Design & Deployment of a Multi-agency Flood Decision Support System

At left: Oroville Dam and Lake Oroville
Source - CA DWR (undated)

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Abstract

This technical note describes how our team of engineers and scientists designed and deployed a decision support system (DSS) that will enhance flood operations in the Yuba-Feather river system—a complex, multiple-reservoir system managed by multiple agencies. The Yuba-Feather river system is located in Northern California in the Sierra Nevada mountain range. The watershed, subject to orographic precipitation enhancement during large scale winter storms, includes populated areas at the confluences of major streams, some regulated and some not. Agencies at local, state, and federal levels monitor and manage flood waters. These agencies include the Yuba County Water Agency, California Department of Water Resources, National Weather Service (NWS), and US Army Corps of Engineers. The agencies sought to enhance their capability to work together in a synergistic way to reduce flood risk to life and property. To achieve this, the team planned, designed, developed, and implemented a reservoir operation DSS that fosters communication and leverages expertise of agencies without hampering their ability to satisfy their individual missions. The DSS incorporates real-time data compiled and stored by the California Data Exchange Center, NWS streamflow forecasts produced using the Community Hydrologic Prediction System, an HEC-ResSim reservoir simulation model, and a graphical user interface. This technical note describes the organizational structure of the DSS and shows how the DSS improves coordination in the Yuba-Feather system during flood events. Limited descriptions of modeling applications (e.g., HEC-ResSim) are included.

KEYWORDS

Decision support system; reservoir operation; system analysis; California; flood management; forecast-coordinated operations

Situation: Flood operations in the Yuba-Feather River system

Watershed description

The Yuba-Feather river system, shown in Figure 1, includes the basins generally upstream of the confluence of the Feather River and the Bear River in northern California, which comprise a total watershed area of approximately 15,490 km^2 (5,980 mi^2). The Feather River watershed upstream of the Yuba River confluence is approximately 10,410 km^2 (4,020 mi^2). The Yuba River watershed upstream of the Feather River confluence is approximately 3,470 km2 (1,340 mi^2). The flood season for the watershed is from November through April. With watershed elevations ranging from approximately 6 m (20 ft) to 2,830 m (9,300 ft), precipitation falls both as rain and snow.

Oroville Reservoir and New Bullards Bar Reservoir are the 2 flood control reservoirs in the watershed. Oroville Reservoir, located 14.5 km (9 mi) east of the city of Oroville, regulates the majority of the Feather River watershed. The upstream contributing area is approximately 9,430 km^2 (3,640 mi^2). New Bullards Bar Reservoir, located 34 km (21 mi) north of Nevada City, is on the North Yuba River and has an upstream contributing area of approximately 1,270 km^2 (490 mi^2). Thus, 31 percent of the Yuba-Feather river system is unregulated. Both of these reservoirs are operated for multiple purposes including hydropower, water supply, flood control, and recreation.

