Design and implementation of an emergency environmental response system to protect migrating salmon in the lower San Joaquin River, California

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Abstract

In the past decade tens of millions of dollars have been spent by water resource agencies in California to restore the native salmon fishery in the San Joaquin River and its major tributaries. An excavated deep water ship channel (DWSC), through which the river runs on its way to the Bay/Delta and Pacific Ocean, experiences episodes of low dissolved oxygen which acts as a barrier to anadromous fish migration and a threat to the long-term survival of the salmon run. An emergency response management system is under development to forecast these episodes of low dissolved oxygen and to deploy measures that will raise dissolved oxygen concentrations to prevent damage to the fishery resource. The emergency response management system has been designed to interact with a real-time water quality monitoring network and is served by a comprehensive data management and forecasting model toolbox. The Bay/Delta and Tributaries (BDAT) Cooperative Data Management System is a distributed, web accessible database that contains terabytes of information on all aspects of the ecology of the Bay/Delta and upper watersheds. The complexity of the problem dictates data integration from a variety of monitoring programs. A unique data templating system has been constructed to serve the needs of cooperating scientists who wish to share their data and to simplify and streamline data uploading into the master database. In this paper we demonstrate the utility of such a system in providing decision support for management of the San Joaquin River fishery. We discuss how the system might be expanded to have further utility in coping with other emergencies and threats to water supply system serving California's costal communities.

Keywords: Dissolved oxygen; Decision support; Modeling; Algae

1. Background

The anadromous salmon fishery in the San Joaquin River Basin has been diminished by a century of water resources development, the expansion of an agricultural economy and increasing urbanization in California's Central Valley. Dams constructed to store water supply for irrigation and municipalities also deprive the salmon from the cool mountain streams and spawning gravels essential for propagation. Irrigation return flows contain salts, nutrients and traces of pesticides that encourage algal growth in the tributaries and main stem of the SJR. These contaminants are harmful to salmon smolts, stressing these juvenile fish at a vulnerable age in their life cycle. Wetland and municipal return flows also contain salts as well as carbonaceous materials which, during summer and fall within reaches where flows are diminished, stress smolts by depleting the river of dissolved oxygen.

The problem of dissolved oxygen sag is recognized annually in the San Joaquin River deep water ship channel (DWSC) – a 12 m deep, 200 m wide channel that was excavated along the River alignment as it transitions from the Valley floodplain into the tidal Delta (Fig. 1). Oxygen demanding substances contributed by upstream agricultural, wetland and municipal sources combine with decaying algal biomass, produced within the San Joaquin River, to create a sag in the dissolved oxygen concentration. The hydraulic transition from the 3 m deep and 30 m-wide river to the DWSC promotes settling of suspended material such as sediment and algae and encourages periodic water column stratification. Dissolved oxygen levels in the DWSC are controlled by factors such as SJR flow, tidal hydrodynamics, water temperature, and occasional high discharges of ammonia from a local sewage treatment plant. Other dissolved oxygen sinks include urban runoff, dairy farms, and managed seasonal wetlands. The sag in dissolved oxygen concentrations can create an effective 22 km barrier to fish migration when concentrations are below the EPA minimum threshold concentration of 5 mg/l. A prolonged dissolved oxygen sag can have a devastating effect on the fishery.

This paper describes an ambitious real-time monitoring, data acquisition, management and decision support system which forms the backbone of an emergency environmental response solution to deal with episodes of low dissolved oxygen in the San Joaquin River DWSC.

2. Flow and water quality monitoring

A large multi-disciplinary and multi-agency team of scientists, engineers, biologists and ecologists have been involved in studies and in routine monitoring of the DWSC and upstream main stem and tributary inflows for the past 4 years. The data gathered by this team range from that produced by short term synoptic studies of parts of the river and ship channel to long term monitoring of water quality and flow. Data are collected in synoptic studies in order to develop an overall understanding of the behavior of the system and in longer term monitoring studies to determine the temporal nature of SJR water quality. Monitoring data can be classified into two categories – discrete sampling (grab samples) performed daily, weekly or bi-monthly and continuous monitoring, typically recorded every 15 min or every hour.

