A MODELING FRAMEWORK FOR IMPROVED AGRICULTURAL WATER-SUPPLY FORECASTING

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Abstract: The National Water and Climate Center (NWCC) of the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) is moving to augment seasonal, regression-equation based water supply forecasts with shorter-term forecasts based on the use of distributed-parameter, physical process hydrologic models and an Ensemble Streamflow Prediction (ESP) methodology. The models will be used to assist in addressing a wide variety of water-user requests for more information on the volume and timing of water availability, and improving forecast accuracy. This effort involves the development and implementation of a modeling framework, and associated models and tools, to provide timely forecasts for use by the agricultural community in the western United States where snowmelt is a major source of water supply. The framework selected to support this integration is the USDA Object Modeling System (OMS). OMS is a Java-based modular modeling framework for model development, testing, and deployment. It consists of a library of stand-alone science, control, and database components (modules), and a means to assemble selected components into a modeling package that is customized to the problem, data constraints, and scale of application. The framework is supported by utility modules that provide a variety of data management, land unit delineation and parameterization, sensitivity analysis, calibration, statistical analysis, and visualization capabilities. OMS uses an open source software approach to enable all members of the scientific community to collaboratively work on addressing the many complex issues associated with the design, development, and application of distributed hydrological and environmental models. A long-term goal in the development of these water-supply forecasting capabilities is the implementation of an ensemble modeling approach. This would provide forecasts using the results of multiple hydrologic models.

INTRODUCTION

The mission of the National Water and Climate Center (NWCC) of the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) is to lead the development and transfer of water and climate information and technology which support natural resource conservation. The functions of the NWCC include:

Natural Resource Planning Support

- Provide water supply forecasts
- Provide water and climate analysis, information, and services for NRCS, partners and customers

Data Acquisition and Management

- Operate the Snowpack Telemetry (SNOTEL) data collection system for the United States
- Design and manage an on-line, quality controlled, national database for NRCS and partners in support of farm, watershed and river basin scale planning

Technology Innovation

- Assess and select technologies required to address resource concerns
- Adapt appropriate technologies

Water supply forecasts are an important function of the NRCS NWCC. Forecasts are developed for hundreds of basins in the western United States and are used by the agricultural community to optimize water use during the irrigation season (Figure 1). The NWCC has historically developed seasonal, regression-equation based forecasts of estimated seasonal streamflow volume. To address the agricultural communities' requests for more information on the volume and timing of water availability, and to improve forecast accuracy, the NWCC is now developing the capability to use distributed-parameter, physical process hydrologic models to provide daily, weekly, and seasonal forecasts using an Ensemble Streamflow Prediction (ESP) methodology.

A primary objective of this model-based forecast effort is the development and implementation of a modeling framework, and associated models and tools, to enable the provision of timely and improved water supply forecasts. The framework selected to support this effort is the USDA Object Modeling System (OMS) (Ahuja et al., 2005; http://www.javaforge.com/project/1781). OMS is a Java-based, integrated, environmental modeling framework that supports the development, testing, and deployment of a wide variety of models and analysis tools. It consists of a library of stand-alone science, control, and database components (modules), and a means to assemble selected components into a modeling package that is customized to the problem, data constraints, and scale of application. The framework is supported by utility modules that provide a variety of data management, land unit delineation and parameterization, sensitivity analysis, calibration, statistical analysis, and visualization capabilities. This paper presents an overview of the concepts and components of OMS and the integrated forecasting system that is being developed and implemented by the NWCC.

OBJECT MODELING SYSTEM (OMS)

As the name implies, OMS adheres to the notion of objects as the fundamental building blocks for a model and to the principles of component-based software engineering (CBSE) for the model development process. OMS as a framework is object-oriented; the models within the framework are composed of objects, or components, as defined in CBSE. These concepts are also the basis for other modeling frameworks such as OpenMI (Gregersen,2007), CCA (Bernholdt,2006), ESMF (Collins,2005), and CMP (Moore,2007).

OMS uses an open source software approach to enable all members of the scientific community to collaboratively address the many complex issues associated with the design, development, and application of distributed hydrological and environmental models. The OMS architecture has been designed so that it can be interoperable with other frameworks supporting agro-environmental modeling in Europe, Australia, North America, and elsewhere.