The system has a long history of large, damaging floods. During a major flood event occurring in February 1986, a
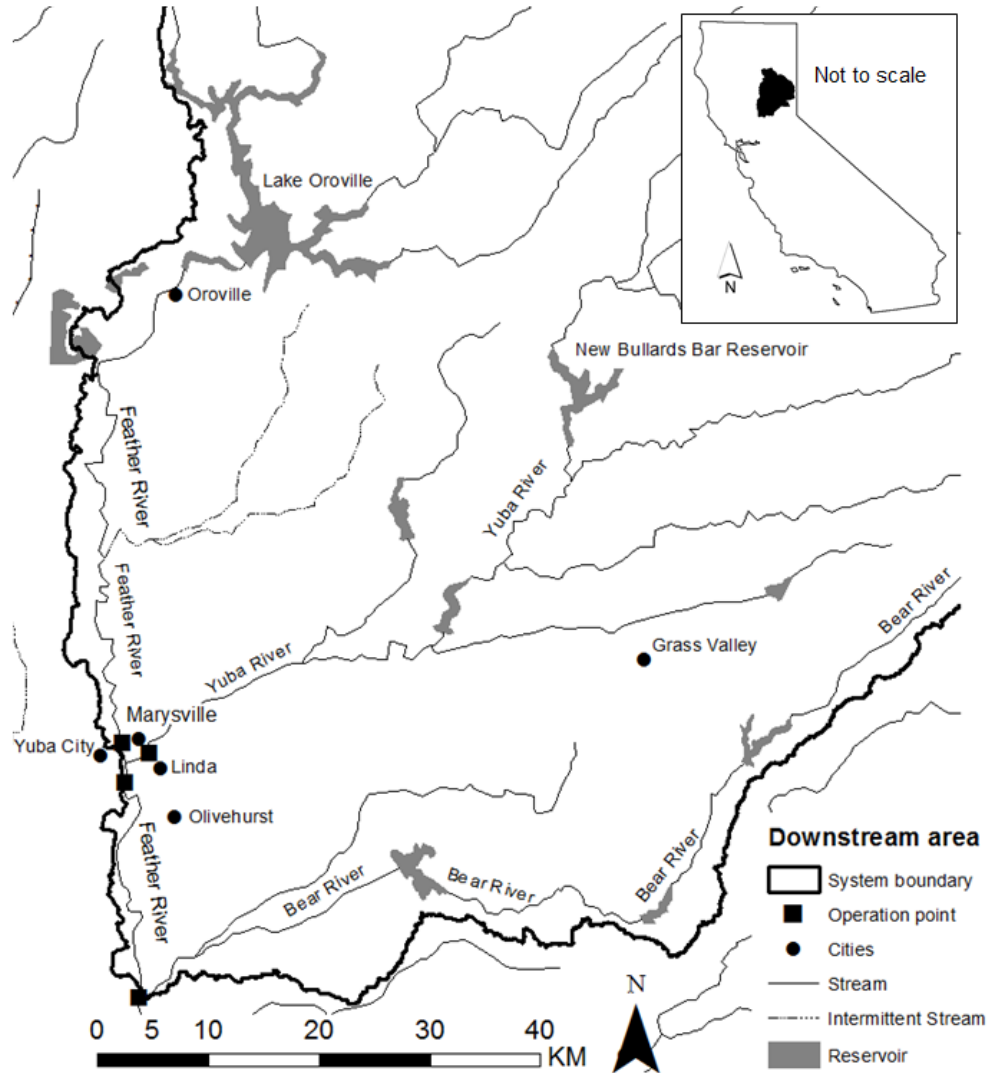

Figure 1. Map of Yuba-Feather study area

levee break along the Yuba River near Marysville caused the towns of Linda and Olivehurst to flood. Over 20,000 people evacuated their homes and property damage of approximately $50 million, in 1986 dollars, resulted (DWR 1988). This same area flooded again in January 1997, this time as a result of a levee break on the Feather River, just downstream of the Yuba River confluence.

Agencies' roles and responsibilities

Water managers at the Yuba County Water Agency (YCWA) and the California Department of Water Resources (DWR) Operations Control Office (OCO) make decisions about the operation of New Bullards Bar and Oroville reservoirs, respectively.

Managers of both agencies get forecasts of reservoir inflows and downstream flows from the joint forecasting service of the National Weather Service (NWS) California-Nevada River Forecast Center (CNRFC) and the DWR Division of Flood Management (DFM). In addition, the US Army Corps of Engineers (USACE) Sacramento District, in accordance with Section 7 of the Flood Control Act of 1944, prescribes regulations for managing reservoir storage allocated for flood control.

Levee conditions are continuously monitored during high water events by DWR, YCWA, and the local levee maintaining agencies that own and are responsible for the levees. If a levee is determined to be compromised, upstream reservoir operations are adjusted accordingly to take this into account.

