Demonstrating Integrated Forecast and Reservoir Management (INFORM) for northern California in an operational environment

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Abstract We describe the principle components of a prototype integrated climate–weather–hydrology forecast and reservoir management system suitable for operational implementation, and the initial demonstration of such a system for improving operational forecasting and water resources management in northern California.

Key words climate and weather forecasting; reservoir management; decision models; uncertainty; operational forecasting; operational management; INFORM

INTRODUCTION

Considerable investments have been made toward improving the quality and applicability of climate, synoptic, and hydrological forecast information, and earlier retrospective studies have demonstrated clearly that the management of water resource systems with large reservoirs can potentially benefit from such information (Georgakakos *et al.*, 1998a,b; Carpenter & Georgakakos, 2001; Yao & Georgakakos, 2001). However, prior to the project described in this paper no focused programme has aimed to quantify and demonstrate these benefits in an operational environment. There are three main reasons why this has not been previously accomplished:

(a) synoptic and climate forecasts include substantial uncertainty, and their effective use in management requires procedures that explicitly account for that uncertainty both in flow forecast and decision models/processes;
(b) existing reservoir management procedures depend on presently available information and operate under set institutional constraints, so that nontrivial technical and institutional changes are required to use information of a different type (i.e. improved hydrological, synoptic, or climate timescale forecasts);
(c) the development and operational application of such systems requires that the technical teams maintain a close relationship with the operational users for several years, and have a clear understanding of their operational environment.

As a result, up to this point few reservoir managers have been able or willing to dedicate the considerable effort required to utilize new approaches and realize the benefits of improved forecast information.

The purpose of the Integrated Forecast and Reservoir Management (INFORM) project is to demonstrate increased water-use efficiency in northern California water resources operations through the innovative application of meteorological/climate, hydrological and decision science. In accordance with its purpose, the particular objectives of INFORM are to:

(a) implement a prototype integrated forecast-management system for the primary Northern California reservoirs, both for individual reservoirs as well as system-wide; and
(b) demonstrate the utility of meteorological/climate and hydrological forecasts through near-real-time tests of the integrated system with actual data and management input, by comparing its economic and other benefits to those accruing from current management practices for the same hydrological events.

Georgakakos *et al.* (2005) provides an introduction to the INFORM project background and goals.

METHODOLOGY

To achieve the general objectives of the INFORM project, the authors performed the following technical tasks in close collaboration with operational forecast and management agencies in northern California:

(a) Created the Oversight and Implementation Committee for project oversight and assistance with system implementation and tests.
(b) Developed, implemented and performed validation of climate and weather INFORM components for northern California with historical data and real-time data.
(c) Developed, implemented and performed validation of hydrological INFORM reservoir-inflow forecasts with historical and real-time data for all major reservoirs of northern California.
(d) Developed, implemented and performed validation of decision INFORM components with historical and real-time data for the northern California water resources management system.
(e) Integrated INFORM system climate, hydrology and decision components and performed initial operational tests producing real-time ensemble forecasts out to lead times of 16 days, four times daily, for the wet season 2005–2006.
(f) Performed assessments of the integrated forecast-decision system value via retrospective simulation experiments.
(g) Held INFORM design, assessment and training meetings with operational forecast and management agency staff.

OUTLINE OF INFORM SYSTEM COMPONENTS

The INFORM software system consists of a number of diverse components for data handling, model runs, and output archiving and presentation. At its current state of development and input data availability, it is a distributed system with on-line and off-line components. The system routinely captures real-time US National Center for Environmental Predictions (NCEP) ensemble forecasts. It uses both ensemble synoptic forecasts from NCEP's Global Forecast System (GFS) and ensemble climate forecasts from NCEP's Climate Forecast System (CFS). The former are used for producing real-time short-term forecasts, and the latter are used off-line for producing longer-term forecasts as needed.

The INFORM ensemble forecast output feeds an off-line decision model component for producing risk-based short- and long-term decision alternatives for a nine-month decision horizon. The INFORM forecast component is implemented at the Hydrologic Research Center (HRC) for real-time use and with data links to the California Nevada River Forecast Center (CNRFC) databases. In addition, the ensemble reservoir inflow forecasts and maps of the ensemble surface precipitation forecasts of INFORM out to several days are posted on a secure internet site for INFORM developing institutions and collaborating forecast and management agencies. The INFORM decision component is implemented at the Georgia Water Resources Institute (GWRI), the US Bureau of Reclamation (USBR) and the California Department of Water Resources (DWR) for off-line use. Figure 1 shows a schematic of the system's distributed configuration, indicating the data links. The arrows point to the site of the database from which the organization initiating the link receives and deposits data.

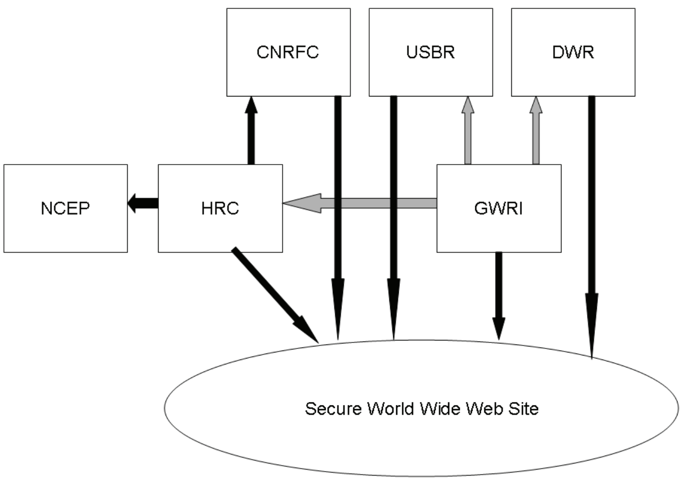

Fig. 1 Schematic diagram of the distributed INFORM system configuration with data links indicated. Black arrows signify real-time data links while grey arrows signify off-line data links.

