

## 7.0 Conclusions and Recommendations

The vision of the Integrated Forecast and Reservoir Management (INFORM) project is to increase efficiency of water use in Northern California using meteorological/climate, hydrologic and decision science. The three primary project objectives of INFORM are to:

- (a) Implement an integrated forecast-management system for the Northern California reservoirs using real-time data
- (b) Perform tests with actual data and with management input
- (c) Demonstrate the utility of climate and hydrologic forecasts for water resources management in Northern California

The first three-year phase of INFORM met the first two objectives by designing and implementing the INFORM forecast-decision system in close collaboration of forecast and management agencies in Northern California, and by testing all of its components with historical data. Chapter 2 of this report documents the design and implementation of the real-time and off-line components of the system. The critical input of forecast and management agencies of Northern California water supply contributed substantially to the final system configuration. Chapters 3, 4 and 5 document the model component formulations and extensive tests with historical data of the precipitation and temperature downscaling model, the hydrologic snow-soil-channel models and of the decision model, respectively.

The first phase of INFORM also provided an initial demonstration of the utility of the INFORM hydrometeorological forecasts for (a) the mid-range management of the large reservoirs in Northern California (Folsom, Oroville, Shasta and Trinity) with real time data from the 2005 - 2006 wet season, and (b) the long range management of the entire Northern California river and reservoir system including the Bay Delta. Chapter 6 of this report contains these initial assessments and suggests that operation of the INFORM forecast and decision system for two to three additional wet seasons is necessary to complete the demonstration. The present chapter discusses the overarching and detailed conclusions of the project, and puts forth recommendations for future development. Conclusions and recommendations are separated into those that concern the INFORM forecast component and those that concern the decision component of the system for easier reference by forecast and management agencies.

### 7.1 Overarching Conclusions

A first conclusion is that, with the present day real-time availability of forecast information from the National Centers for Environmental Prediction (NCEP) and with real time observed precipitation and temperature as well as hydrologic model state values from the California Nevada River Forecast Center (CNRFC), integrated forecast-management systems are realizable as operational decision support tools for management and planning of California water resources. Such systems assist water managers to translate forecasts and their uncertainty into risk-based policies. They

advance current operational practices by (a) incorporating forecast uncertainty in decisions on a range of time scales, and (b) allowing for regional coordination of management decisions.

With respect to the INFORM forecast component, simulations and ensemble forecasts averaged over lead times from 6 hours to 5 days, when compared against historical and real time observations have skill for mean areal precipitation (MAP), mean areal surface air temperature (MAT), and reservoir inflows for a range of elevations and latitudes and for spatial scales ranging from a few hundred square kilometers to several thousand square kilometers.

The most significant contribution of the decision support system is to provide an integrated planning and management framework and tools that address three critical challenges: (a) Quantitative and explicit forecast utilization by the decision tools and processes; (b) Integration of planning, management, and operational decision making tools and functions within each management agency; and (c) Establishment of a common set of analytical tools that facilitate agency communication, cooperation, and coordination.

## **7.2 Specific Conclusions**

### **7.2.1 Forecast Component**

Several additional conclusions pertaining to the forecast component are supported by the INFORM work reported in this document. These are listed below:

1. MAP from the INFORM 10-km-resolution orographic precipitation model using boundary conditions from large scale (2.5°x2.5°) NCEP reanalysis explains 20 – 40 % of the historical (CNRFC estimated) 6-hourly MAP variance for most Sierra Nevada catchments. The model generally tends to overestimate low MAP values. It produces higher scores for catchments with higher exposure to 700mbar wind flow from the upstream boundary point. The exposure of the INFORM domain Sierra Nevada catchments is such that for the Oakland boundary point, southwesterly flow produces higher scores than northwesterly flow. The explained portion of observed precipitation variance increases substantially for forecast averaging times greater than 6 hours.
2. Gridded estimates of 6-hourly surface air temperature from the INFORM surface temperature downscaling model using boundary conditions from large scale (2.5°x2.5°) NCEP reanalysis compare well with corresponding historical station measurements in the INFORM domain during the wet season. A tendency for underestimation was noted for some northern catchments in the INFORM domain of Northern California.
3. The ensemble streamflow prediction (ESP) methodology when used with the hydrologic models of the INFORM system and with historical MAP and MAT data generates ensemble flows that are generally reliable and with good