New Bullards Bar Dam and Reservoir, © Justin Smith / Wikimedia Commons, CC-By-SA-3.0 (see References section)

Operational challenges

The primary challenges in operating Oroville and New Bullards Bar reservoirs are that (1) decisions about system operation are made by several state and local agencies, with input and guidance from federal agencies, and (2) efficient and effective exchange of information is needed to support those operations.

Other operating challenges in the basin include:

• Large contributing watersheds.
• Common downstream operating points that are affected by releases from multiple reservoirs operated by independent agencies.

• The flashy nature of the watersheds upstream of the reservoirs. Conditions and reservoir inflows can change on an hourly basis, providing little time to carry out operational decision making.
• Long travel times between reservoirs and downstream operating points. The travel time from Oroville Dam to the most downstream operating point at Nicolaus is approximately 24 hr.
• Relatively large contribution of unregulated flow, especially on the Yuba River. Approximately two thirds of the Yuba River watershed is unregulated.
• Runoff from both rainfall and snowmelt.

Operational decision making

When New Bullards Bar and Oroville store excess runoff from the contributing basins, they can reduce excessive flows in the Yuba River at Marysville and in the Feather River at Yuba City. This storage of floodwaters may also reduce the flows in the Sacramento River, thus reducing risk of flooding at Sacramento.

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Oroville is operated considering flow and the corresponding water levels, and how those compare to operation thresholds at Yuba City. New Bullards Bar is operated similarly for thresholds at Marysville.

In addition to operation that considers these individual thresholds, the reservoirs are operated jointly for locations downstream of the Yuba-Feather confluence. This joint operation calls for "sharing" the space available in the downstream channel in such a way that the maximum releases made from each reservoir vary, depending on the state of storage in the reservoir. For example, the reservoirs are operated for a threshold of 8,500 m^3/s (300,000 ft^3/s) at the confluence of the Yuba and Feather rivers. However, the channel capacity in the Feather River above Yuba City is 5,950 m^3/s (210,000 ft^3/s), and the channel capacity in the Yuba River above Marysville is 3,400 m^3/s (120,000 ft^3/s) (USACE 1970). Operators must therefore coordinate to ensure that the 8,500 m^3/s (300,000 ft^3/s) threshold is not exceeded below the confluence.

During flood periods, operational decisions for the reservoirs are made generally as follows:

1. Weather and water conditions are monitored throughout the basins. Measured rainfall, snowpack, temperature, channel water level, lake level, and reservoir release data are compiled at the DWR California Data Exchange Center (CDEC) and stored in the CDEC database.

2. NWS CNRFC and DWR DFM staff retrieve the data from the CDEC database, in addition to required meteorological forecasts from NWS CNRFC, and forecast reservoir inflows, local flows (uncontrolled flows downstream of the reservoirs), and water levels throughout the basin. The runoff forecasts are made with the NWS CNRFC's Community Hydrologic Prediction System (CHPS) modeling infrastructure (Roe et al. 2010).

3. Reservoir operators use the inflow, local flow, and water level forecasts to make decisions about releases, including decisions about current operations—how much to release now, and future operations—how much to release in the future if the forecasts are correct (or, perhaps, not correct). Reservoir pool draw downs can also be considered prior to a storm's arrival. However, basing release decisions purely on forecasted precipitation is not the standard of practice in the Yuba-Feather system. When making release decisions, the operators consider the needs of their customers, the authorized operation purposes, approved operation rules, and the current state of their reservoirs.

4. Operators select the release schedule for each reservoir (releases that the operators intend to make in the near future) after evaluating and comparing alternative release forecasts. They provide the release schedules to NWS CNRFC and DWR forecasters. This step is necessary because these releases—for which the operations agencies have considerable latitude, depending on conditions at the site and throughout the basin—have significant impact on downstream flows. The release information arrives at the State-Federal Joint Operation Center (JOC) in a variety of formats, through various formal and informal routes. This information is stored in the CDEC database and relayed to the NWS CNRFC operations floor.

