Report for 2004UT46B: Data Fusion for Improved Management of Large Western Water Systems

Publications

- Conference Proceedings:
  - Khalil, A. and M. McKee. 2004. Hierarchical Bayesian analysis and statistical learning theory, I: Theoretical concepts. In: Proceedings of the 2004 Water Management Conference, Water Rights and Related Water Supply Issues, U.S. Committee on Irrigation and Drainage. Salt Lake City, October, 2004. pp. 433-444.
  - Khalil, A. and M. McKee. 2004. Hierarchical Bayesian analysis and statistical learning theory, II: Water management application. In: Proceedings of the 2004 Water Management Conference, Water Rights and Related Water Supply Issues, U.S. Committee on Irrigation and Drainage. Salt Lake City, October, 2004. pp. 445-455.
  - Khalil A. and M. McKee, 2004. An adaptive model paradigm for water resources management. In: AWRA Annual Conference, Orlando, Florida. November, 2004.
  - Pande, S., L. Bastidas, E. Rosero, M. McKee, W. Shuttleworth, H. da Rocha, and S. Miller. 2005. Effects of Data Uncertainty on Parameter Uncertainty within a Multi-Objective Parameter Estimation Framework. Presented at the Annual Meeting of the American Geophysical Union, San Francisco, December, 2005.
  - McKee, M. 2005. Real-time Management of Irrigation Facilities in the Sevier River Basin. Presented at the Utah Water Users' Workshop, St. George, Utah, March, 2005.
- Articles in Refereed Scientific Journals:
  - Khalil, A., M. McKee, M. Kemblowski, and T. Asefa. 2005. Basin-scale water management and forecasting using multi-sensor data and artificial neural networks. J. American Water Resources Association.
  - Khalil, A., M. McKee, M. Kemblowski, and T. Asefa. 2005. Sparse Bayesian learning machine for real-time management of reservoir release. Water Resources Research (W11401).
  - Asefa, T., M. Kemblowski, M. McKee, and A. Khalil. 2005. Multi-time scale stream flow prediction: The support vector machines approach. J. Hydrology.

    - Kaheil, Y., M. Gill, M. McKee, and L. Bastidas. 2006. A New Bayesian Recursive Technique for Parameter Estimation. Water Resources Research (in press).
    - Gill, M., M. Kemblowski, and M. McKee. 2006. Soil Moisture Data Assimilation using Support Vector Machines and Ensemble Kalman Filter. Water Resources Research (in press).
- Dissertations:
    - Oman, Lizzette. 2006. Use of Bayesian Belief Network to Quantify the Uncertainty in Estimates of Salt Loading from an Irrigated Watershed. Unpublished MS Thesis, Department of Civil and Environmental Engineering, Utah State University, Logan, Utah.

Report Follows

Data Fusion for Improved Management of Large Western Water Systems

Problem

The relative scarcity of water in the western U.S. is increasing due to population and economic growth, pollution, and diversification of the types of demands that are being placed on water use (e.g., traditional consumptive uses such as irrigation and municipal supply, as well as emerging uses for such concerns as water quality maintenance and endangered species protection). This increasing relative scarcity brings: (1) a greater need to more intensively manage the resource, and (2) a requirement for better information about the current and potential future states of our water resources systems so that management decisions can be better informed.

In spite of these increasing needs for better water resources management information, investments in traditional water resources data collection programs (e.g., point stream flows, snow pack, soil moisture, etc.) are declining at the federal and state levels. For example, USGS support for maintenance of several stream gages in Utah has been withdrawn in recent years due to a lack of state cost-sharing commitments. In contrast, investments on the part of other Federal agencies (that have not traditionally played a significant role in support of water resources management) in new data collection methods are increasing (e.g., satellite imagery of land cover, snow cover, ocean surface temperatures, etc.; radar estimation of precipitation; aircraft and satellite imagery for estimation of evapotranspiration). These new data streams will have to be used to back-fill the decline in availability of traditional data. Moreover, analytic methods will need to be developed to apply to these data in order to improve the quality of the information base available to managers of large water systems.

Today's managers have not been schooled in new ways of collecting data or in the analytic approaches required to understand the data. Before new methods of gaining information and making decisions can be practical, investments must be made to place the resulting capabilities into the hands of the water managers who need them. These must be practical and effective, and the water managers must themselves see the value of the information that results.

