1.6 CRITICAL HYDROMETEOROLOGICAL NEEDS AND INTEGRATED, MULTI-DISCIPLINARY DSS FOR WATER RESOURCE MANAGERS IN THE BUREAU OF RECLAMATION

Dr. Dave Matthews * and Dr. Donald Frevert
Technical Service Center, Bureau of Reclamation,
Denver, Colorado

1. BACKGROUND

Water supply variability creates much uncertainty in how we manage the limited freshwater resources of our planet. Multi-disciplinary decision support systems (DSS) are required to assist decision-makers in meeting the challenges of climate extremes from drought to floods for optimal water resources management. These DSS need accurate and timely hydrometeorological information for reservoir operations and river basin management and planning. This paper discusses the decision support systems and their application using relational data bases and state-of-the-technology forecasts used by the Bureau of Reclamation (Reclamation), US Department of the Interior, to make its water storage and conveyance facilities less vulnerable to variations in the water cycle including extremes of droughts and floods. We draw upon collaborative efforts at Reclamation to partner with research teams at National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS), National Aeronautic and Space Administration (NASA), Natural Resources Conservation Service (NRCS), US Army Corps of Engineers, and other agencies involved in the analysis and prediction of water supplies and demands, precipitation, and related phenomena.

Reclamation serves over 31 million Americans in 17 Western States, providing over 9.3 trillion gallons of water and 45 billion kilowatt hours of electricity, and delivers irrigation water to over 140,000 farms each year. Consequently, river basin managers must have timely data from remote areas that are often inaccessible in winter, and have a means of quickly analyzing the impacts of precipitation and snowmelt on streamflow for routine river system management, and emergency responses to extreme events. Therefore, Reclamation uses a variety of hydrometeorological observing systems that it maintains, and cooperates with other agencies in collection of additional data. Reclamation's hydrometeorological and early warning systems provide data for decision support tools. Reclamation's Science and Technology studies focus research in the Watershed and River Systems Management Program (WaRSMP) on providing water resource managers with the most timely and accurate information for complex, interdisciplinary decisions using advanced decision support systems and relational data bases. Streamflow forecasts, and surface energy and water budgets are an integral part of the hydrology used in the decision process. These are needed on time scales from near real-time for flash floods and evaporation - crop consumptive use / water conservation needs, to days, weeks, months for daily operational decisions, and seasonal and interannual for annual operations plans, and up to decadal for long-range planning. Shifting demographics and climate variations create new challenges for integrated, multi-disciplinary decision support systems (DSS) that water managers and planners can apply to developing sustainable fresh water supplies for the West. These DSS integrate "the law of the river", riverine ecosystem and recreational needs with traditional irrigation, municipal and industrial uses, and hydropower generation, and economic trade-off analyses.

Reclamation cooperates with other agencies including: National Oceanic and Atmospheric Administration (NOAA), USGS, NRCS, and National Aeronautic and Space Administration (NASA), who collect, transmit, and analyze hydrometeorological information that we use in the Hydrologic Data Base (HDB) described by Matthews et al (1997, 1999, 2000). This paper will describe current and planned efforts to meet Reclamation's hydrometeorological needs, interdisciplinary modeling and decision support system tools and approaches used in major river basins served by Reclamation's facilities from Upper Columbia to the Rio Grande.

2. RIVER SYSTEM DECISION SUPPORT MODELS AND SYSTEMS

Reclamation uses a variety of decision support systems to assist the water operations managers in their daily reservoir and river system operations. One of the latest technologies used is the RiverWare modeling framework. This powerful general purpose modeling system was developed at the Center for Advanced Decision support for Water and Environmental Systems (CADSWES) in the Civil and Environmental Engineering Department, University of Colorado in partnership with Reclamation, Tennessee Valley Authority, and other agencies (Zagona et al., 2001). RiverWare is a product of the Watershed and River Systems Management Program - a cooperative interagency effort to develop and implement flexible and robust river basin management tools for the benefit of managers and decision makers using a data centered approach. In addition to Reclamation and the USGS, a number of other agencies and universities have made substantial contributions to the success of the program. Further information on WaRSMP is available at