Discrete monitoring, in the case of the San Joaquin River DO study is usually performed by State and Federal agencies, often for regulatory purposes. Quality assurance tends to be good for these data since they often involve field samples that are analyzed in certified analytical laboratories. These laboratories often have a full time quality assurance expert on staff who is trained in formal data and error reporting procedures. Continuous water quality monitoring sometimes may be performed synoptically from instruments, deployed for fixed periods of time, but more commonly from permanent gauging stations. Continuous flow and water quality data, when collected according to established quality assurance procedures, are invariably more accurate – however, they are also more difficult to collect, more prone to suffer from equipment malfunction and often must be obtained from different sources. Real-time (continuous) flow and water quality monitoring is the protocol of choice for the San Joaquin River DO project because continuous monitoring is essential for modeling and forecasting of algae growth and transport in the San Joaquin River. Continuous monitoring also allows measurement of diurnal fluctuations in concentrations of certain analytes such as chlorophyll and dissolved oxygen that would be missed with discrete monitoring. If tied into existing real-time data collection systems (Quinn et al., 1997 and Quinn et al., 1998) or into Supervisory Control and Data Acquisition (SCADA) systems, continuous monitoring can be deployed at low cost. Maintenance can be simplified by having local water district personnel, trained in correct water and water quality sampling techniques, involved in site and instrument upkeep.

3. Data acquisition

Data collection techniques employed will depend largely on the entity responsible for data collection and the maintenance schedule of the field sensors. In the case of the stations operated by federal agencies (US Geological Survey and US Bureau of Reclamation) and state agencies (Department of Water Resources), all of which have responsibility for river flow monitoring, access to real-time and censored continuous flow and water quality data may be provided via a website. Most agencies publish data once it has been reviewed, error checked and approved. The State-financed California Data Exchange (CDEC), which primarily provides river and stream data for flood forecasting and emergency evacuation purposes, polls a variety of state, federal and local stations either by phone modem, cellular phone, radio or satellite. Many agencies are converting cellular phone and land-line telemetered stations to GOES satellite-based technology. These satellite-based systems are more costly to install, more difficult for data retrieval and are limited to one-way communication from data collection platform to satellite to base station. An advantage of GOES satellite technology, besides its minimal maintenance cost after installation, is that it lends itself to data retrieval automation. Computer programs or UNIX scripts can be written to retrieve the data, error-check it and parse it into formats that models such as used by the flow and hydrodynamic models used for flow and water quality forecasting.

Continuous monitoring stations for flow and water quality monitoring that are located within a local water district can sometimes be operated and maintained by these entities for a considerable savings in annual costs. However, these arrangements may have costs associated with more complicated data retrieval. A number of water districts employ SCADA telemetry to monitor both diversions and drainage, to operate pumps and control valves. Data acquisition is most easily accomplished either by asking the water district to e-mail or ftp the requisite data daily or weekly or by allowing individual limited access to the computer that controls the SCADA system through the local area network firewall.

4. Data collection platform security

Cyber attacks on environmental monitoring systems have not been viewed as a significant enough problem in the past to merit much publicity. However, vulnerability assessments conducted in the US since September 11, 2001 have revealed significant risks to environmental monitoring and control systems. Kubel (2004), reporting on survey statistics published by Carnegie Mellon's CERT Coordination Center, found more than 82,000 hacking incidents to SCADA systems used for environmental monitoring in 2002. The author also quotes the Federal Bureau of Investigation's Crime and Security Report for 2003 which identified that 78% of security breaches were from Internet connections, 30% from internal systems and 18% from dial-up modems. This report quantified the loss from 251 respondents at $201 million.

Many data loggers that are accessible through dial-up land lines and cellular phone modems have been designed with several layers of password protection to prevent the uploading of corrupt programs that would compromise data integrity. Data loggers attached to environmental monitoring systems are perhaps not attractive enough targets to serious minded hackers and cyber terrorists. Nevertheless, vendors of data collection platforms are beginning to provide additional security features in recognition of perceived vulnerabilities. SCADA systems which provide monitoring and control can be compromised and the impacts of a security breach are more potentially damaging. Separating networks from the operating environment using firewalls and virtual private networks (VPN) is becoming standard policy with authentication and authorization protocol requirements for access. Encryption algorithms are being used to communicate user names and passwords over the network to provide added security.

