as well as increased river flows. Thus, we need to account for these correlations in order to accurately project future flood risk and levee vulnerability.

As noted above, the highest historical water levels in the Delta have been caused by increased river input rather than variations in sea level. The future behavior of daily and longer–time scale river flows will be strongly affected by climate change. Changes in the seasonal timing of flows on California rivers is a predicted consequence of increased atmospheric greenhouse gases (e.g., Gleick 1986; Stewart et al. 2004; Maurer et al. 2006). This shift results from warming, which increases the fraction of precipitation as rain, and thus increases rainy-season (winter) runoff and river flows, and reduces late-season runoff and river flows, which result primarily from snow-melt. Because this phenomenon results from warming, it is a robust prediction even though different climate models do not agree on the magnitude or sign of predicted changes in precipitation (Maurer and Duffy 2005).

Changes in river flow timing of the sort predicted to result from warming have been observed on major rivers in California. (Figure 1) (Roos 1991; Stewart et al. 2004). This consistency between model results and observations lends credibility to the predictions. Nonetheless, recent analyses by Maurer and Duffy (2005) indicate that observed changes in river flow timing have not yet exceeded those possible from natural climate variability.

Thus, observed changes in river flow timing are consistent with predicted effects of increased greenhouse gases, but also with natural variability.

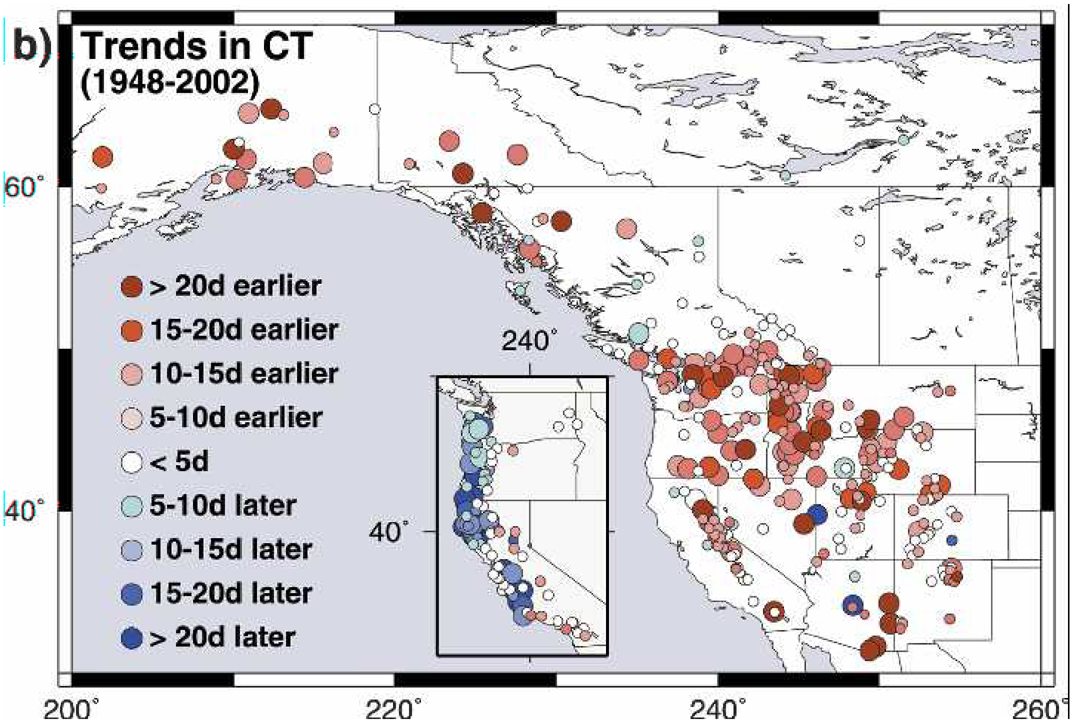

Figure 1: Observed changes in the seasonal timing of river flows in California.

On Figure 1, colors indicate 50-year trends in date when half of total annual flow has occurred. (Thus, red indicates a river where flow is occurring earlier in the year.) Main panel shows results for snow-fed rivers; inset shows results for other rivers. Earlier flows on snow-fed rivers only indicate that earlier flows are due to a combination of reduced snow and earlier snow melt, resulting from warming (Stewart et al. 2004).

On Figure 2, flows are calculated using the VIC surface hydrology model driven by meteorology obtained from 11 different climate models, shown in the legend. Despite different predicted temperature and precipitation responses to increased atmospheric CO2 in the different models, the prediction of increased winter season flows and reduced late-season flows is robust. The increases in winter flows suggest increased flood risk during that season. From Maurer and Duffy (2005).