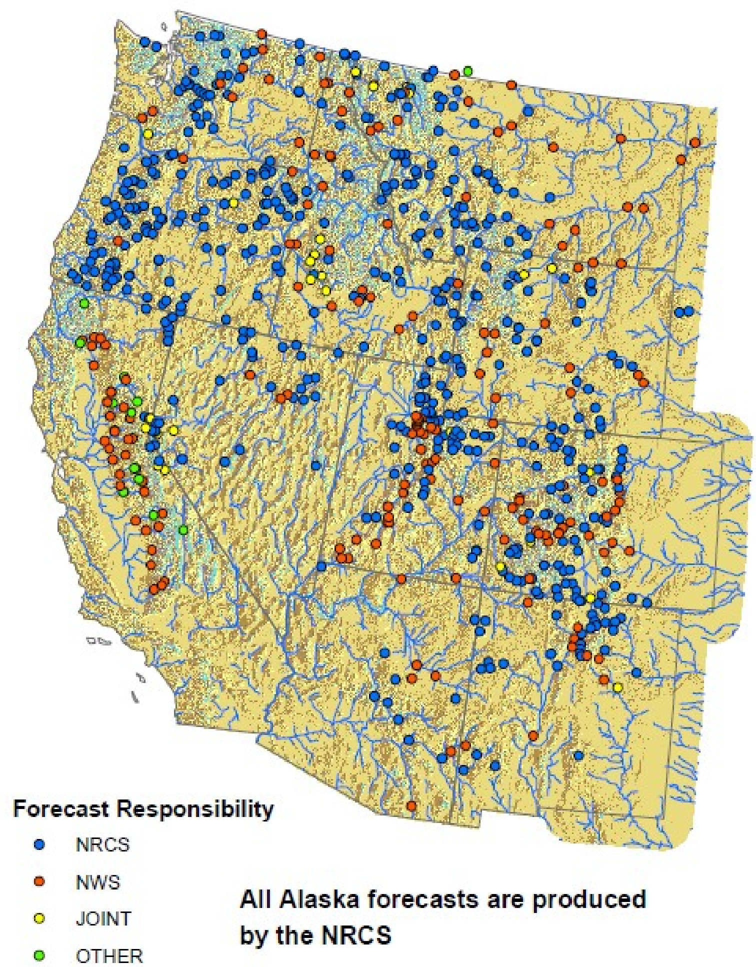

Figure 1 Seasonal water supply forecasting responsibility.

Component-based Modeling: Components are the main building blocks of simulation models in OMS. A component is a modeling entity that implements a single modeling concept. Components typically represent a unique concept in a model like a physical process, a management practice, or a specific data input. A component can also be hierarchical by containing other, finer grained components contributing to the larger goal. Components can be implemented in Java, Fortran, C, and C++.

Component design in OMS is considered to be *non-invasive* for component developers, which makes it unique among other CBSE-based frameworks. That is, model components are designed as plain objects, but include meta data by means of annotations. Modelers do not have to learn an extensive object-oriented Application Programming Interface (API), nor do they have to comprehend complex design patterns. OMS plain objects use the annotations to communicate the location of component-associated processing logic, and data flow.

There are three main categories of annotations. Mandatory Execution Annotations provide essential information for component execution. They describe method invocation points and data flow between components. Supporting Execution Annotations support component execution by providing additional information about the kind of data flow, physical units, and range constraints that might be used during execution. Documentation Annotations are used to support the use of documentation, databases, and other content management systems and tools.

All parameters and variables within a component are declared using annotations. An example declaration of the parameter hru_area (below) includes information about its Role as a parameter, Description or definition, Unit of measure, the bounding dimension of its array size, and use as an input array of doubles:

```
@Role(PARAMETER)
@Description("HRU area ,  Area of each HRU")
@Unit("acres")
@Bound ("nhru")
@In public double[] hru_area;
```

An example declaration of the component input variable tavgf includes information about its Description or definition, Unit of measure, the bounding dimension of its array size, and use as an input array of doubles:

```
@Description("Average HRU temperature. [temp]")
@Unit("F")
@ Bound ("nhru")
@In public double[] tavgf;
```

An example declaration of the component output variable basin_potet includes information about its Description or definition, Unit of measure, and use as an output double:

```
@Description("Basin area-weighted average of potential et")
@Unit("inches")
@Out public double basin_potet;
```

When components are combined to create a model, OMS uses the annotation information to identify the logic and data flows among the components and creates an executable model consistent with this information. A full description of annotations and their use is available in the OMS Developer and User Handbook which can be obtained at http://www.javaforge.com/project/1781.