5. NWS CNRFC and DWR forecasters use the release schedules to complete the system-wide forecast, routing the releases and combining those with forecasted runoff from the uncontrolled subwatersheds downstream of the reservoirs.

The overall decision-making process can be characterized as iterative. The NWS CNRFC must forecast inflows so operators can make release decisions. But the operators must be able to determine the downstream impacts of the releases, including the combined effects of releases at and below the Yuba-Feather confluence. And, NWS CNRFC must know the release schedule to forecast stages downstream. In short, the release decisions require the forecasts, and the forecasts require release decisions. Effective interaction and information exchange are critical for both.

Task: Develop forecast-coordinated operation DSS

Motivation for new decision support system

Forecast-coordinated operation (F-CO), as the name implies, formalizes the mechanism for exchange of information (hydrologic forecasts, as well as weather data and operation information) among the cooperating agencies. With F-CO, forecasters provide estimates of reservoir inflows, downstream unregulated flows, and preliminary downstream regulated flows. In turn, reservoir operators provide anticipated releases based on these flow estimates. The reservoir operators are not obliged to make those anticipated releases, but they are simply indicating that, based upon the best available information and their interpretation of the operation rules and goals, the reported releases are most likely. This sharing of information is facilitated with a DSS. The F-CO DSS ensures that the information exchange takes place in an efficient, coordinated manner. In the past, a lack of agency coordination has not resulted in flooding in the Yuba-Feather system. Rather, recognizing that agency coordination challenges exist, the F-CO DSS was developed as a preventative measure against future flooding.

Goals and objectives

The overarching goal of the F-CO DSS is to reduce flood risk through coordinated management of reservoir releases.

This goal is achieved through enhanced information exchange between cooperating agencies. This provides operators with better information to support operational decision making and provides forecasters with better information upon which to base more reliable and timely forecasts of future downstream conditions, which cities and counties use to implement flood action and evacuation plans. To reach this goal, initial development of the DSS had to meet the following objectives: enhance data compilation and handling to facilitate forecast updates whenever necessary; enhance data and information sharing among operators, regulators, and forecasters; and link to a powerful reservoir and river system simulation application, so that both operators and forecasters can have access to the analytical processing tool for studying "what if" scenarios as they make release decisions.

As deployed, the F-CO DSS for the Yuba-Feather river system satisfied all of the goals and objectives noted.

Related works

Decision support systems have been widely employed to manage reservoir operations for various goals. Labadie et al. (2005) described a DSS for the daily operation of a parallel reservoir system in the Geum River Basin of Korea. Precipitation forecasts and rainfall-runoff models were used to develop water supply forecasts for the basin. Then, optimal reservoir operation strategies were computed to meet demands for industries, municipalities, agriculture, hydropower, and low-flow augmentation.

Triana and Labadie (2000) developed a DSS for the Mahaweli system in Sri Lanka. The DSS uses fully dynamic optimization to maintain irrigation water supply requirements and to maximize hydropower generation. The Mahaweli system consists of 2 unconnected subsystems. Nonetheless, these subsystems must be optimized in parallel to meet common energy demands. For both Labadie et al. (2005) and Triana and Labadie (2000), flood control was not considered.

Shim et al. (2002) describe a prototype spatial DSS for coordinated flood control operations in the multireservoir Han River Basin of Korea. The DSS consists of a hydrologic data monitoring system, a GIS module, a flood forecasting module, a multireservoir operation module, and a database management system. All of the DSS components are supported by a graphical user interface (GUI). Unregulated inflow forecasts produced in the flood forecasting module are input into the multireservoir operation module where a dynamic optimization model computes optimal reservoir

release decisions. Ford and Killen (1995) describe a DSS developed to improve flood prevention and control in the Trinity River basin of Texas, where 17 major reservoirs are owned and operated by 4 government agencies and an electric utility. For this DSS, a database management system is integrated with a watershed runoff simulation model and a reservoir operation simulation model to forecast regulated flows throughout the basin.