These are information problems facing managers of large water systems toady, especially large irrigation systems, in several places in Utah as well as in many other arid river basins in the western US.

Research Objectives

Research is needed to develop the data now becoming available from emerging remote sensing sources into useful information for all temporal and geographical scales of water resources management. This must be done in such a way as to maximize the total value of the information coming from both these new, emerging data sources and from the traditional water resources monitoring approaches. Further, the products of such research must be of practical use to the water resources managers who (1) are now losing access to traditional data sources and (2) have not been trained in how to access and use the information flowing from new remote sensing capabilities. In addition, the research products must also be of use to a growing range of stakeholders who have heterogeneous technical backgrounds and skill levels.

The purpose of this project is to develop a significantly enhanced capability within the state of Utah--that will also be appropriate for application in the arid West--to more efficiently manage the state's scarce water resources by exploiting emerging technologies in data collection and analysis.

The objectives of the research are to:

1. Develop and test methodologies from statistical learning theory for combining meteorological and hydrological data from traditional and new remote sensing sources to produce information valuable to managers of large water resources systems. These methodologies will be directed at supplying information for improving water management decisions on problems having a wide range of time and spatial scales (e.g., from daily reservoir releases and canal diversions to long-term commitments for reservoir operations and water exchanges).

2. Develop and implement inexpensive and effective web-based methodologies to disseminate the resulting decision-relevant information to all potential stakeholders.

3. Evaluate and report on the results of the application of the methodologies.

Methodology

The Sevier River Basin, managed by the Sevier River Water Users Association (SRWUA), and the area served by the Emery Water Conservancy District (EWCD) were case study areas for the project. Project research personnel have excellent working relationships with the SRWUA and EWCD, as well as with the Provo, Utah, office of the US Bureau of Reclamation, who assists both the SRWUA and EWCD in the maintenance, operation, and extension of the monitoring programs that collect, archive, and display real-time data on the state of both of these large water systems.

Research Tasks

Development of Models from Statistical Learning Theory

The project will extend and exploit advanced information technologies to design and test better tools for the management of scarce water resources at the geographic scale of a river basin. The major objective of this research effort is to develop and implement a set of tools that can be used to reconcile data and measurements that come from various sources and are characterized by different temporal and spatial scales of resolution, such as NASA remote sensing information and local, on-ground measurements such as stream flow data collected by the USGS. The tools will be used to fuse various pieces of information into one coherent and seamless representation of river basin states, both current and predicted. The resulting information will be provided to stakeholders, decision-makers, and water managers using modern information technologies.

This effort will take advantage of recent research experience to formulate a general framework for hydrologic data assimilation and forecasting, utilizing the following components:

- Bayesian Belief Networks (BBNs). This is a graph-based methodology that was developed by the AI community over the last decade. It is recognized as the most consistent and powerful tool for building statistical expert systems, and is used, for example, by the army to fuse intelligence information coming from multiple sources. Project researchers have published the results of research using this tool for various water and environmental problems (for example, see Ghabayen and McKee, 2003; Ghabayen et al., 2003, 2004, 2006), and a graduate student on the project will examine the use of BBNs in assessing uncertainties in salt loading estimates in the EWCD. The effort this year will focus on full web-based implementation of the BBN that was constructed last year for the EWCD.

- Statistical Learning Theory (SLT). This approach constitutes a general framework for machine learning, and is currently a subject of intensive research in academia and industrial research laboratories. It provides a sound and very efficient environment for building statistical models that include physical insights into the modeled phenomena. Researchers on this project have used this approach to build models for subsurface quality monitoring network design, evaluating information value for groundwater measurements, and spring runoff predictions. Examples of development of models from STL applications that show excellent promise for application to the problems posed for this research include Hassan and McKee (2003), Pande and McKee (2003), and Khalil and McKee (2003). Work this year will involve the web-based implementation of the models constructed last year for improved operation of Piute Reservoir (see Khalil and McKee, 2004a, 2004b) and short- and long-term forecasting of stream flow in the upper Sevier River Basin (Khalil and McKee, 2005). The planned implementation of the Piute Reservoir operations model includes the computer systems programming to connect the model to the reservoir gate controllers in such a way that, with human supervision, the model will be directly operating the reservoir during the irrigation season.