OMS is based on the Java platform but it is inter operable with C, C++, and FORTRAN on all major operating systems and architectures. Language Interoperability is based on a DLL centric Java Native Access (JNA) integration that now supports all versions of FORTRAN, C, and C++ on all major architectures in 32 and 64 bit. FORTRAN and C/C++ programmers can continue to use their respective tools to create components and then use one of the Java integrated development environments (IDEs) to annotate and assemble components into a model, create simulations for testing and validation, and package model instances for deployment.

Components in OMS always execute multi-threaded. Sequential execution is just a specific case of multi-threaded execution where the data flow requires the sequential execution of components. If data flow allows it, components are executed in parallel. No explicit thread coding is needed to make this happen. OMS models are data flow driven. The execution of components is driven by data flow dependencies. There is no explicit/manual control of an execution sequence of components. The multi-threading capability provides runtime flexibility for simulation execution. Models can be executed in different environments that scale from a notebook to a computing cluster to a cloud.

Model Support and Analysis Components: A variety of components are available to support the creation, visualization, and analysis of model input and model simulation results. These include graphical and statistical analysis tools, the USGS Luca multiple-objective step-wise parameter calibration tool, and Ensemble Streamflow Prediction (ESP) functionality.

Parameter Calibration: A multi-objective, step-wise, automated calibration procedure was presented by Hay et al. (2006) and shown to be an effective calibration technique. This approach uses the Shuffled Complex Evolution (SCE) global search algorithm (Duan et al., 1993) to calibrate parameters for hydrologic models implemented in the Modular Modeling System (MMS) (Leavesley et. al., 1996). A wizard-style graphical user interface (GUI) called Luca (Hay and Umemoto, 2006b) has been developed to enable users to build a multiple-objective, step-wise calibration procedure in an easy and systematic manner. The functionality of Luca has been modified and implemented in a script format for use in OMS. Additional calibration methodologies are planned for future integration to OMS.

Ensemble Streamflow Prediction (ESP): The ESP methodology being used is a modified version of the National Weather Service's ESP procedure (Day, 1985). The ESP procedure uses historic or synthesized meteorologic data as an analogue for the future. These time series are used as model input to simulate future streamflow. The initial hydrologic conditions of a watershed, for the start of a forecast period, are assumed to be those simulated by the model for that point in time. Typically, multiple hydrographs are simulated from this point in time forward, one for each year of available historic or synthesized data. For each simulated hydrograph, the model is re-initialized using the watershed conditions at the starting point of the forecast period. The forecast period can vary from a few days to an entire water year.

A frequency analysis is performed on the peaks and/or volumes of the simulated hydrograph traces to evaluate their probabilities of exceedance. The ESP procedure uses historical meteorological data to represent future meteorological data. Alternative assumptions about future meteorological conditions can be made with the use of synthesized meteorological data. A few options are available in applying the frequency analysis. One assumes that all years in the historic database have an equally likely probability of occurrence. This gives equal weight to all years. El Nino, La Nina, and PDO periods have also been identified in the ESP procedure, and these can be extracted separately for analysis. Alternative schemes for weighting user-defined periods, based on user assumptions or *a priori* information, are also being investigated.

An ESP visualization tool is available for ESP trace analysis (Figure 2). The tool computes the frequency analysis and displays a list of all the historic years used with their associated probability of exceedance. Exceedance probabilities can be computed by either streamflow volume or peak. A visual display of user-selected ESP traces is provided. Traces can also be sorted by selected climatological indices such as El Nino, La Nina, and PDO.