Our forecast-coordinated operation solution: Overview

Design and development process

The DSS was designed and developed through close coordination between the agencies and with the assistance of their consultants. Design documents were prepared and proposed solutions were compared against the original design. Components and solutions that met the constraints and requirements the best were selected.

One of the constraints identified by the cooperating agencies was that the system needed to be developed and implemented without extensive research and development. Rather, it needed to be built using existing, well-known technology. Developers also had to work within the agencies' budgetary and resource constraints.

Scope of the decision support system

The F-CO DSS enables reservoir operators and other cooperating agencies to complete these tasks:

- Report changes in spillway gate settings or low-level outlet outflows.
- View CDEC information such as system flows, stages, and reservoir elevations.
- Report and share projected releases.
- View effects of projected releases on downstream flow.
- Analyze alternative system operation decisions.

By design, the F-CO DSS enables users to assess the hazard tradeoffs (e.g., river stages) associated with specified reservoir release decisions. The F-CO DSS provides reservoir operators with an interactive tool to evaluate the cumulative downstream impact of their release decisions and the release decisions of those operating other upstream reservoirs. The consequences of those hazards (e.g., damage), and the probabilities associated with them, however, are not considered.

The overall F-CO DSS client-server configuration and the flow of data and information among the components are shown in Figure 2. In the following paragraphs, we refer to the process diagram shown in Figure 2 using the labels assigned to each arrow.

Operational decision support begins with reservoir inflow and local flow forecasts provided by the NWS CNRFC using CHPS. Real-time data are continuously sent from the field to the CDEC database (1A). CHPS retrieves these data from CDEC (1B) and uses them, along with NWS-generated meteorological forecasts (1C), to produce the required reservoir inflow and local flow forecasts. These flow forecasts are sent to and stored in the CDEC database (2A), permitting efficient, rapid exchange with all agencies involved.

The initial reservoir inflow and local flow forecasts are retrieved from the CDEC database (2B), and the HEC-ResSim program is executed to find an initial reservoir release forecast (3A). That initial release forecast is published to the CDEC database, secure from public access. HEC-ResSim is executed on a server managed by DWR CDEC staff. To ensure continuity of operations, NWS CNRFC also maintains within CHPS a version of the HEC-ResSim program, and initial reservoir inflow and local flow forecasts are sent here (2C), in addition to the CDEC HEC-ResSim program. Thus, in the event of a failure of communications with the operators or delay in transmitting release schedules, NWS CNRFC staff can simulate operations following basic operating rules, forecasting both a release schedule and resulting system-wide flows and water levels, and send those forecasts to CDEC (3B).