* Corresponding Author: Dr. Dave Matthews, US Bureau of Reclamation, PO Box 25007 (D-8510), Denver CO80225-0007; email: dmatthews@do.usbr.gov web: http://www.usbr.gov/rsmg

http://www.usbr.gov/rsmg/rsmgwtrmg.htm

The primary modules under development are the RiverWare modeling system, the Hydrologic Database (HDB), and the Modular Modeling System (MMS). MMS is a generic, physical process modeling system that can be used to develop models of a variety of physical processes including precipitation-runoff models. RiverWare and HDB are being developed at CU-CADSWES. RiverWare is a reservoir and river systems operations and planning modeling tool that allows the user to construct and customize the physical behavior of the river network without the need for software programming. The user further constructs the operating policy for the network and supplies it to the model as "data" (i.e, the policies are visible and capable of being explained to stakeholders; secure, yet able to be modified for policy analysis). RiverWare models can be run at a variety of time steps ranging from 1-hour (detailed operations, hydropower and physical processes) up to annual (long range planning). Among the many successfully deployed RiverWare models are the Colorado River planning model (CRSS), the Colorado River operations model (the Annual Operating Plan), the Upper Rio Grande Water Operations Model, and TVA's water and power scheduling model. Fulp and Harkins (2001) provide an example of how the RiverWare framework was used to develop policy regarding the impacts of surplus flows on the Colorado River.

The RiverWare - Hydrologic Data Base concept integrates the most current streamflow forecast into the modeling system to assist in decision-making and optimization of river system operations.

Decision Support System Tool Box

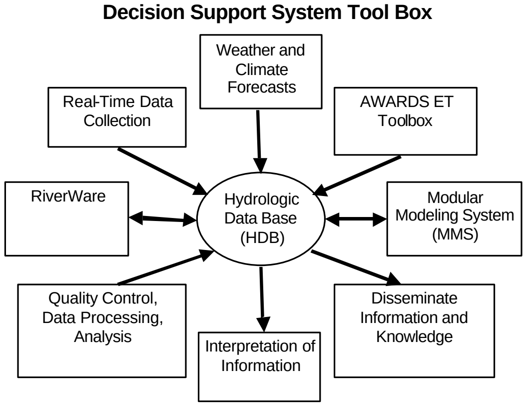
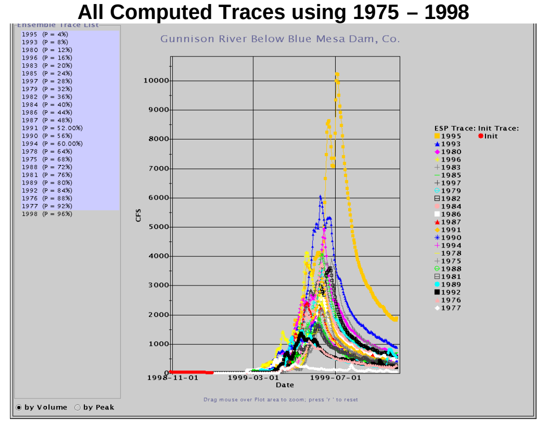


Figure 1. Schematic showing the decision support system tool box - a data centered approach for real-time river system decision-making. (Fulp et al, 2002)

Forecasts of streamflow hydrographs from the Modular Modeling System that are based on the most current spatial distribution of precipitation, temperature, and snowpack are provided for key nodes in the RiverWare model. In addition, forecasts from the Advanced Hydrologic Prediction Services – National Weather Service River Forecast System (NWSRFS) can be used by RiverWare. These streamflow hydrographs need to have relative certainty of the forecast defined.

Today, Reclamation's water managers use historic hydrographs that show the ~10%, 50%, and 90% exceedence forecast based on historic data. Improved forecasts should incorporate the uncertainty or conditional probability for these streamflow hydrographs. An example from the Modular Modeling System for the Gunnison Basin is shown below in Figure 2.

MMS ESP Tool
All Computed Traces using 1975 – 1998



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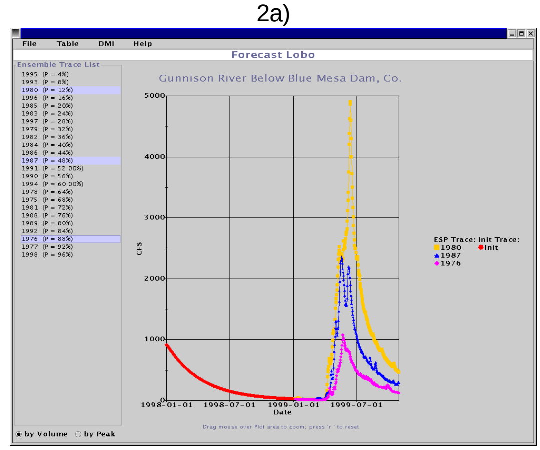

2b)

Figure 2. Example of Ensemble Streamflow Predictions (ESP) from the MMS for the Gunnison Basin using data from 1975-1998, showing the range of seasonal hydrographs predicted (left), and selected representative traces for years expected to represent current "conditional" forecast range (right). (Fulp et al, 2002)

At present, the selection of the most representative set of traces is somewhat subjective. New research is needed to more objectively forecast and predict explicitly the expected set of representative hydrographs. This may be performed from stochastic forecasts (Salas et al, 2002).