resolution in terms of predicting the 30- to 90-day wet-season flow volumes being in the upper or lower third (tercile) of their distribution. Notable exception is the case of Shasta inflow volumes being in the upper tercile of their distribution, for which the ensemble forecasts over estimate the observed frequencies. For all the application reservoirs, results for upper terciles are more reliable than those for lower terciles, and 30-day inflow volumes are associated with more reliable results than 60- and 90-day inflow volumes.

4. Improvement in reliability is limited when statistically-downscaled climate forecast system (CFS) ensemble forecasts of monthly-resolution are used to condition the ESP. This is also evident from the intercomparison of the decision model results corresponding to unconditional ESP and CFS-conditioned ESP (see Section 7.2.2).
5. Sensitivity analysis of the snow model of the INFORM hydrologic forecast component (also used by CNRFC for operational forecasting in the Sierras) resulted in the identification of the snow depletion curve as the most important parameterized curve for calibration. This curve influences significantly the evolution of snow accumulation and ablation during the wet season. This analysis also showed that systematic or random errors in surface air temperature input to the snow model result in significant perturbations of the snow water equivalent evolution.
6. Evaluation of the operational CNRFC hydrologic model simulations using historical data of unimpaired flows showed that the model simulations capture the overall hydrologic response well. Poor performance during periods of medium to low flows at some catchments within the INFORM domain is often associated with regulation in upstream reservoirs which alter the downstream natural flow. Model performance is poorest overall during summer months (August through September). Also, during the wet season, performance is generally better in early winter than in late winter and spring. Model snow water equivalent evolution is in agreement with that of daily observations from point sensors, with better agreement at lower elevations.
7. The INFORM hydrologic model simulations with historical data exhibit performance that is very similar to the analogous simulations of the CNRFC operational model. The INFORM model simulations capture the observed hydrologic response for all the watersheds well with respect to timing and magnitude and without significant bias.
8. The initial evaluation of the real-time performance of the forecast component of the INFORM system with data from the wet season 2005-2006 (“dry run”) and with some interruptions of the real-time links to CNRFC and NCEP, showed that, over several catchments, for several periods, and for lead times out to 5 days, the MAP and MAT 8-member ensemble forecasts contained the

observations. For northern catchments within the INFORM domain, there is a tendency for overestimation of MAP and MAT in higher elevations and a tendency for underestimation in lower elevations.

9. Real-time reservoir inflow ensemble (8-member) forecasts by the INFORM system showed skill for several important flow events, catchments and lead times out to 5 days, when compared to unimpaired flow estimates by CNRFC (treated as observations for these evaluations). In some cases interruption of real time links to CNRFC and NCEP led to poor initial conditions for some forecast preparation times with biased resultant ensemble flows. The good performance of simulations with observed MAP and MAT corroborates this conclusion. Folsom and Oroville reservoir inflows are somewhat delayed with respect to CNRFC unimpaired flow estimates. Significant spread of the ensemble forecasts was observed in several cases. These results were obtained without any bias adjustments of the downscaling model output. A simple adjustment of the INFORM MAP ensemble forecasts yielded substantially improved ensemble reservoir inflow forecasts.