Figure 2.
DSS process
schematic
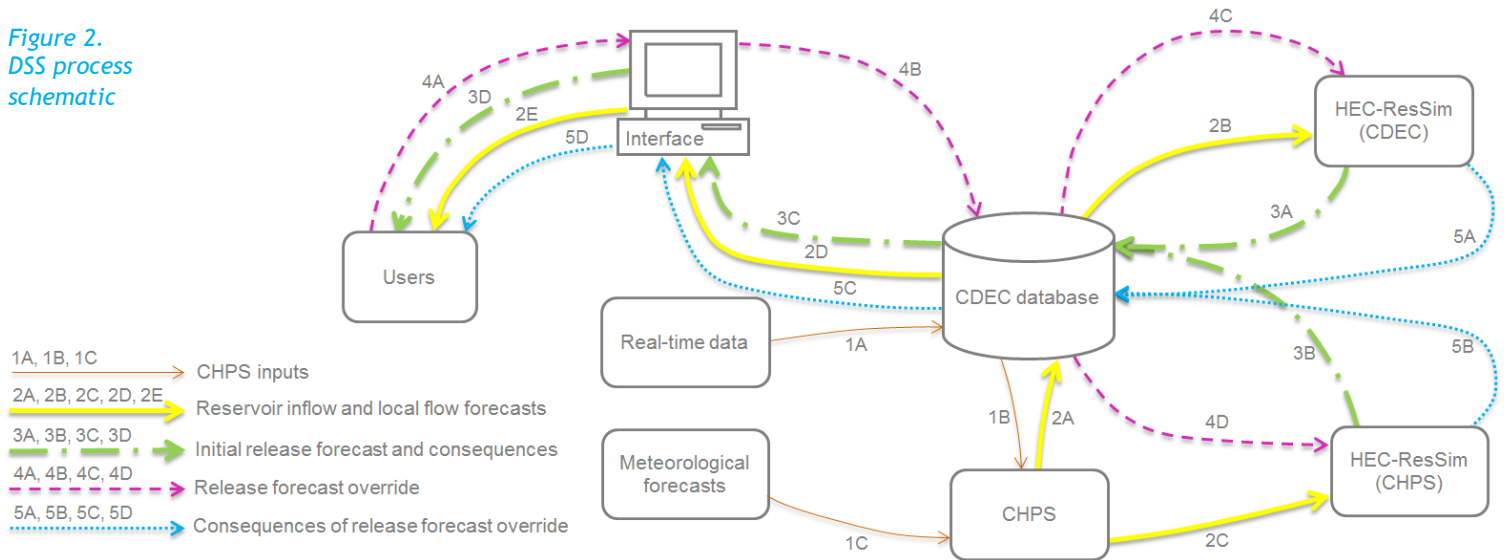
The NWS CNRFC version of HEC-ResSim is identical to the DWR CDEC version. Procedures are established among the agencies to ensure that the HEC-ResSim versions are fully synchronized.

The CHPS reservoir inflow and local flow forecasts (2D) and the initial release forecasts from HEC-ResSim (3C) are made available through the F-CO interface to reservoir operators and other users (2E and 3D, respectively). The operators can override and alter the release forecast through the F-CO interface (4A). If they alter the release forecast, the F-CO server transmits the new values back to CDEC (4B), where they are stored temporarily in a secure area. Then, the modified release forecast is retrieved and analyzed with HEC-ResSim (4C), and the impacts of those release decisions are published to CDEC (5A). The NWS CNRFC's version of the HEC-ResSim model also can retrieve and analyze the modified release forecast (4D), and publish the impacts of those release decisions to CDEC (5B). These results are accessible through the F-CO interface (5C), providing operators with a system-wide assessment of the impacts of the changes that they propose (5D).

Once operators are satisfied that they have selected the best releases, they post to the CDEC database their release schedule, with information flowing from the operators to the CDEC database and finally to CHPS. With the release schedule, routings are completed, and the final system-wide forecast is completed by NWS CNRFC and DWR DFM forecasters. This system-wide forecast is posted again to the CDEC database, where it is available for public access.

Tentative reservoir release schedules are made 5 days out from the time of forecast. During a flood event, these re-lease schedules can change at any time, but generally these schedules are adjusted when new streamflow and reservoir inflow forecasts become available or as water-shed conditions change. The approximate peak flow travel time on the Feather River from Oroville Dam to Yuba City is 16 hr. On the Yuba River, the approximate peak flow travel time from New Bullards Bar Dam to Marysville is 8.5 hr. Therefore, the approximate emergency response lead time from the time of reservoir release to the time that those releases affect major population centers is between 8.5 and 16 hr.

Our forecast-coordinated operation solution: Details of components

CHPS

NWS CNRFC and DWR DFM staff process and quality control hydrometeorological data from the CDEC database, as well as other sources such as the US Geological Survey (USGS). Meteorological forecasts are gathered from NWS sources and refined by the NWS CNRFC Hydrometeorological Analysis and Support (HAS) unit. Using CHPS, staff hydrologists generate forecasts of watershed runoff, including both reservoir inflows and the local, uncontrolled flows downstream of the reservoirs. These forecasts are stored in the CDEC database for dissemination and use by DWR OCO, YCWA, and USACE.