3. INTEGRATION OF EMERGING DATA ASSIMILATION SYSTEMS – LAND DATA ASSIMILATION SYSTEMS

The Land Data Assimilation System (LDAS) team at NASA Goddard Space Flight Center (GSFC) is developing a system that runs multiple land surface models, assimilating and using as forcing the latest in surface observations and remotely-sensed data both operationally and retrospectively. The emphasis of LDAS is on capturing the most realistic representations of land surface states and dynamics over large areas and at high resolutions. The main hydrometeorological variables that LDAS focuses on are soil moisture, evaporation, snow cover, runoff, precipitation, and surface energy budget variables. All of these can aid water resource managers in flood and drought assessments and prediction. This effort is conducted in partnership with National Centers for Environmental Prediction (NCEP), Office of Hydrologic Services, NWS, University of Washington, Princeton University, and others. It is a powerful new tool for analysis and prediction.

LDAS research efforts are divided between two main projects: North American LDAS (NLDAS) and Global LDAS (GLDAS). Both projects share the same underlying objectives: LSM development, use of observations as forcing data, and the assimilation of different satellite and radar information. A few differences do exist between the two projects, but as the two develop side-by-side they serve to strengthen each other's growing utility for applications and use by atmospheric prediction models. Overall, the NLDAS and GLDAS projects are characterized as real-time, distributed, uncoupled, land-surface simulation systems on, respectively, a U.S. national domain at 0.125 degree resolution and a global domain at 0.25 degree resolution. Both LDAS projects use a suite of different LSMs running in tandem on these grid systems and driven by common surface forcing. Some of the Land Surface Models (LSM) currently incorporated into LDAS include Mosaic, NCEP, Oregon State University, United States Air Force, and Office of Hydrology (NOAH) model, and the Community Land Model (CLM). Additional LSMs are being brought into LDAS which include the Variable Infiltration Capacity model (VIC) and the Catchment Land Surface Model.

Other major components of the LDAS projects include replacement of atmospheric model-based forcing with observations, assimilation of remotely-sensed and in-situ measurements into the LSMs, and output validation and calibration of the LSMs. Using observations to drive land surface models (e.g. precipitation and radiation), biases present in coupled atmospheric-land surface model systems can be avoided. In the NLDAS project, the modeled precipitation is replaced with a merged product consisting of "Stage IV" WSR-88D, gage precipitation, and modeled precipitation from the NCEP Eta Data Assimilation System (EDAS). Downward shortwave and longwave radiation products used are from GOES satellites. GLDAS also has replaced some of its modeled fields with satellite-derived precipitation like the NASA GSFC 3-hourly merged-satellite product (includes Geostationary IR, SSM/I, TRMM). As for radiation fields, GLDAS uses global downward shortwave and longwave radiation products from the Air Force Weather Agency's (AFWA).

Demonstrating the use and added value of LDAS output in Reclamation's operations and decision-support tools is becoming a major part of LDAS's applications research. Reclamation applies the latest emerging technologies in decision support modeling to enable river systems operations managers to make better-informed decisions. The key river basin modeling technology includes RiverWare and the Agricultural Water Resources Decision Support - Evapotranspiration Toolbox system (AWARDS-ET Toolbox). RiverWare is a river modeling and water accounting system which provides a flexible framework for developing and running site specific models that incorporate the "law of the river" and other policy constraints. It simulates the routing of the river flow operations through dams, hydropower plants, and maintains the contracts for water delivery to irrigators, recreational, municipal and industrial demands. Even though Reclamation uses several hydrological modeling tools for RiverWare, spatially-distributed fields like soil moisture are not fully accounted for in their operations. If such fields were included, they could help increase the accuracy of Reclamation's water resource accounting. Figure 3 provides a conceptual schematic of how we envision the integration of LDAS remote sensing products into Reclamation's DSS.