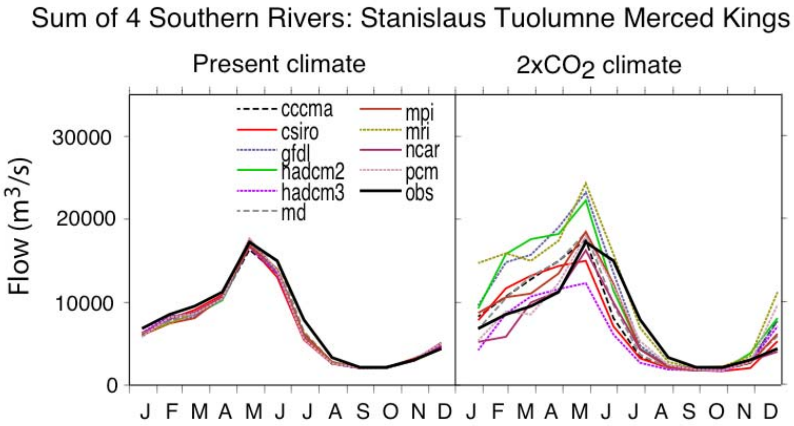

Figure 2: Simulated flows on 4 rivers in the Southern Sierra in the present climate (left) and in a climate resulting from a doubling of the atmospheric concentration of carbon dioxide (right).

Altered river flow timing has consequences for both water supply and flood risk. While a number of studies (e.g., Zhu et al. 2005) have quantitatively assessed impacts on the water supply, this is not true of flood risk. Water-supply impacts are projected based on monthly-mean river flows; flood risk depends on daily-timescale flows, for which published projections are not available. Thus, quantitative assessments of future river flows or flood risk in the Delta are not available “off-the-shelf.” Nonetheless, large predicted increases in monthly-mean wintertime river flows (e.g., Maurer et al. 2006) make increased daily timescale flows, and thus increased flood risk, seem highly likely.

In addition to flood risk, climate change will affect Delta salinity values through sea level rise, and will affect levee vulnerability through possible changes in local wind speeds and/or directions. Finally, the DRMS project needs statewide temperature projections in order to estimate future water demand. Thus, the DRMS project needs projections of the following climate-related quantities:

- Sea level, including short-term variations, and the effects of astronomical tides (Task 1);
- Flow rates on rivers feeding the Delta, which are needed on daily or shorter time scales (Task 2);
- Local wind speeds and directions, which are needed to estimate wind/wave effects on levees (Task 3); and
- State-wide near-surface air temperatures, which are needed to estimate water demand (Task 4).

We outline below approaches to projecting all these quantities.

2.0 TECHNICAL APPROACH

As noted above, the key quantities needed to estimate climate-change impacts on the Delta are projections of sea-level rise, daily-timescale flows on rivers feeding the system, and local wind speeds and directions. All these will be handled probabilistically, as a way of accounting for uncertainties in the regional-scale manifestations of climate change.

- **Task 1: Sea Level Rise**

As discussed above, flood risk depends on sea level on daily or shorter time scales. Furthermore, sea level fluctuations in the Delta are smaller than those on the coast. Fortuitously, Cayan et al. (2006) have recently completed a careful and thorough study projecting future sea level rise in California; this includes changes in the mean level as well as in short-term fluctuations about the mean. Sea levels for the period between the present and 2100 are projected, based on results of two global climate models and two greenhouse gas emissions scenarios.

Cayan has generously offered to make these results available to the DRMS; hence, our approach to estimating future sea levels will be based as closely as possible on the projections of Cayan et al. (2006). This will save effort, and resources and will speed the completion of the project. This approach also adheres to the overall DRMS philosophy of using existing results whenever possible. Although the report focuses primarily on coastal sea levels, sea levels in the Delta are discussed. It is not clear how much effort will be needed to adapt the results of Cayan et al. (2006) for use by the DRMS project. At a minimum, we will need to make projections for the 2200 time frame.

Cayan et al. (2006) model instantaneous local sea level as the sum of several terms:

    - Mean sea level rise, which is based on GCM projections of thermal expansion, and estimates of increased ocean mass (melting of land ice) estimated from a simpler climate model. Three future-climate scenarios are considered.
    - Astronomical tides, taken from projections in the published literature for coastal tides, and adjusted using an empirical correction factor to estimate tidal fluctuations in the Delta.
    - El Nino fluctuations, based on a historical, empirical relationship between Nino 3.4 SSTs and non-tidal sea level.
    - Synoptic fluctuations, based on a historical, empirical relationship between non-tidal sea level and local sea-level pressure and wind stress.