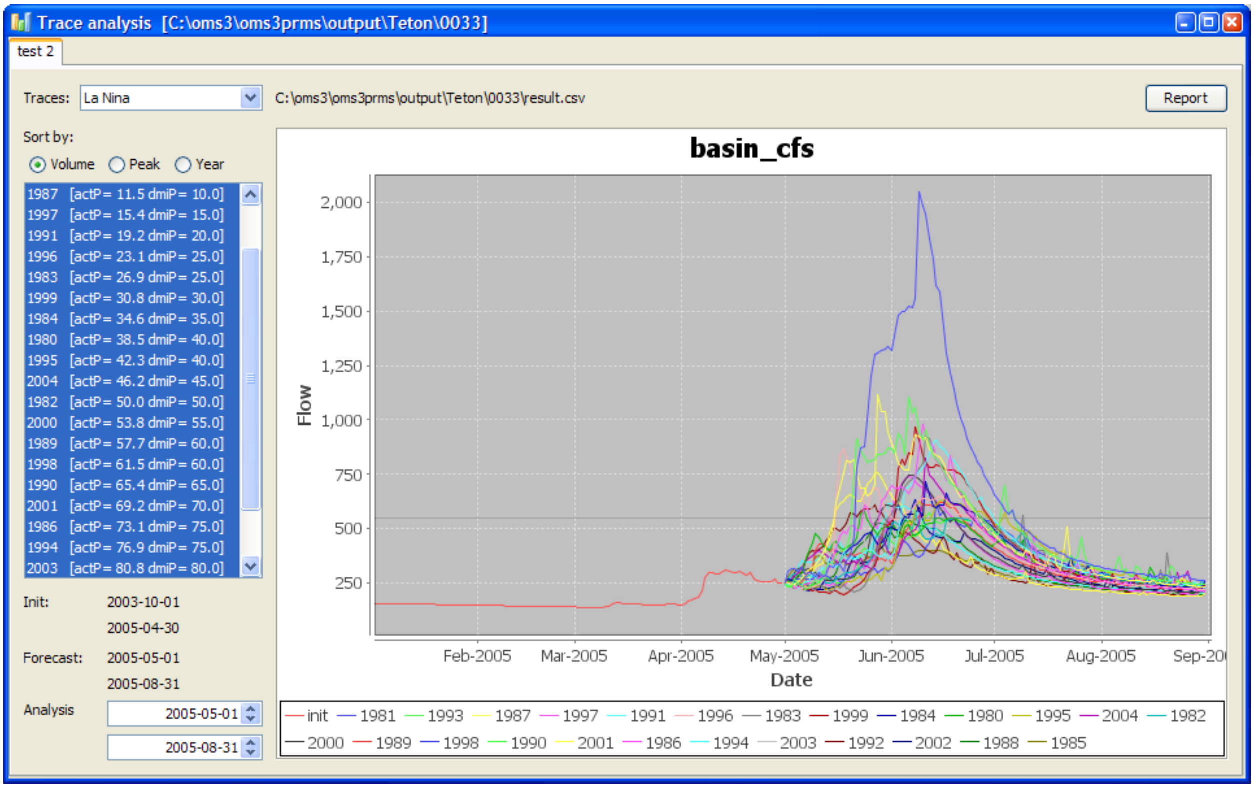

Figure 2 ESP visualization and analysis tool.

INTEGRATED FORECAST SYSTEM

A fully functioning forecast system will require the integration of all the capabilities of OMS with the operational requirements, functions, and tools at the NWCC. Steps to making the integrated system operational include 1) initial test watershed selection; 2) watershed model selection; 3) characterization and parameterization of selected watersheds; 4) development and implementation of a real-time data retrieval and update system; 5) development and testing of procedures to analyze and de-bias ESP results; and 6) development of tools to disseminate forecast results.

Test Watershed Selection: Watersheds identified as highly managed, with competing water uses, will be some of the first to be modeled. Six to ten basins will be used in the initial application. However, once the system is fully operational, all areas where there is a need for additional forecast products will be included in the system.

Model Selection: A long-term goal in the development of water-supply forecasting capabilities is the implementation of an ensemble modeling approach. This would provide forecasts using the results of multiple hydrologic models run on each basin. However, to focus on the development, testing, and implementation the modeling framework and forecast toolbox, and the integration of forecast results into the decision-making process, a single model will be used in the first stage of development. Additional models will be added as process components in the OMS library through time.

The model selected for the initial system development is the USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley and Stannard, 1995; Leavesley et al., 2006). The capabilities of PRMS for use in snowmelt runoff simulation applications (Leavesley, et al. 2003; Hay et al., 2006a) and as a component in water-supply and environmental decision support systems (Leavesley et al., 1996; Leavesley et al., 2002; Leavesley et al., 2008) have been demonstrated in a number of publications.

PRMS is a distributed-parameter, physical-process watershed model that operates at a daily time step. Distributed-parameter capabilities are provided by partitioning a watershed into units, using characteristics such as slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. Each unit is assumed to be homogeneous with respect to its hydrologic response and to the characteristics listed above. Each unit is termed a hydrologic response unit (HRU). A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRUs, weighted on a unit- area basis, produces the daily watershed response.

Snow is the major form of precipitation in the western US, and the major source of streamflow. The snow components of PRMS simulate the accumulation and depletion of a snowpack on each HRU. A snowpack is maintained and modified both as a water reservoir and as a dynamic heat reservoir. A water balance is computed each day and an energy balance is computed for two 12-hr periods each day. The energy-balance computations include estimates of net shortwave and longwave radiation, the heat content of precipitation, and approximations of convection and condensation terms.