- Sensor and Data Fusion for Irrigation Demand Forecasting. One PhD student to be partially supported by this project will focus on the application of SLT techniques to develop better models for short-term forecasting of irrigation diversion requirements.

The system operations models built to date have been directed at improving the efficiency of water supply. There has been little work, however, to exploit the vast wealth of real-time canal diversion data, real-time meteorological data, GIS data on cropping patterns and command areas served by specific canal reaches, and, very importantly, the short-term forecasts of precipitation and evapotranspiration available from NOAA. This task will involve the development and application of SLT methodologies to re-scale the large footprint of the NOAA forecasts down to a scale useful for predicting evapotranspiration requirements of the land area served by specific reaches of canals. From this, required canal diversions will be forecasted for one to seven days in advance. If such forecasts can be made reliable, they will provide information of significant utility to canal and reservoir operators. The models will be developed and tested from data available in the Sevier River Basin.

Specific models to be developed and/or implemented this year will likely consist of:

- A model for providing long-term forecasts of spring runoff in the Upper Sevier River Basin (to be implemented on the SRWUA web site)

- A model for managing short-term operations for Piute Reservoir in the Upper Sevier Basin (to be implemented on the SRWUA web site, and then tested for reliability)

- A BBN model for estimating monthly and annual salt loading from the San Rafael River into the Colorado River, and quantification of uncertainty in those estimates (to be implemented on the EWCD web site)

- A model to provide short-term (one to seven days) forecasts of irrigation demands on a canal reach basis

Implementation of Models

The models all be integrated with the SRWUA or EWCD databases and implemented on the websites of those organizations. Implementation will be accomplished through collaborative work among USU project staff, representatives of the managing water districts, and contractors who work for the districts to maintain the water resources monitoring systems, databases, and websites.

Evaluation and Dissemination of Results

In addition to the use of standard statistical methods for assessing the quality of model predictions, the project will conduct an analysis of the real-time performance of the operation of the short-term forecasting models as they are being applied during the 2005 irrigation season. As necessary, project personnel will work directly with end-users in the SRWUA and EWCD to identify and correct problems with the models, and to educate the users in proper model operation and interpretation. The lessons learned from these interactions will be documented and recommendations for implementation and management of such models within the institutional framework of these types of water resources organizations will be documented. In addition to the use of web-based dissemination of research products, the results of the project will be published in the normal academic venues.

Principal Findings

Water Management in the Sevier River Basin

Real-time operations models were developed using methods from statistical learning theory. These include artificial neural network (ANN) models, support vector machine (SVM) models, and "lazy learner" (LL) models. These models have been constructed to help provide real-time management information for determining releases from Piute Reservoir and diversions into the Sevier Valley/Piute Canal. The models have been made operational on the SRWU website for use by reservoir and canal operators. Comparisons of model predictions versus actual canal operations are given in Figure 1.