  - **Task 1.1: Adapt Sea Level Rise Projections to Delta.** The sea level rise projections of Cayan et al. (2006), which apply to coastal stations, will be adapted to apply to the Delta region.
  - **Task 1.2: Cayan et al. Project a Maximum of 0.72 m Sea Level Rise by 2100.** Other models and scenarios that they considered resulted in substantially lower projections. The IPCC Third Assessment Report (2001) projected increases in mean sea level ranging from 9 to 88 cm by 2100. By analogy with the last interglacial (~130KA), Overpeck et al. (2006) argue that sea level rise due to anthropogenic climate change might be much greater than this—up to several meters. However, this process might require many centuries to complete, so impact on sea levels in the DRMS study horizon might be small.

  - **Task 1.3: Estimate Sea Level Rise for 2200.** The projections of Cayan et al. (2006) cover the period 2000–2100. We will use these projections and simple scaling relationships to estimate sea levels for 2200.

- **Task 2: Daily Timescale River Flows**

The other key ingredient—projected future daily timescale river flows—is more difficult to obtain than sea-level rise projections, since published projections do not exist. Below we describe a process for predicting daily-timescale river flows that is based on the latest science and can be completed within time and budget constraints. This approach adheres to the overall DRMS philosophy of using existing results whenever possible.

The effects of climate change on daily-timescale river flows result from the combination of multiple interacting factors: precipitation amounts will change on daily and longer time scales; the form of mountain precipitation will shift from snow to rain; evaporation will tend to increase, surface albedos and soil moisture content will change, etc. Further complicating the picture is the fact that these effects will not be spatially homogenous within the State, due to variations in elevation, baseline climate, and other factors. Because of this complexity, future-climate river flows should be predicted using physically-based models, rather than simpler approaches such as ad hoc alterations to the statistics of historical river flows.

Unimpaired future daily-timescale river flows in California were recently simulated as part of preparing the upcoming "Report to the Governor and Legislature on Climate Change" (http://www.climatechange.ca.gov/climate_action_team/reports/index.html). For this Report, Prof. Edwin Maurer of Santa Clara University calculated daily-mean unimpaired river flows for 20 major rivers in California. These rivers are those needed as inputs to the Calsim II water operations model, and include the major inflows feeding the Delta. These flows were calculated using the Variable Infiltration Capacity (VIC) (Liang et al. 1994) surface hydrology model, using meteorological input from simulations of the 21st century performed for the upcoming IPCC 4th Assessment Report, and archived at Lawrence Livermore National Laboratory (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). To aid in quantifying uncertainties, river flows were calculated based on output from 22 independent climate models. As discussed below, we propose using these simulated unimpaired flows for this project, with modifications to estimate after-reservoir flow values.

The VIC model treats the surface energy budget, snow on the ground, soil moisture, runoff, and river flows, and related processes. It is driven by meteorological input (precipitation, near-surface temperatures, and downwelling solar radiation), obtained in this case from simulations of the 21st century performed with global climate models (GCMs), and using scenarios for future greenhouse gas emissions.

VIC and other surface hydrology models require daily-mean meteorological input. Daily-timescale results of GCMs, however, are not always reliable. In particular, GCMS have a tendency to predict too many rainy days and not enough rain per rainy day (Mearns et al. 1995; Duffy et al. 2003; Sun and Solomon 2006). This would result in a tendency to underestimate flood risk. We therefore drive VIC with daily mean precipitation values estimated from monthly-mean GCM results using statistical relationships derived from observations. This "temporal downscaling" process assumes that the relationship between monthly precipitation amounts and daily precipitation amounts will be fixed as climate changes. In essence, this procedure assumes that the number of rainy days per month will remain fixed under climate change, and that any change in monthly precipitation amounts will come in the form of changes in precipitation intensity (precipitation amounts on days when significant precipitation occurs).