5. Data management

Discrete monitoring data need to be stored using best practices if it is to be readily shared and made available to support real-time decisions. Although much of the discrete data provided is not mission critical for the provision of real-time flow and water quality forecasts, these data are essential to developing and understanding of the dynamic ecology of the system and it was considered important in the current project to provide these data in a timely manner to project participants. Each data provider needs to store and manage data reliably in order to contribute it to a distributed data and information system. Coordinated relational database management systems (RDBMS) have greatly assisted with Bay/Delta and tributary monitoring data management because of their ability to store and relate the diverse types of physical/chemical (e.g., water quality, hydrodynamics, meteorological), biological, terrestrial, wetland, fisheries, GIS and modeling information collected in the region.

Data submitted to an RDBMS is stored along with those from other providers in tables related to each other according to key fields (location, date/time, data type, etc.) and made accessible online via any computer with Internet access (Fig. 2). Data users can perform simple and refined queries obtaining the data they need from numerous sources quickly and efficiently from a central comprehensive database or database node compared to the hours or days it might take otherwise. In its most simple form, an RDBMS may be implemented using a relatively simple table structure (e.g., with MS Access software or attribute tables of a GIS) for the data providers. In the comprehensive implementation, the RDBMS is implemented as a full object relational model using a specific database vendor. The comprehensive system can also be distributed to local nodes (locally situated servers) where large amounts of data are being used, and/or where obtaining data using a browser is slow.

The RDBMS used in our application is named the Bay/Delta and Tributaries Cooperative Data Management System (BDAT) and is a two-level data management system including a normalized and a warehouse database residing on a main server. Employing the BDAT to manage and distribute Bay/Delta and tributaries monitoring data saves time and cost compared to comparable systems. The BDAT includes an interface to upload bulk data and a web-based interface to retrieve and display data by web clients (e.g., desktop web browsers). Data loading into BDAT comes from multiple, local client databases (Fig. 3). These local databases are typically developed in MS Access by the BDAT team working together with the data provider, a process that also serves to help providers better organize their data and manage it once the system is in place. Alternatively, if a client is currently using Access or another relational database, data conversion programs could be written. Data in the various client databases are combined and synchronized with existing data on the server using database replication. A record of all transactions between the main server and local databases is kept such that this, combined with the method of synchronization, ensures version control between incoming and stored data.

Because BDAT is already a Geographic Information System (GIS)-aware system, it includes the capability to store and retrieve/display GIS data. Furthermore, its web query interface is capable of formulating queries using both spatial and/or tabular criteria. In addition to the local client databases, other servers containing GIS data can be integrated into the system and GIS information delivered to the Internet for general access or to different locations for collaborative analysis.

Many of groups involved in the project do not currently have a sufficiently developed RDBMS to participate in such a data enterprise with other monitoring groups, so those local databases need to be developed. Common usage of these databases by monitoring groups addresses several items that should be considered in a distributed environment. The modern technology and concept of a relational database improve the data provider's data management capabilities when compared to the common use of Excel or ASCII files by agencies not currently employing this method. A local MS Access client database is one such system that meets this need while also providing the infrastructure for enterprise wide data management.

Agencies adopting this technology are better able to manage their own data. It is not necessary for participants to use the same software, platform, or data model in order to exchange information with BDAT. This solution reflects the preference by data providers to manage their data locally so that they can perform data quality assurance analysis and provide quality control of their data prior to uploading to a central location such as BDAT. Local MS Access client databases readily meet this need for smaller data sets that do not include binary data types. This necessitates a mechanism for maintaining version control of the data and for tracking and ultimately re-propagating these edits. MS Access client database applications can easily be programmed to meet this need and those in production already do. In cases where data providers already have reliable existing databases, other options, are implemented to provide the optimal solution to convey and integrate their data.