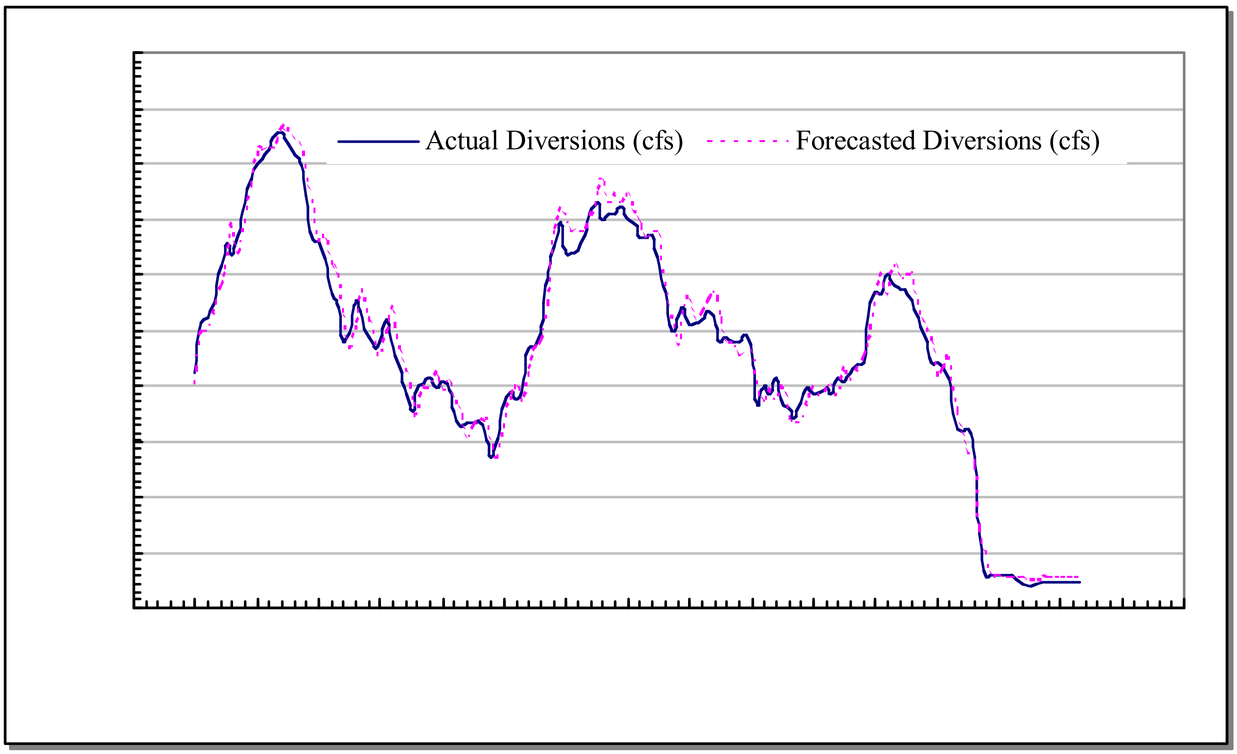

Figure 1. Comparison of Actual Sevier Valley/Piute Canal Diversions in 2002 with ANN Model Forecasted Diversions

Short-term predictive models were also built using artificial neural network approaches to forecast diurnal flows from Clear Creek into the Sevier River. An example of these forecasts, made hourly for a period 24 hours in advance, is given in Figure 2.

Long-term predictive models were constructed to forecast stream flows at the Hatch gage in the Upper Sevier River Basin. These predictions come from an artificial neural network model that uses historical stream flow data, Snotel data, and sea surface temperature anomaly data from the Pacific and Atlantic Oceans. A comparison of the forecasts obtained from the ANN model versus historically measured flows is shown in Figure 3. The work shown in Figures 1-3 has been recently published (Khalil et al., 2005).

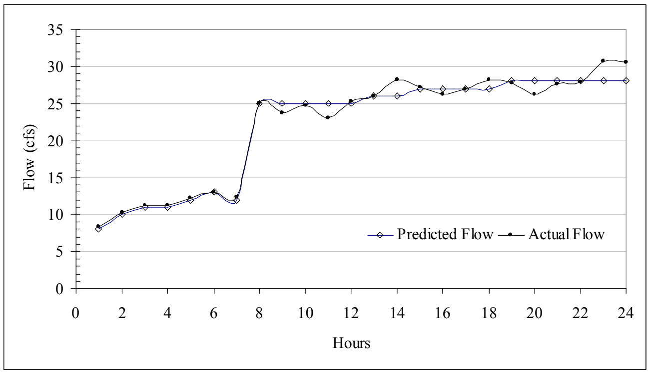

Figure 2. Predicted Versus Actual Diurnal Fluctuation of Flows in Clear Creek on 4/4/2001

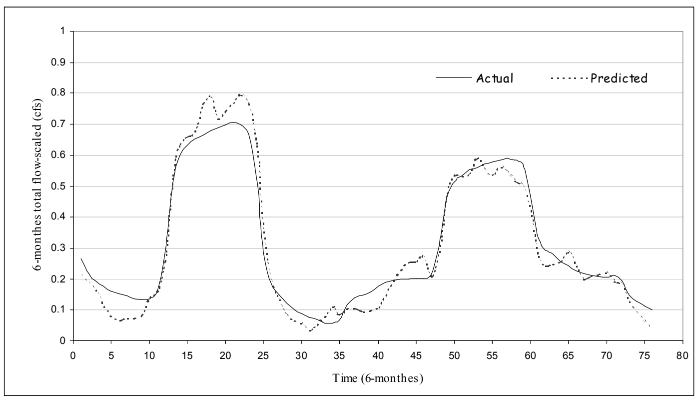

Figure 3. Time-Series Performance of the ANN Model in Predicting Seasonal Flows at Hatch