### **7.2.2 Decision Component**

Specific conclusions related to the decision support system and its applications are noted below:

1. The INFORM DSS includes four planning and management decision layers aimed to address long range system planning (monthly resolution/one to two years horizon), mid range management (daily resolution/several months horizon), short range management (hourly resolution/one day horizon), and near real time operations scheduling (hourly hydro power unit commitment and load dispatching). The INFORM DSS models are interlinked to ensure consistency across modeling layers, both with respect to physical system representations as well as with respect to the flow of decisions.
2. The INFORM DSS is designed to support participatory decision making processes in which stakeholder agencies evaluate the benefits and risks of possible management decisions and develop consensus on the way forward. To this end, the INFORM DSS first quantifies the associated benefits and risks by deriving applicable planning and management tradeoffs. Once the stakeholder agencies reach agreement on acceptable risks and equitable benefits, the INFORM DSS can be used to develop the planning and management policies that realize the agreements made.
3. *Value of Stochastic vs. Deterministic Forecasts:* Extensive assessments described in Chapter 5 and 6 demonstrate that using full forecast ensembles (as opposed to a single sequence) improves management performance for all forecast schemes and all projects. In the case of Folsom and the climate conditioned ESP forecast model, stochastic management completely avoids flood damage, which in the

- case of deterministic forecasts amounts to 220 million dollars. Thus, the opportunity loss of ignoring forecast uncertainty in management models and processes can be rather costly.
4. The value of the hydrologic ESP and climate conditioned ESP models is assessed by comparing their performance with that of the historical analog and perfect forecast models in retrospective simulations. These assessments (Chapter 6) indicate a consistent performance ranking across all reported criteria and projects, with the perfect forecasts performing best, followed by the climate conditioned ESP, the hydrologic ESP, and the historical analog forecasts. Relative performance differences are more pronounced for Folsom, where flood damage increases from 0 (perfect and climate conditioned forecasts) to 220 million dollars (hydrologic ESP and historical analog forecasts), and Oroville, where maximum release increases from 88,773 cfs (perfect forecasts) to 133,303 cfs (climate conditioned ESP forecasts) to 169,254 cfs (hydrologic ESP and historical analog forecasts). The same relative performance is noted with respect to spillage and energy generation, albeit with less pronounced differences. Thus, the assessments demonstrate that hydro-climatic forecasting schemes can benefit reservoir management.
  5. The retrospective assessments also show that climate conditioned ESP forecasts cause the deepest reservoir draw downs, followed by the historical analog, the hydrologic ESP, and the perfect forecasts. In light of the same reliability thresholds used by all management models, this result implies that, on the average, forecast ensembles exhibit widest spread for the climate conditioned ESP, becoming progressively less wide for the historical analog, the hydrologic ESP, and the perfect forecasts. Thus, the previous favorable conclusion regarding the climate conditioned ESP forecasts should be reviewed further in light of the long range drought risks that reservoir draw downs may pose. This aspect suggests that the value of climate conditioned ESP forecasts for reservoir management can be improved.
  6. Although forecast ensemble reliability is most important for reservoir management, the range (or spread) of the forecast ensemble is also critical. Among the forecasts that exhibit the same reliability (of containing the true inflows), those with the narrowest ensemble range are most effective. According to this criterion, the hydrologic ESP is shown to a better forecasting scheme than the historical analog. A third important forecast attribute is the forecast lead time. In general, the value of forecasts in reservoir management increases with increasing reliability, precision (as measured by the ensemble spread), and effective lead time.
  7. An important aspect of adaptive management methods such as the ones implemented in the INFORM DSS is that they can increase the effective lead time of the forecasts by managing uncertainty system wide. This attribute provides

adaptive methods with a clear advantage over heuristic and static regulation schemes.