CDEC database

The central database component of the DSS resides with the CDEC data management system. For the DSS, the CDEC database management system facilitates exchange of data among the agencies. It also serves as a central clearing house for the reservoir simulation tool, storing both the inputs and the outputs.

The database management system stores hydrometeorological data that are collected within the Yuba and Feather river basins, and then provides those to the NWS CNRFC and DWR DFM for use within CHPS. This F-CO database server stores the inflow and local flow forecasts from CHPS in an Oracle database. This information is subsequently retrieved for display to reservoir operators and for use within the reservoir simulation model. In addition, release schedules are stored here so that they may be exchanged among models and users.

All agencies involved in Yuba-Feather operations have access to the CDEC database on the F-CO database server.

Reservoir simulation application

HEC-ResSim is the USACE's standard-of-practice reservoir simulation model for both real-time and planning applications (USACE 2007). After careful consideration and evaluation of alternatives, the Yuba-Feather F-CO study team selected HEC-ResSim as the DSS's reservoir simulation application. Various real-time flood forecasting applications of HEC-ResSim are described in USACE (2011).

In the F-CO context, HEC-ResSim follows a specified set of operation rules to compute an initial release forecast, given reservoir inflows and local flows. HEC-ResSim retrieves the required reservoir inflows and local flows from the CDEC database in the DSS. Then, HEC-ResSim routes the release forecast and combines routed flows with local flows to compute flows throughout the system. The result of the reservoir simulation is a set of flow hydrographs at key downstream locations. The model extends downstream to Nicolaus on the Feather River, just below the Feather-Bear confluence.

As mentioned earlier, and as illustrated in Figure 2, HEC-ResSim is deployed at both the F-CO simulation server within CDEC and within CHPS. To facilitate coordinated use of the model, including changes to the HEC-ResSim model configuration and settings, the F-CO DSS includes a detailed set of plans and procedures to keep the HEC-ResSim configuration database synchronized between CDEC and CHPS.

F-CO interface

The F-CO interface, a screenshot of which is shown in Figure 3, is the operators' interface to the DSS. It facilitates operator specification of scheduled reservoir releases, operator access to the reservoir simulation tools and results, and operator access to data shared within the F-CO. The interface is installed via a Web browser connected to the CDEC website. Once accessed, a Java application on that site automatically downloads onto the local computer. This application is used to access the files and information on the F-CO simulation server.

For entering scheduled releases, the interface allows for a common, systematic way for reservoir operators to report their releases to CDEC. In the past, these release schedules had been emailed, faxed, or communicated by telephone. These scheduled releases are used for downstream flow forecasts.