In FY 2004, work focused on development and statistical verification of an hourly operational model for predicting required releases from Piute Reservoir. The modeling process utilizes a combination of support vector machines and relevance vector machines (RVMs) to screen incoming data to recognize outliers and/or "drift" in the underlying probability distribution of the input data, develop a revised predictor model if drift in the underlying distribution is detected, and then make a prediction for required reservoir releases for the next hour. Adoption of the RVM approach for developing the predictor model has provided the capability of estimating confidence intervals on the prediction made by the model. This capability, which has not been previously possible, gives the reservoir operator valuable information about the uncertainty in the prediction made by the model. The suite of models is designed to run in real time and to provide the reservoir operator with an hour-by-hour recommendation for releases needed from the reservoir in order to meet downstream demands for nine irrigation canals. It does this in order to meet water orders that arrive 24 to 48 hours in advance of deliveries, even though travel times from the reservoir to the end of the furthest canal is on the order of five or six days. The suite of models was developed using data from the 2001 and 2002 irrigation seasons, and then tested against the 2003 and 2004 irrigation seasons. Figure 4 provides a comparison of actual reservoir releases and model-generated recommendations for release quantities, as well as confidence intervals, for the 2003 season. The suite of models developed for real-time operation of Piute Reservoir was programmed re-programmed according to specifications required by the SRWUA. This has been implemented on SRWUA computers and its output made available to reservoir operators. At the time of preparation of this report, the SRWUA is evaluating the performance of the model and plans to turn give direct control of Piute Reservoir to it.

The modeling approach and findings relative to model performance were published in Khalil et al. (2005).