8. CALSIM and the INFORM DSS simulation model were compared with respect to river node flows, the X2 location (interface of saline and fresh water), and major reservoir storages. The comparison results confirm that the INFORM simulation model is consistent with CALSIM and can be used to represent the response of the Northern California system at the same accuracy level.
9. Long range planning retrospective assessments demonstrate the ability of the INFORM DSS to determine the capacity of the system to meet increasing water stresses. It is shown that 50% of the base water demand scenario (defined by Tables G-5 and G-6) can be fully met throughout the assessment horizon, without causing violation of any other system requirement (such as minimum flows, Delta environmental conditions, etc.). By contrast, increasing water demand targets to 60% of the base water demands brings about water supply deficits (Delta demand and south exports) and fails to keep the Delta X2 location less than 80 km from the Golden Gate Bridge during the 1991-1992 dry years. This level of water stress also leads to greater reservoir fluctuations including five to six years of full conservation storage depletion. On average, reservoir levels are 10 to 20 feet lower than those of the 50% base demand scenario. Scenarios of higher water demands would lead to more frequent and more severe water shortages and failures to meet other system requirements. Thus, the water stress that uses up the system capacity to meet its objectives is estimated to be between 50% and 60% of the base demands. The assessments also demonstrate that better forecast information improves system performance and mitigates the impacts of increasing water stress.
10. Comparing the results of long range planning and mid range management assessments reveals an incompatibility between the respective decision models and processes. The main difference between the assessments is that the mid range assessment manages the reservoirs *individually* and does not include potential interactions that might arise as part of the need to meet Delta demands and environmental conditions. To a certain extent, this approach reflects current practices which during flood periods focus on individual reservoir management (daily or sub-daily operations), while for purposes of long range planning consider the entire system (monthly operations). The assessments show that this incompatibility between planning and management may compromise system performance and lead to potential failures. This incompatibility between mid range management and long range planning can be addressed by expanding the mid range management scope to include a system wide, rather than an individual reservoir, perspective.

### **7.3 Overarching Recommendations**

Perhaps the most important recommendation arising from this work is to continue the INFORM demonstration experiments for two or (more usefully) three additional operational seasons beyond the system “dry run” wet season of 2005-2006 in continued close collaboration with the forecast and management partner agencies in Northern California. These additional operational seasons are necessary for the reliable evaluation of the INFORM system performance and utility in specific situations, for the application of any system corrections and adjustments that appear necessary from system evaluation, for the establishment of a protocol for its operational use by the collaborating agencies; and for exploring alternative applications for the system that have been suggested by sponsor agencies.

A second overarching recommendation pertains to the use of the INFORM system in a stand-alone mode for climate change simulations. The INFORM system closely emulates several of the actual forecast and management procedures used in routine operations in Northern California. As such, it constitutes a realistic simulation system for impact analysis in this region using the output of state-of-the-science global climate models that predict climatic variability and change. Such impacts include potential future climatic influences on precipitation, temperature, and snowmelt and runoff patterns in the Sierra Nevada resolved on the scale of INFORM catchments (from hundreds to thousands of square kilometers), the effects of increased demand scenarios, and the effectiveness of alternative management scenarios for improved water-use efficiency.

### **7.4 Specific Recommendations**

#### **7.4.1 Forecast Component**

As discussed in Chapter 6, one of the limitations of the present INFORM system implementation as regards the short-range forecast component is the ensemble size. At present, the INFORM system ingests eight NCEP global forecast system (GFS) ensemble members to produce eight ensemble-member forecasts of MAP and MAT fields, and reservoir inflow. There are currently fifteen GFS ensemble members produced by NCEP; the reason INFORM uses only eight of these is the limited capability of the INFORM computational server, which is based on eight computational processing units (CPUs). A fifteen- or twenty-CPU multiprocessing configuration is recommended to allow ingest of all available GFS ensemble members resulting in improved ability to use the INFORM system generated ensemble forecasts in a probabilistic context for validation and for decision support. Along this line of future work, the authors also recommend experimentation with statistical/probabilistic methods for effective ensemble size increases.

In contrast to the GFS INFORM system input (forecast lead time up to 16 days), NCEP climate forecast system (CFS) input consists of surface precipitation and temperature fields with monthly resolution. Efforts during this first phase of INFORM to have NCEP make available in real time the CFS-computed three dimensional fields

with (at least) twice daily forecast preparation times have not been successful (due to NCEP resource limitations as discussed in Chapter 2). This is an important issue for INFORM for two reasons:

- (a) the decision component requires reliable ensemble forecast input that spans the scales from hours to months to accommodate the multiple objectives of reservoir management; and
- (b) the current methods for downscaling and the resultant statistical characteristics of the short-range (GFS-based) and long-range (CFS-based) forecast are different yielding statistical discontinuities for the INFORM forecast ensembles at the transition times (from 16 days to 30 days of forecast lead time) and between the first and the rest of the forecast months.