PRMS uses daily inputs of solar radiation, precipitation, and maximum and minimum air temperature. Where solar radiation data are not available on a daily basis, estimates are computed using existing algorithms in PRMS. Estimates of daily shortwave radiation received on a horizontal surface are computed using air temperature, precipitation, and potential solar radiation. PRMS also has the ability to use gridded fields of snow-covered area and/or snowpack water equivalent to update simulated snow-covered area and snowpack water equivalent states on each HRU.

Watershed Characterization and Parameterization: The GIS Weasel (Viger and Leavesley, 2007) is a geographic information system (GIS) interface for applying tools to delineate, characterize, and parameterize topographical, hydrological, and biological basin features for use in a variety of lumped- and distributed-modeling approaches. It is composed of Workstation ArcInfo (ESRI, 1992) GIS software, C language programs, and shell scripts.

Distributed basin features are typically described using a concept of 'hydrologic response units' (HRUs). HRUs are areas delineated within a watershed, or area of interest that reflect a model's treatment of spatially distributed attributes, such as elevation, slope, aspect, soils, and vegetation. HRUs can be characterized using these attributes. Methods to estimate selected spatially distributed model parameters have been developed for the PRMS model. Digital databases used for parameter estimation in the USA include: (1) USGS digital elevation models; (2) State Soils Geographic (STATSGO) 1 km gridded soils data (US Department of Agriculture, 1994); and (3) Forest Service 1 km gridded vegetation type and density data (US Department of Agriculture, 1992). Spatially distributed parameters estimated using these databases include elevation, slope, aspect, topographic index, soil type, available water-holding capacity of the soil, vegetation type, vegetation cover density, solar radiation transmission coefficient, interception-storage capacity, stream topology, and stream reach slope and length.

Data Retrieval and Update System: Data retrieval software has been developed to retrieve data for user-selected SNOTEL, meteorological, and streamflow sites for each modeled watershed. Meteorological data for NWS stations are retrieved from the NOAA Regional Climate Center network using an interagency agreement between NOAA and NWCC. Meteorological data for SNOTEL stations are retrieved from the NWCC SNOTEL data site. Streamflow data are retrieved from the USGS National Water Information System (NWIS). All data are then combined into the OMS data file format and are ready for model use.

A model data file is created for each basin to include all meteorological and streamflow data available to the current date. Throughout the forecast season, when a model forecast run is requested, the data file is queried to obtain the date of the last data entry. This date is compared to the current date to identify the additional period of data needed to provide a current forecast. The data retrieval software then pulls data not only for the period identified but will pull all data for two months prior to the current forecast period to insure that any data updates are included in the data file. The data file retrieval procedures are automated with no user intervention required.

Post-processing Forecast Analysis: The streamflow traces produced by the ESP procedure individually and collectively contain bias due to the uncertainties inherent in hydrologic modeling. In addition, the width of the band defined by the set of traces is generally too narrow to represent all sources of prediction uncertainty. Consequently, ESP traces must be post-processed to remove bias and to set the variance to an appropriate value. A few basic approaches to this problem are presented in a number of recent publications. The methods can be briefly described as:

Quantile Mapping: Quantile mapping is one method used by Hashino et al. (2007) and Wood and Schaake (2008) to adjust a given value computed from the ensemble traces (in these examples, a seasonal volume) by matching quantiles from the cumulative distribution function (CDF) of the ensemble with those of observed flows. From this procedure, one ends up with an ensemble of adjusted values from which flow values corresponding to standard published exceedance probabilities can be computed.

Regression: A simple regression using model simulated streamflow (for a desired streamflow quantity, such as a seasonal volume) as the predictor variable and the corresponding observed flow as the target variable can be used as a way to adjust (or “calibrate”) the forecasts. This is a simple and direct way to obtain a forecast using the conditional distribution of observed flow given the predictor variable. In Bayesian terms, this is the posterior distribution. A regression approach like this is a simple and straightforward way to model the posterior distribution directly rather than modeling the prior and likelihood functions (Krzysztofowicz and Reese, 1989; Seo et al., 2006).

Hashino et al. (2007) develop the regression using the model simulated flows from the calibration period as the predictor variable. Wood and Schaake (2008) instead use the ensemble mean from retrospective ESP forecasts over the calibration period as the predictor variable, which is a more accurate representation of the actual forecasting situation.