GFS ensemble forecasts of three-dimensional atmospheric fields are captured, archived, ingested and quality controlled in real time for further use. Dynamic down-scaling components that use the ingested GFS ensemble fields produce corresponding ensemble gridded forecasts of surface precipitation and temperature over the INFORM application area of northern California. A Geographic Information System (GIS) locates the gridded forecasts over the terrain of northern California in geodetic coordinates and estimates mean areal precipitation and surface air temperature for all ensembles and forecast lead times, and for the hydrological catchments that comprise the drainage areas of interest. Hydrological models use the downscaled ensemble forecast mean areal quantities as input to produce ensemble forecasts of snow depth and snow melt during the cold season, and of surface and subsurface runoff and streamflow, including reservoir-site inflow, throughout the year.

CFS ensemble forecasts of surface air temperature and precipitation, with monthly resolution and with a nine-month maximum forecast lead time, are also captured in real time by the INFORM data ingest system at HRC. At a user-specified time, a probabilistic downscaling component uses the ensemble CFS forecasts and produces high spatial and temporal resolution surface precipitation and temperature estimates for each hydrological catchment in the INFORM region. The hydrological component of INFORM is then engaged to produce ensemble reservoir inflow estimates for the primary reservoir sites of interest. Downscaling and hydrological forecasting is done off-line (typically once per month) in this case of CFS processing. The short-term (GFS-based) and long-term (CFS-based) ensemble reservoir inflow forecasts of INFORM are blended to produce a consistent series of input to the decision component.

The INFORM DSS is designed to support the decision making process, which is characterized by multiple decision makers, multiple objectives, and multiple temporal scales. Toward this goal, the INFORM DSS includes a suite of interlinked models that address reservoir planning and management at hourly, daily, seasonal, and over-year time scales. The DSS includes models for each major reservoir in the INFORM region, simulation components for downstream river reaches as necessary to incorporate downstream decision objectives, optimization components suitable for use with ensemble forecasts, and a versatile user interface. The decision software runs off-line, as forecasts become available, to derive and assess planning and management strategies for all key system reservoirs. The DSS is embedded within a user-friendly, graphical interface that links the models with the database and helps visualize and manage results. A policy assessment model has also been developed and is part of the DSS.

Training and collaboration with staff of CNRFC, USBR and DWR has produced an efficient distributed INFORM system for ensemble forecasting with multiple lead times coupled with risk-based management and planning. Details on the INFORM system component design and model formulation are given in Georgakakos *et al.* (2006).

OUTLINE OF INITIAL DEMONSTRATION ACTIVITIES

Retrospective runs of the INFORM system were made with historical observations and archived atmospheric forecasts. Assessments were performed between the INFORM system decisions and actual system decisions as regards flood control, water conservation, hydroelectric power production, and ecosystem health metrics. For the 2005–2006 winter real time assessments were made for the short and long range forecasts and for the INFORM decision component performance.

With respect to the real time initial demonstration, the INFORM system correctly forecast a high likelihood of wetter spring 2006 conditions for the region reservoirs, and the INFORM decision component indicated that, with low risk, additional water conservation would be possible compared to actual reservoir system operations in

Northern California. The interested reader is referred to Georgakakos *et al.* (2006) for a complete set of results and detailed discussion of assessments performed during this first phase of INFORM.

OVERARCHING CONCLUSIONS

There are several technical and specific conclusions that have been drawn from the outcomes of the project in the areas of meteorology/climate, hydrology, and decision science (Georgakakos *et al.*, 2006). The most important conclusion of the report is that, with the available real-time availability of forecast information from the US National Centers for Environmental Prediction and with real-time observed precipitation and temperature as well as hydrological model state values from the California Nevada River Forecast Center, integrated forecast-management systems are realizable as effective operational decision support tools for management and planning of California's water resources. Such systems assist water managers in translating forecasts and their uncertainty into a range of effective risk-based policies. In addition, these systems can 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.

OVERARCHING RECOMMENDATIONS

Perhaps the most important recommendation arising from this work is to continue the INFORM demonstration experiments for several 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 kilometres), the effects of increased demand scenarios, and the effectiveness of alternative management scenarios for improved water-use efficiency.

BENEFITS

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 for increased water use efficiency. The mutual technology transfer and science cooperation between research centres 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.

Acknowledgements The work reported in this document was co-sponsored by the following federal and state programs: Ecosystem Restoration Program of the California Bay Delta Authority (prior CALFED), the Public Interest Energy Research (PIER) Program of the California Energy Commission, and the Climate Program Office (CPO) of the National Oceanic and Atmospheric Administration (NOAA). Supplemental support for scientific research using components of the INFORM system was provided by the California Applications Project of the Scripps Institution of Oceanography; that program is funded by the NOAA Climate Program Office. Administrative support was provided by the Hydrologic Research Center. The work is a joint effort between the Hydrologic Research Center (HRC) of San Diego, California, and the Georgia Water Resources Institute (GWRI) at the Georgia Institute of Technology in Atlanta, Georgia; the former with primary contributions in the areas of climate and hydrological forecasting and the latter with primary contributions in the area of decision support for reservoir planning and management. The ideas and opinions expressed in this article are those of the authors and need not necessarily reflect those of the funding agencies.

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