The data structure used in any local client database must be flexible enough to allow for user specific extensions or expansions yet also one that provides a standard and consistent format so data can be consolidated after it leaves the local environment with other data sets. Local MS Access client databases already developed for integration with BDAT include all of these features.

6. Data connectivity and data retrieval

Direct Database Connection is the simplest mechanism that allows a Data Provider's database (e.g., MS Access) to communicate with the comprehensive system. MS Access clients in the BDAT setup are currently using Direct Database Connection. This protocol is adequate when the two parties can fully coordinate their database administrative actives. Altering the design of the database on each end needs to be coordinated by both parties. This technology is readily available and typically does not require extensive software or system administration support. Data are moved from the local client to the comprehensive system using programmatic replication.

The Data Retrieval component of BDAT should address the needs of the data users. The candidate technology for the advanced users using a browser includes the BDAT's GIS enabled technology for extraction of data from BDAT. The BDAT interface allows for extraction of the tabular and the spatial data. Many specific web-based information sites have been developed that use data from BDAT participants. These include forecast modeling, spring run reporting, simulation modeling, etc. The ability to develop information systems that can convert data into information, based on access to a comprehensive set of Bay/Delta and Tributaries data greatly enhances many operational, adaptive management and research efforts already underway in the region. Using distribution technologies, therefore, provides the opportunity for many groups to develop customized data retrieval systems that meet their specific needs or to develop processes that convert data into information that they can share with other interested parties via the Internet or other types of media (Fig. 2).

Casual users are provided with a lightweight and easy to use interface to effortlessly obtain data and metadata associated with their queries. This interface has been developed in conjunction with a mapping service (such as those offered by ESRI's, ArcIMS) to offer a web-based map associated with specific data sets stored in the database.

7. Dissolved oxygen modeling

The DO monitoring and decision support system for the San Joaquin River DWSC and upper watershed is driven by hydrodynamic water quality simulation models of the river and estuary (Rajbhandari, 2001). Simulation modeling of the estuary, and the development and calibration of the DO routines within the simulation model, are data driven and rely on available real-time data sources. Error checking and data consistency procedures are not performed on real-time data but are performed routinely at regular intervals before raw data can be considered to be published data. In the BDAT system published and real-time data repositories are separated with comprehensive metadata descriptors to ensure that users acquire the appropriate data for their purpose. A powerful data browser, data parsing and retrieval engine allow easy matching of data uploads to match the requirements of the model. Within the study region, many groups have been combining real-time, historic field data with forecast Delta operations in the DSM2 model code in order to forecast hydrodynamic, water quality, and particle fate within the Delta on an ad hoc basis for several years. To help accomplish this task, BDAT was used as a source of data for DSM2 because of its unique ability to provide data from multiple sources, and provide data in a standard format that was directly useable by the model.

8. Dissolved oxygen forecasting models

Management solutions to address the Stockton DWSC problem will require forecasting DO conditions in the SDWSC based on the current hydrological and hydrochemical state of the Basin. A goal of real-time DO forecasting is to improve coordination of activities among those entities that directly benefit from and depend on the resources of the San Joaquin River. If the models underlying the decision support system are based on sound science they can help in the identification of key data gaps, as well as allow for adaptive expansion or contraction of water quality monitoring plans, as relationships between important factors become better understood and good surrogate alternative metrics are developed. In a system where the system monitoring is sub-optimal and data history is uneven among monitoring sites it is difficult to deal quantitatively with the uncertainty of water quality model predictions as prescribed by many modeling professionals (McIntyre and Wheater, 2004 and Newham et al., 2004). Monitoring systems need to be fully adaptive and opportunistic – recording important and representative environmental responses to natural and anthropogenic stressors at the least cost.

A description of the hydrodynamic water quality model DSM2-SJR and preliminary calibration results appeared in Quinn et al., 2003 and Quinn et al., 2004. Continuing work within the agencies is directed at improving model computation efficiency and developing a GIS-based model interface to allow the model to take advantage of recent developments in object-based programming and geometric networks. The current geometric network representation of the San Joaquin River, DWSC and Delta allows point and click querying of the model data at each nodal point of the network. Since the geometric network is superimposed on a 1:100,000 scale map of the region it allows direct matching of model data and data obtained from water quality monitoring stations in the Basin.