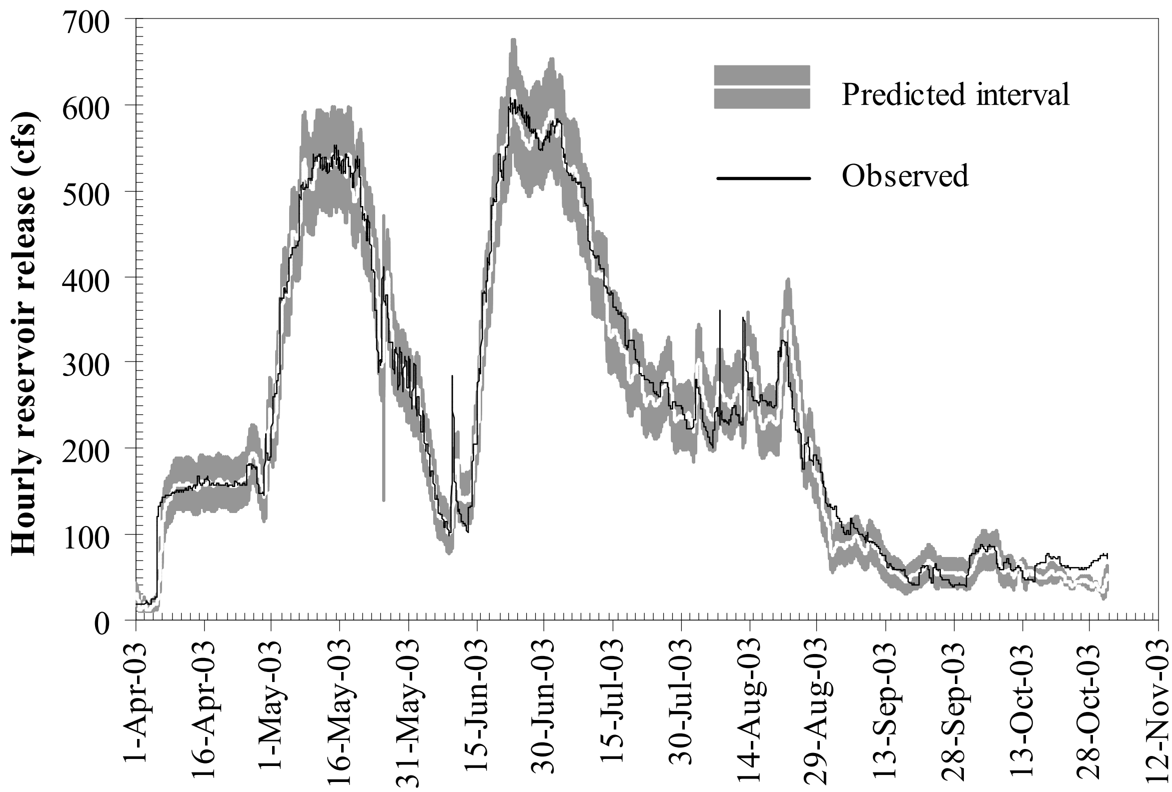

Figure 4. Comparison of Actual Piute Reservoir Releases in 2003 with the SVM/RVM Model Forecast Releases

Salt Loading in the San Rafael River Basin

Work in FY 2004 focused on statistical analysis of data available from historic stream flow and salt concentration measurements, including the real-time data provided in the on-line database operated by the Emery Water Conservancy District (EWCD) (see http://www.ewcd.org/). This dealt mainly with analysis of statistical relationships between stage and discharge, and between conductivity and salt concentration for the major tributaries (Huntington, Cottonwood, Rock, and Ferron Creeks) of the San Rafael River (see Figure 5). This was done to provide the basis for a Bayesian belief network (BBN) model that can be used to quantify the uncertainty in the estimate of salt loading from the basin.