Adjustment by a Constant: Olsson and Lindström (2008) used a simple additive constant approach to adjusting ensemble quantiles. They first computed six ensemble quantiles, that is, the flow rate corresponding to 98, 75, 50, 25, and 2% exceedance probabilities for each day in the forecast period (they were only looking at short-term forecasts of a few days in length). Then they determined the frequency over the calibration period in which the observed flow fell into these six intervals for each forecast day. The observations did not fall within the ensemble-derived flow intervals with the correct frequencies. Their adjustment scheme for the ensemble involved adding a constant flow value to each of the six computed ensemble quantiles for each day in the forecast period. These six constants were calibrated to achieve a good match between adjusted ensemble quantiles and the observed flow quantiles.

Time Series Modeling: Seo et al. (2006) applied a recursive autoregressive time series technique to adjust ESP traces for short-term (up to 5 days) streamflow predictions. This is the only technique of the four that retains individual traces after post-processing. This method also requires real-time daily streamflow data, so it would only work where these data are available.

These four post-processing methods will be integrated into the OMS tool set and evaluated for their performance in providing improved water supply forecasts. A number of statistical measures will be used to evaluate and quantify forecast performance and forecast improvement.

Forecast Dissemination and Decision Making Services: Currently, seasonal water supply forecasts are produced on the first of the month, from January to June for all western U.S. forecast points. A majority of the forecast points are updated every two weeks at the request of water users and managers. Since these statistical forecasts are based on static time periods, the forecasters make data projection assumptions, in order to satisfy these requests. The updating process is not straight forward and is time consuming. The results of the forecast models are then presented in tabular fashion in various state Water Supply Outlook Reports and/or through links to server files on the internet (www.wcc.nrcs.usda.gov/wsf).

The NWCC also produces a small number of automated seasonal water supply forecasts on a daily basis, using statistical regression techniques and SNOTEL data. These forecasts, based on climatic conditions on each day of the water year are produced on the NWCC web page and linked to the various State Offices. They have been of great benefit to the more knowledgeable water users and managers, in that they illustrate the current trend in basin water conditions. However, they are based solely on SNOTEL snow water content (swe) of the snow pack and the cumulative seasonal precipitation. There are recognized problems with data quality control, lack of hydrograph analysis, and the absence of physical watershed characteristics that a distributed hydrologic model would define.

There have been requests dating back several years from irrigators and others for the NWCC to provide expected hydrograph analysis to supplement the existing statistical models. It is felt that physical parameters that are modeled, such as snow covered area, soil moisture content, snowpack water equivalent could significantly reduce the forecast error and provide for more efficient use of agricultural water resources.

The deliverables of the integrated forecast system will be incorporated into an on-line map-based portal to facilitate access, retrieval, and use of the forecast products. The portal will be deployed through the NWCC web site, or provided as a service available to end-user systems or portals.

RESEARCH RELATED ASPECTS

Associated with the development and implementation of this forecast system are a number of research issues that will also be addressed. These include:

Evaluation of De-biasing Methods for ESP Forecasts: The four de-biasing methodologies described above will be evaluated as to their effectiveness in providing improved forecasts of water supply.

Evaluation of Alternative Climate Scenarios in ESP: The use of climate generators for creating ensembles of climate scenarios for use as input to ESP provide an alternative approach to the direct use of historic data as an analog for future conditions. Selected climate generators will be compared with the current ESP methodology.

Evaluation of Alternative Precipitation Distribution Methods: Alternative precipitation distribution methods will be evaluated for the range of climatic and physiographic regions represented by the forecast region of the western US. Current precipitation distribution components available in OMS include the XYZ, de-trended Kriging, and inverse distance methods.

Development of an Ensemble of Models for Forecasting: A long-term goal in the development and implementation of the forecast system is the use of an ensemble modeling approach. The first phase of system development, testing and application will be conducted using the PRMS model. However, once the system is tested and operational, additional models will be evaluated and integrated into the system with the assistance of the model developer.

SUMMARY

Forecast system development and testing will be conducted in the 2010 water year. The initial focus will be on the system mechanics and component integration needed to provide on-demand, real-time forecasts for the 6-10 basins select as the initial test set. When all components are functioning properly, the focus will then shift to the analysis and improvement of forecast results. It is at this stage that the research related aspects of the project will be implemented. New basins will also be added to the system in a priority order determined by the forecast hydrologists at NWCC. When fully tested and implemented, the integrated model system will provide timely and improved water-supply forecasts for agriculture and for all water managers and interested user groups at hundreds of forecast points in the western US.

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