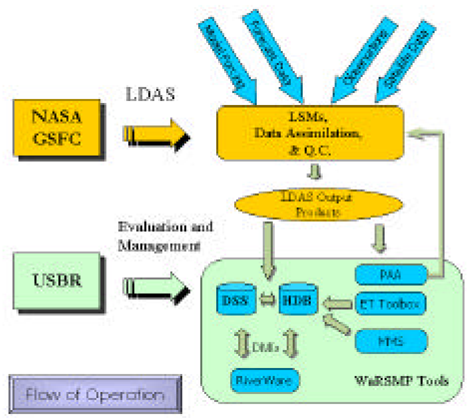

Figure 3. Schematic for the planned flow of information from NASA GSFC to Reclamation. The incorporation of different LDAS LSM output and testing of the various data assimilation techniques in Reclamation's river system operation models and decision support systems can provide a means to improve drought and flood analysis and prediction and enable water resource managers and engineers to make more informed decisions. (Arsenault et al, 2002)

The schema for integrating data from LDAS into the water manager's decision support toolbox is shown in Figure 3. It characterizes the main components from observations and predictions that are assimilated in LDAS and then transferred to Reclamation's data base either the USACE Data Storage System (DSS) or the Reclamation Hydrologic Data Base (HDB) which then link via Data Management Interfaces (DMIs) to RiverWare and other decision models like the ET Toolbox and the Modular Modeling System (MMS). The Precipitation Accumulation Algorithm (PAA) provides estimates from radar of the gridded quantitative precipitation snow water equivalent or rainfall (Hunter and Holroyd, 2002). The ET Toolbox computes the demands for water - consumptive losses of water by crops and riparian vegetation, MMS computes the supply in terms of precipitation/snowpack runoff and streamflow.

4. ADVANCED HYDROLOGIC PREDICTION SERVICES

The National Weather Service River Forecast Centers (RFC) are the primary sources of streamflow forecasts. These are now using the AHPS suite of streamflow forecast models which incorporate the latest emerging multi-sensor hydrologic modeling and prediction technologies. The California-Nevada RFC has been testing the AHPS extended streamflow forecasts on the Truckee Basin. These products include a suite of streamflow forecasts and probabilistic information of value to water operations decision-makers.

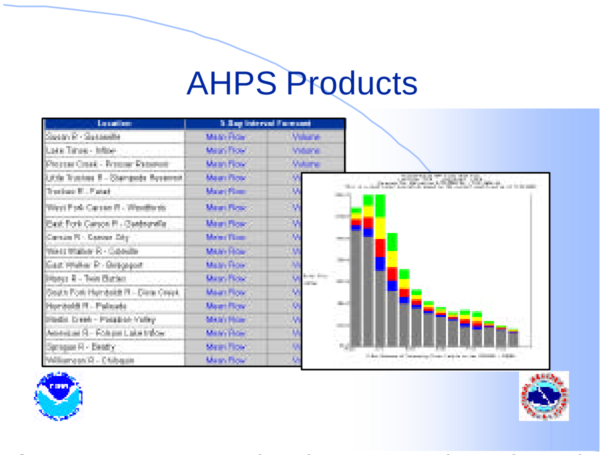

Figure 4. An example of AHPS products from the CNRFC showing the probabilistic forecast of the 5-day mean flow at the Farad Gauge from May 22 to July 31, 2002. (Hartman et al, 2002).

In addition to the probabilistic ranges shown in Figure 5, an ensemble of hydrograph predictions are provided at key nodes in the river basin. Figure 5 shows how these are computed in the AHPS mode of integrating multi-sensor and historic information to make the most accurate forecast.

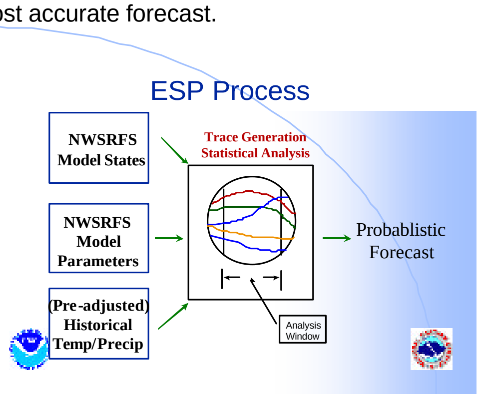

Figure 5. Extended Streamflow Prediction process that integrates the NWSRFS model states with model parameters and historical temperature and precipitation information to generate hydrologic traces that yield probabilistic forecasts. (Hartman et al, 2002).

5. WATER DEMAND FORECASTING – AGRICULTURAL WATER RESOURCES DECISION SUPPORT – ET TOOLBOX

Predicting consumptive use demands by agriculture and riparian vegetation are very important for water resource managers. Current scientific applications use the Penman evapotranspiration method to estimate consumptive needs of crops. The purpose of the AWARDS system is to improve the efficiency of water management and irrigation scheduling by providing guidance on when and where to deliver water, and how much to apply. The AWARDS system has been designed for use by reservoir system operators, water district staff, and on-farm irrigators. Real-time information is provided on the web at this site:

http://www.usbr.gov/rsmg/awards/index.html

The primary purpose of the ET Toolbox is to estimate high-resolution daily rainfall and water depletions (crop and riparian vegetation ET, and open water evaporation) within specified river reaches, and to ftp these daily values for input into RiverWare, which is the river modeling and wate accounting system used by the Upper Rio Grande Water Operations Model (URGWOM). The URGWOM is a multi-agency effort to develop a numerical computer surface water model that will cover the Rio Grande from its headwaters in Colorado to Fort Quitman, Texas. The primary purpose of this model is a daily water operations accounting tool that can be used for basin-wide water management and planning.