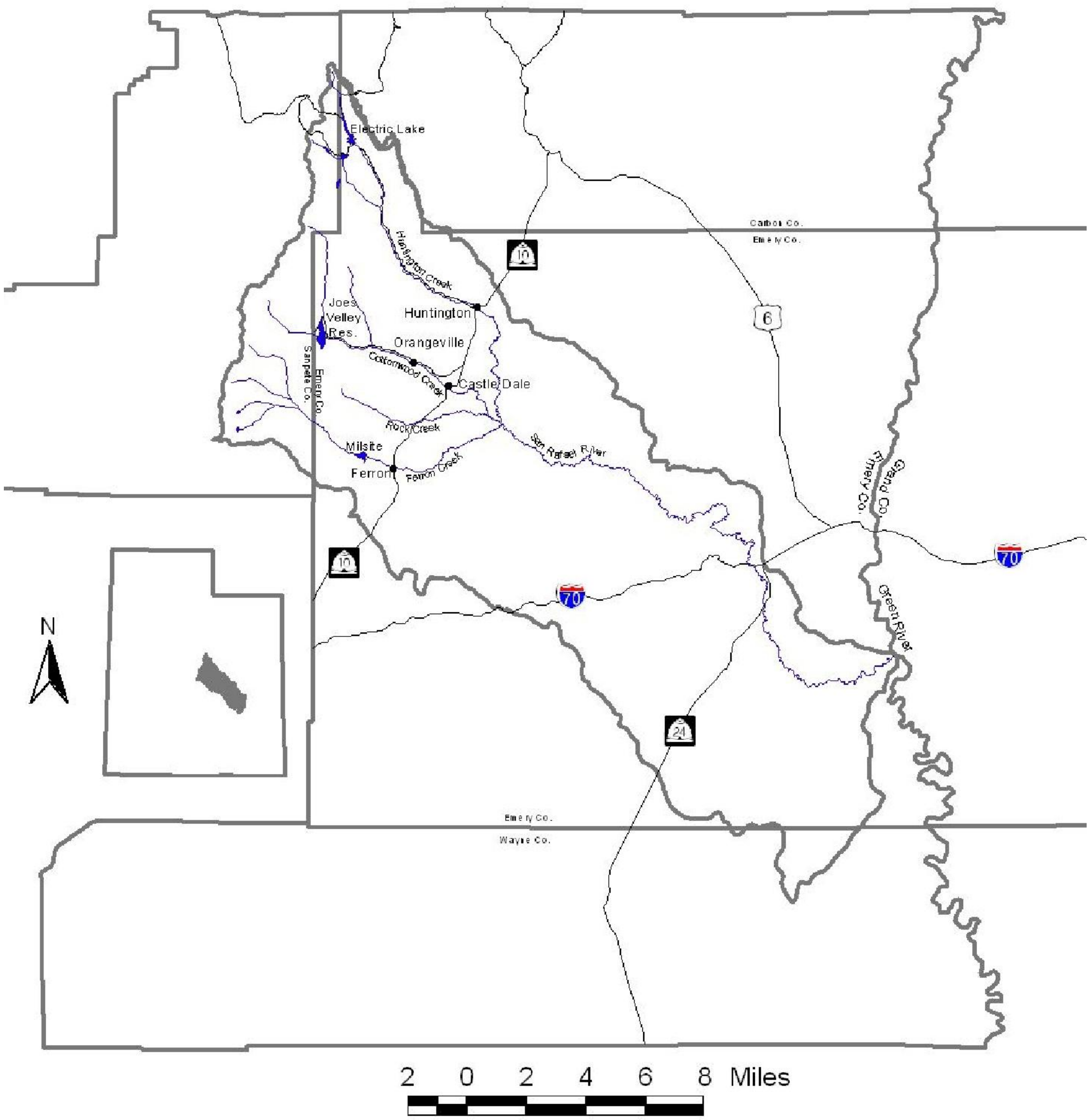

Figure 5: San Rafael River Basin

Two alternative BBN models have been constructed that estimate total daily, weekly, monthly, and annual salt loading from the San Rafael drainage into the Green River. These models have the general form shown in Figure 6. Flows in the San Rafael are modeled as the sum of estimated flows in the four tributary creeks that converge to form the San Rafael. Salt loading in the San Rafael is modeled as the sum of the estimated salt load from the four tributaries. Uncertainty in these estimates is due to instrumentation/measurement uncertainty and uncertainty in the relationships between stage (which is measured) and flow (which is estimated from stage), and between electrical conductivity (which is measured) and salt concentration (which is estimated).