In addition to the temporal downscaling described above, GCM results are spatially downscaled and bias corrected as described below, before being passed to VIC. To adapt GCM output for hydrological study we will apply a bias correction technique originally developed by Wood et al. (2002) for using global model forecast output for long-range stream flow forecasting, later adapted for use in studies examining the hydrologic impacts of climate change (Hayhoe et al. 2004; Maurer and Duffy 2005; Payne et al. 2004; Van Rheenan et al. 2004). This is an empirical statistical technique that maps precipitation and temperature probabilities (at a monthly scale) during a historical period (such as 1950-1999) from the GCM to the concurrent historical record. The historical observational data set for this effort will be the gridded National Climatic Data Center Cooperative Observer station data aggregated up to a 2° latitude-longitude spatial resolution. The quantiles for monthly GCM simulated precipitation and temperature are then mapped to the same quantiles for the observationally based CDF. For temperature, the linear trend will be removed prior to this bias correction and replaced afterward, to avoid increasing sampling at the tails of the CDF as temperatures rise. In this way the probability distribution of observations will reproduced by the bias corrected climate model data for the overlapping climatological period, while both the mean and variability of future climate can evolve according to GCM projections. For spatially interpolating the monthly bias-corrected precipitation and temperature, we will apply the method of Wood et al. (2002, 2004), which for each month interpolates the bias corrected GCM anomalies, expressed as a ratio (for P) and shift (for T) relative to the climatological period at each 2° GCM grid cell to the centers of 1/8 degree hydrologic model grid cells over California. These factors are then applied to the 1/8 degree gridded precipitation and T, the resolution of the final product.

The models used in the work described here are state-of-the-art and are thoroughly documented. Another asset is that the use meteorology from multiple climate models gives an indication of climate uncertainty, i.e., uncertainty resulting from imperfect understanding of the climate response to increased greenhouse gases and other perturbing factors. Thus, the work described above gets us most of the way to what we need; its principal limitation is that the end-product is unimpaired river flows, whereas what is needed for this project is after-reservoir flow rates.

We recommend following tasks for simulating river flows:

- **Task 2.1: Obtain Projections of Unimpaired River Flows Used for Governor's Report.** These data exist at Santa Clara University and should be obtainable with minimal work.
- **Task 2.2: Prepare Probabilistic Projections of Unimpaired River Flows.** This will consist of (1) extracting flows near years 2055 and 2105 from the time series simulated by Maurer; and (2) combining results from multiple models into one probabilistic distribution.

  - **Task 2.3: Reservoir Operations Modeling.** The above activities will predict natural (unimpaired) flows on rivers entering the Delta. Flood-risk, however, depends on actual flows; these are significantly influenced by the operation of upstream man-made reservoirs, which can absorb strong surges and thus reduce flood risk. We therefore need to perform at least simplified reservoir operations modeling, in order to convert projected unimpaired flows to actual flows entering the Delta. We will therefore apply simple reservoir operations models for the major upstream reservoirs. We will assume, at least initially, that reservoir "rule curves" will be the same in the future as today.

- **Task 3: In-Delta Wind Velocities**

As noted above, projections of in-Delta wind velocities are needed to estimate future effects of wind/wave action on levee integrity. It is plausible to argue that these wind velocities might increase in the future, since in a warming climate the land-sea temperature gradient, which is the primary driver of winds through the Delta, is thought to be likely to increase. Typical global climate models do not have sufficient spatial resolution to credibly estimate wind velocities on the scale of the Delta; even typical nested models (which use ~50-km grid spacing) may not be adequate. M. Snyder et al. at UC Santa Cruz are as leading experts on future-climate winds in California (Snyder et al. 2003; Diffenbaugh et al. 2003a, 2003b). In collaboration with M. Snyder, we will evaluate and analyze existing simulations performed at UC Santa Cruz; we will use these to project changes in in-Delta wind velocities. In addition, we will research the existence and availability of other suitable simulations, and will extract daily wind velocity statistics from any that we may find.

- **Task 4: Statewide Near-Surface Air Temperatures.**

Future water demand depends on both demographic and climatic factors. Of these climatic factors, the most important is near-surface air temperature. We will obtain projections of future near-surface air temperatures for 2050 and 2100 form simulation results submitted to the IPCC 4th Assessment report data archive at Lawrence Livermore National Laboratory. Uncertainties will be estimated by including results from a number of independent climate models and a number of IPCC SARS greenhouse gas emissions scenarios.

- **Task 5: Coordination, Synthesis, and Documentation.**

Results pertaining to climate change will be used by the hydrodynamics modeling (DeGeorge and Gross) and flood risk (MacDonald et al.) subgroups. We will coordinate closely with them to ensure that they receive the information they need in the correct format, etc. Work performed on all climate-related topics will be summarized and documented. This will include description of methods used, assumptions made, uncertainties, references to published literature, etc.

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