Availability of three dimensional forecasts from CFS twice daily would lead to a seamless downscaling component for INFORM resulting in physics-based downscaling methods throughout (rather than a mix of physics-based and statistical methods) and in improved performance through single adjustment strategies of downscaled precipitation and temperature for the entire forecast horizon. It is thus highly recommended that CFS input analogous to GFS input be made available. Should such ensemble forecast fields become available, it is recommended that the necessary changes to INFORM structure for real time ingest and downscaling be made to use the new data.

As discussed in Chapter 3, Chapter 6 and in Section 7.2.1 above, during this first phase of the INFORM project, no adjustments in the GFS forecast input, downscaled forecast precipitation and temperature, and forecast reservoir inflow were effected in real time or for the historical validation. Simple adjustments, applied off line to the downscaled forecast precipitation fields for sensitivity testing, removed biases in the magnitude of ensemble forecast reservoir inflows, and promise significant improvements in real time ensemble forecasts for real time implementation. It is thus recommended that during the second phase of the INFORM project, adjustments are considered and implemented. The main issues to be resolved in this regard concern whether adjustments of the physical structure of the precipitation and temperature downscaling models are adequate to correct for biases or whether statistical bias adjustment of various forecast fields is necessary. Candidate physical structure adjustments for the precipitation downscaling model are the incorporation of (a) surface friction effects, (b) temperature gradient effects, and (c) convection. Candidate physical structure adjustments for the temperature downscaling component are (a) improvement of initial temperature interpolation and (b) temperature advection. If statistical bias adjustment is necessary, regression relationships between corresponding forecast and observed quantities may be used.

#### **7.4.2 Decision Component**

As indicated in Section 7.2.2, there is a need to rectify the incompatibility between mid range management and long range planning by expanding the mid range model scope

to include a system wide, rather than an individual reservoir, perspective. This can be accomplished by incorporating river routing models for the reaches downstream of the major reservoirs and by representing the Delta and south water export operations with a daily resolution. In addition to *synchronizing* the long and mid range system representations, this modeling extension will enable the decision system to more explicitly address fish related flow requirements.

A second useful modeling addition would be the inclusion of a monthly river temperature model to ensure that reservoir management is also responsive to fish requirements related to temperature.

Lastly, a more direct linkage between CALSIM and INFORM DSS can be established to leverage complementary model strengths. It is recommended that the planning process use both models in the following iterative manner: First, the INFORM DSS can be employed to generate long range planning tradeoffs and associated reservoir release policies based on seasonal hydro-climatic forecasts. Second, the INFORM DSS policies and forecasts can be used by CALSIM to develop a more detailed spatial representation of the system processes (inflows, withdrawals, returns) that are more meaningful to individual stakeholders. It is recommended that this process be automated and become user friendly as part of the INFORM DSS.

## **7.5 Benefits to California**

A significant benefit of this first phase of INFORM for Northern California is its contribution toward the integration of operational water supply forecast and management activities by federal and state agencies toward increased water use efficiency. The mutual technology transfer and science cooperation between research centers and operational agencies is another. Lastly, even in its current prototype form, the INFORM system provides a unique resource for operational and management agencies in Northern California. These agencies may benefit by using this system as a tool for evaluating potential decision policies pertaining to the use of Northern California's water supply during real time operations and for seasonal planning, both for the present and future years.

Key operational agencies for the implementation of the demonstration project were the U.S. National Weather Service (NWS) California-Nevada River Forecast Center (CNRFC), the California Department of Water Resources (DWR), the U.S. Bureau of Reclamation Central Valley Operations (USBR CVO), and the Sacramento District of the U.S. Army Corps of Engineers (USACE). Other agencies and regional stakeholders contributed through active participation in project workshops and, indirectly, through comments and suggestions conveyed to the INFORM Oversight and Implementation Committee (OIC).