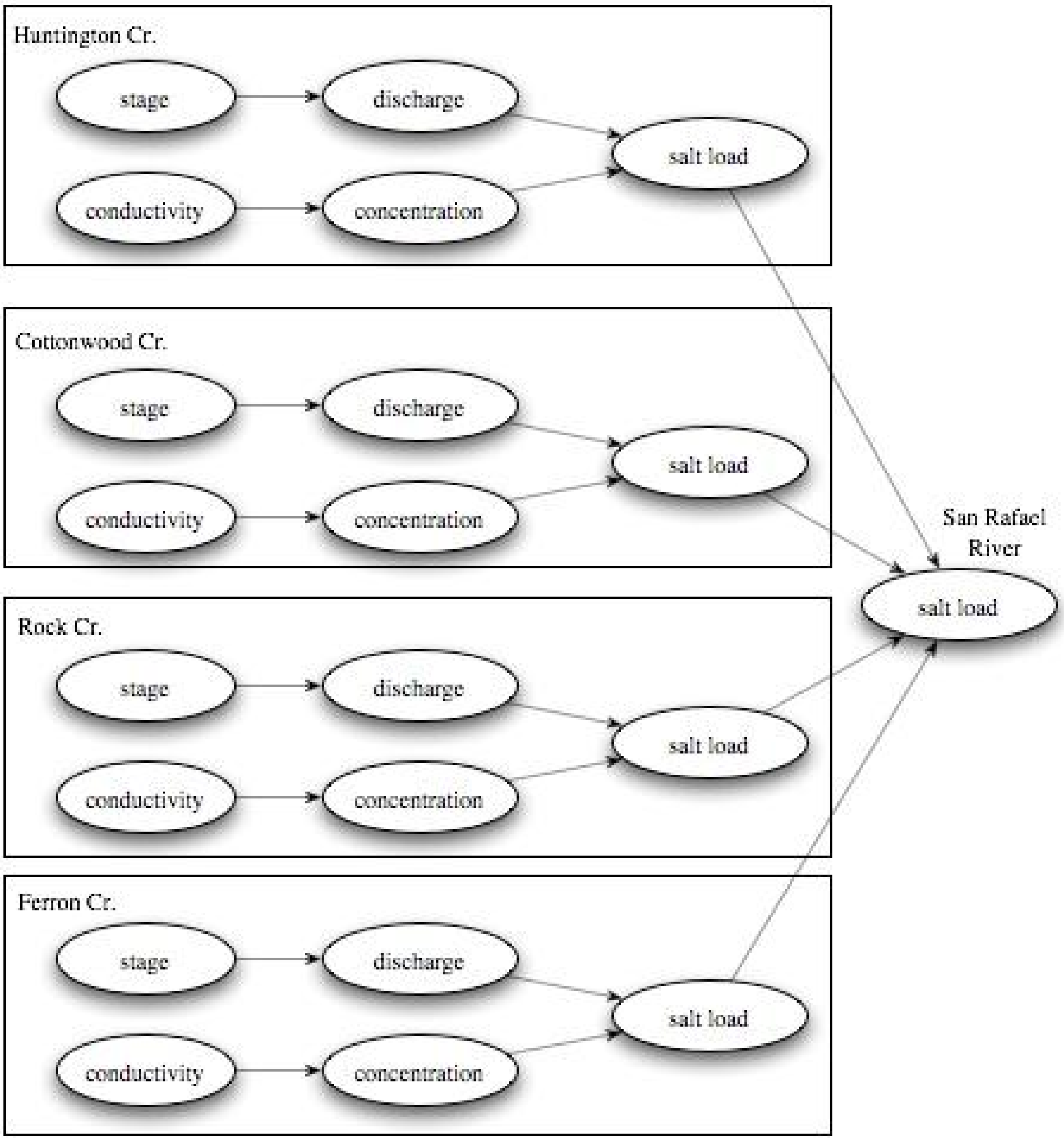

Figure 6: General BBN Design for Estimating Salt Loading to the San Rafael River from the EWCD

These models use hourly data available from the EWCD real-time data collection system to populate the marginal probability distributions for the stage and electrical conductivity nodes. The uncertainty in the relationship between stage and discharge and between conductivity and salt concentration is encoded in the BBN for each tributary. The BBN can then estimate salt concentration and flow rate, as well as quantify the uncertainty in those estimates. Salt loading for each tributary is simply the product of the estimated flow and salt concentration. The total loading to the San Rafael is simply the sum of the loading estimates of the individual tributaries. The BBN can calculate this estimate on a daily basis, and it can obtain weekly, monthly, and annual estimates of salt loading by simply summing the daily estimates.

Data available from the EWCD monitoring network are sufficient to estimate annual salt loading for two years. The BBN models show an annual loading of approximately 100,000 to 150,000 tons/year, which is consistent with estimates made in other studies. However, the BBN models also show 95 percent confidence intervals that are as much as ±50,000 tons/year, indicating that salt loading estimates are subject to considerable uncertainty. Application of backpropagation analysis indicated that the major sources of uncertainty in the loading estimates lie in the estimates of stream discharge. These analyses showed that investments in better flow measurement devices would be the most effective way to decrese the uncertainty in the final salt loading estimate.

The research conducted on the EWCD salt loading issue is reported in Oman (2006). At the time of preparation of this report, work is underway to prepare and submit a manuscript that describes this research for publication in a professional journal.

Significance

The Sevier River Basin, managed by the Sevier River Water Users Association (SRWUA), and the Emery Water Conservancy District (EWCD) in Utah have been used as case studies and experimental sites. They were chosen because of their significant size, their importance in the agricultural sector of the state, their highly developed on-line databases, and the willingness of local water resources managers to cooperate with the research and make use of the outputs of the project. The project has focused on development of data sensor fusion approaches to reduce the uncertainty that accompanies significant water management decisions through the implementation of real-time management and long-term forecasting models. In the case of the Sevier River Basin, these models are useful for real-time reservoir release and canal diversion decisions and for long-term forecasting of water availability. For the EWCD, the modeling is resulting in improved estimates of salt loading into the Colorado River from the region, as well as improved quantification of the uncertainty in these salt loading estimates. The output of these models is being utilized for development and deployment of decision-support systems that are being made available to water managers from these organizations. Project staff continue to work with these water districts to help integrate these models with their local database systems so that the resulting information will be available to water managers and stakeholders via the internet.

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