For using HEC-ResSim, the interface displays forecasted reservoir inflows and local flows, along with the initial release forecast computed by HEC-ResSim when it strictly follows the specified operation rules. Operators then enter their scheduled release forecast through the interface for their specific reservoir, and run the HEC-ResSim program on the server to see the downstream flows and future system states that result from their release forecast. To accomplish this, the operator's release forecast is stored temporarily in the F-CO database, and the HEC-ResSim program is executed on a server at CDEC. The results following the release forecast are stored temporarily in the F-
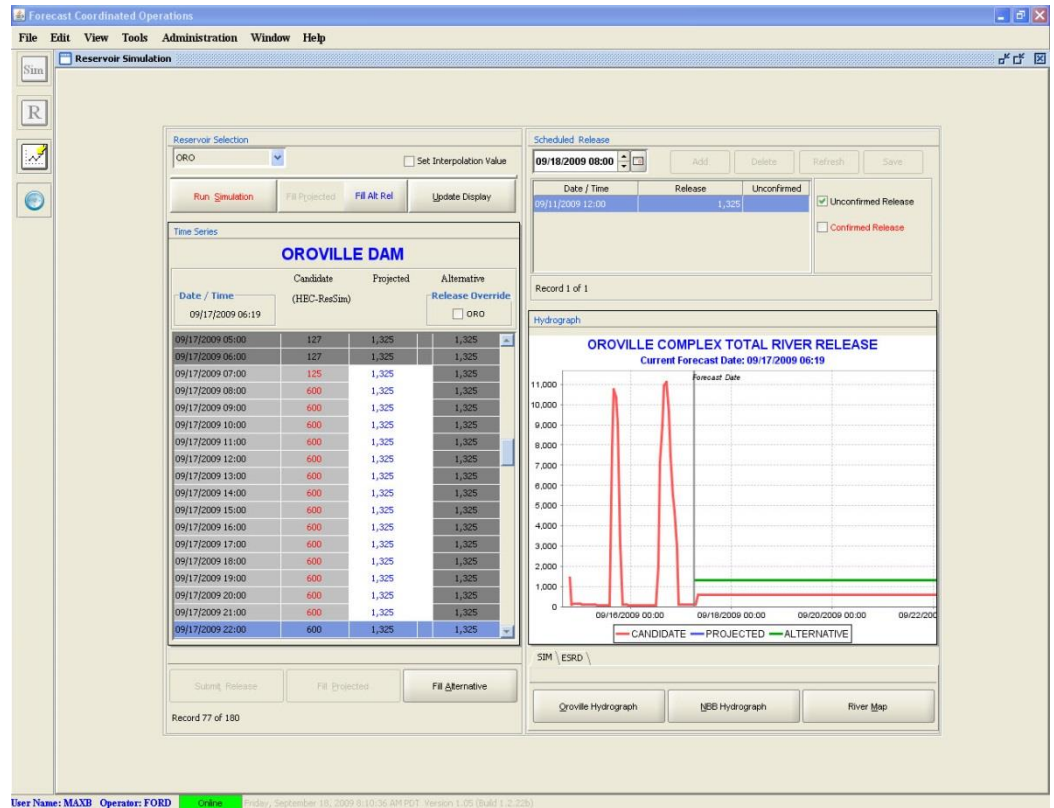

Figure 3. F-CO graphical user interface

CO database, and again made available for operator inspection.

The process can be repeated until the operator is satisfied with the release forecast, at which time he or she will post a release schedule to the CDEC database. From here, the release schedule is retrieved by CHPS, and a final system-wide forecast is issued by NWS CNRFC.

Also available through the F-CO interface is the ability for an operator, or other authorized user, to test system operation in a "sandbox." Releases for both Oroville and New Bullards Bar can be specified and simulated through the HEC-ResSim program without exposing the results to other operators or users. This facilitates the evaluation of "what if" scenarios prior to posting a release schedule to the CDEC database.

Operational experience

The F-CO DSS components used by DWR and YCWA operators have been developed and deployed. While agencies have used the F-CO DSS operationally since 2008, no flood event with a magnitude large enough to stress the Yuba-Feather flood control system has taken place subsequent to deployment. Nonetheless, annual exercises have been held every year where DWR, YCWA, NWS, and USACE staff practice using the F-CO DSS under hypothetical flooding conditions. In addition to providing valuable practice, these exercises also facilitate the identification of possible improvements to the DSS components. Every year, there have been continuous refinements to the F-CO DSS based on feedback received during the operational exercises.

Staff from multiple agencies participate in an F-CO exercise

Lessons for others

A multi-agency DSS spanning over a large watershed with multiple reservoirs is new to California.

In developing and implementing this DSS, important lessons were learned: 1) Use existing, familiar, and reliable technology whenever possible; 2) if the use of new technology is required, select software appropriate for the task; 3) involve all stakeholders; 4) develop a plan for long-term operation and maintenance of the DSS; 5) design the DSS knowing that changes to its components are inevitable;

and 6) accommodate the DSS to users of all levels of expertise.

Perhaps most important, the success of the Yuba-Feather F-CO DSS can largely be attributed to a strong management team of individuals with the authority to commit resources within their agencies and units. This commitment is reinforced by qualified contractors responsible for assisting with the organization, facilitation, development, and technical support of the DSS.

Acknowledgments

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