The ET Toolbox builds on the AWARDS system, adding Geographic Information System (GIS) land use to specify acreage, crop and riparian water use, and open water evaporation estimates for each Hydrologic Rainfall Analysis Project (HRAP) grid cell (resolution about 4km x 4km) along the Middle Rio Grande. The land use data are combined with weather station data-based ET estimates as calculated with a modified Penman equation to develop cell-by-cell water use estimates, adjusted for radar rainfall estimates, in acre-feet and cfs. Figure 6 shows the schematic of the water distribution system used by the Upper Rio Grande water operations managers.

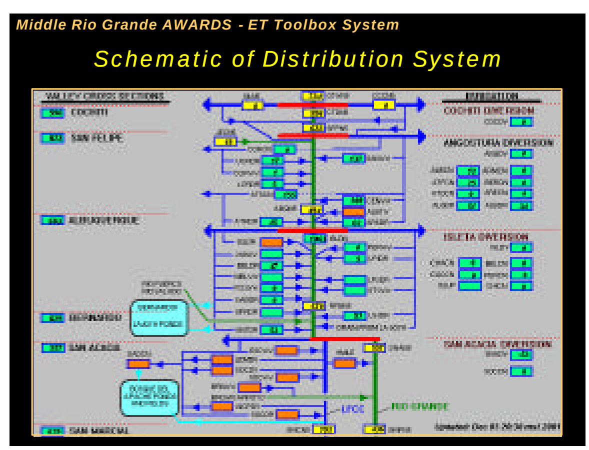

Figure 6. Schematic of Middle Rio Grande Distribution system with real-time updates of diversion flows computed.

The products on the Internet include real-time access to weather station and stream gage data from the Middle Rio Grande Conservancy District (MRGCD), radar rainfall estimates, and links to USGS streamgage data. The AWARDS/ET Toolbox system also receives daily weather data from the New Mexico Climate Center at New Mexico State University (NMSU) for calculating ET and Internet posting. Graphical plots of 5-day and 10-day running averages of daily ET are available to help detect water requirement trends. Other plots include total daily agricultural, riparian and urban ET.

The National Centers for Environmental Prediction (NCEP) Eta model weather forecast parameters at 12-km grid resolution are used for the ET Toolbox's ET forecasts for today and the next two days. The ET Toolbox uses the Eta model 0600 UTC (0000 MDT) run's 3-hr forecasts for temperature, relative humidity, and wind speed, plus the forecast cumulative solar radiation and precipitation for 0600-0600 UTC. From the 3-hr forecast values, the ET Toolbox selects the maximum and minimum temperatures, and calculates the average relative humidity and wind speed. The Eta model-based 24-hr ET forecasts from the previous day are used in the ET Toolbox when weather station data are unavailable.

ET Toolbox Research

Future ET Toolbox research could include studies to (1) implement daily open water calculations with actual daily areal extent updates, (2) revise evaporation coefficients based on results of open water field studies, (3) improve the riparian vegetation ET coefficients and make other equation changes based on the results of the ET field studies, and (4) determine if adding soil moisture fields from Land Surface Models and observations, and soil types and slope, can be used in the ET Toolbox to improve the efficiency of water management. Further information on the ET Toolbox is available at:

http://www.usbr.gov/rsmg/awards/ettoolbox.html

6. SUMMARY AND CONCLUSIONS

Water variability creates much uncertainty in how we manage the limited freshwater resources of our planet. The variations of climatic extremes from droughts to floods pose serious challenges to forecasters and water managers who need to understand the uncertainty of forecasts. This paper has described the many new emerging technologies that provide exciting opportunities for improving water resource management through applications of better science. This paper has touched upon several new tools under development in NOAA, NASA, USGS, and within Reclamation that water managers are able to apply today. The RiverWare and Hydrologic Data Base provide a unique multi-disciplinary approach to integrating the best hydrometeorological forecasts into a set of models that synthesize the scientific, engineering, legal, environmental and economic data to provide information that decision-makers can readily use.

Future work should continue these partnerships and develop others to enhance the analysis and prediction of water supply and demand.

7. ACKNOWLEDGEMENTS

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