9. Stakeholder communication

An important element of real-time water quality management is to communicate rapidly with stakeholders about the model forecast of impending DO violations and to allow simulation of the effects of potential remedial measures that may be undertaken to avoid these events. Examples of these measures include the operation of hydraulic barriers upstream of the DWSC, drainage reuse and recycling in agricultural water districts and adjusting the timing of wetland water return flows to the SJR. Web sites have been created for the stakeholder process, through which these individuals can login, see a calendar of events, request model runs, and view model results in graphs, superimposed on GIS maps.

Many groups who participate in monitoring in the region, including multiple agencies, academic, private, and stakeholder entities collect large amounts of environmental data. These data currently exist in diverse formats and in different databases with inconsistent, and in some cases, difficult means to access. The goal of the BDAT data management and sharing effort is to promote collaboration and interaction among its members. Therefore, environmental data need to be easily and seamlessly stored, integrated, versioned and distributed to data users for analysis, GIS and modeling applications. Sharing of data facilitates the development of a comprehensive understanding of the status, trends, and environmental processes pertinent to the San Joaquin Basin, and helps guide adaptive management of natural resources in the Delta and upper watershed. The BDAT approach does not require various data/information providers to adopt particular sets of vocabularies, software, etc, but can provide a suite of technological solutions for various groups interested in sharing data and information.

10. Application of BDAT for emergency response

Application of BDAT to the dissolved oxygen issue in the DWSC is ongoing. It is likely to take several years to have all the components in place to make the emergency response system for dissolved oxygen fully operational. In order to demonstrate the utility of the BDAT system another decision support application related to the endangered salmon fishery is described. In November 1999, an interagency recommendation was made to close an intertie channel in order to protect out-migrating juvenile salmon smolts and prevent them from being drawn into the giant pumps that deliver water to agriculture in the San Joaquin Basin and the southern California coastal cities. The closure of the intertie gates roughly corresponded with the neap tide. Water quality levels in the Delta were already approaching several of the water quality standards, and by early December 1999, the municipal water quality standard for chloride was violated. In mid-December 1999 a statutory team of individuals assigned to the task of real-time operations, used real-time flow and water quality data provided by the BDAT system to operate the intertie gates on a tidal basis in order to offer protection to remaining out-migrating salmon, while allowing some fresher Sacramento River water to pass through the intertie in order to improve Delta water quality conditions. Due to the need to make a quick decision, the DSM2 model was used to forecast water quality in the Delta based on this proposed operation of the intertie gates. Planned upstream inflows and export pumping rates at the two large Delta facilities were input into DSM2. In the autumn of 2000, DSM2 was used to forecast the impact of several different intertie gate operations well in advance of the actual operations. The primary concern at the time was "what impact would tidal operations of the intertie on Central Delta water quality?". Based on these DSM2 forecasts, which did not show a marked increase in Central Delta salinity, export pumping rates and gate operations continued without any major changes.

11. Summary

An emergency response management system has been described in this paper which will assist in forecasting episodes of low dissolved oxygen in the DWSC and help to guide remedial measures that will prevent damage to the fishery resource. The emergency response management system has been designed to interact with a real-time water quality monitoring network and is served by a comprehensive data management and forecasting model toolbox. The various technologies in use to acquire flow and water quality data and telemeter these data to a central data depository were discussed as well their respective vulnerability to compromise. The Bay/Delta and Tributaries (BDAT) Cooperative Data Management System was described and its importance in collecting critical information on all aspects of the ecology of the Bay/Delta and upper watersheds highlighted. It was argued that the complexity of the problems faced in California's Bay/Delta ecosystem dictates data integration from a variety of monitoring programs. Innovative strategies using custom data templates to serve the needs of cooperating scientists who wish to share their data and to simplify and streamline data uploading into the master database were described. In a topical example we demonstrated the utility of such a system in providing decision support for management of the San Joaquin River fishery. Ongoing research and development work is looking into how the current system might be adapted and enhanced to provide crucial decision support to other environmental emergencies as well as possible terrorist threats to the water supply system serving California's costal communities.