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A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling

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Abstract:

A modular approach to model design and construction provides a flexible framework in which to focus the multidisciplinary research and operational efforts needed to facilitate the development, selection, and application of the most robust distributed modelling methods. A variety of modular approaches have been developed, but with little consideration for compatibility among systems and concepts. Several systems are proprietary, limiting any user interaction. The US Geological Survey modular modelling system (MMS) is a modular modelling framework that uses an open source software approach to enable all members of the scientific community to address collaboratively the many complex issues associated with the design, development, and application of distributed hydrological and environmental models. Implementation of a common modular concept is not a trivial task. However, it brings the resources of a larger community to bear on the problems of distributed modelling, provides a framework in which to compare alternative modelling approaches objectively, and provides a means of sharing the latest modelling advances. The concepts and components of the MMS are described and an example application of the MMS, in a decision-support system context, is presented to demonstrate current system capabilities. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS distributed models; modular models; parameter estimation; decision support systems

INTRODUCTION

The multidisciplinary nature and increasing complexity of environmental and water-resource problems have expanded the use of distributed modelling approaches that can incorporate knowledge from a broad range of scientific disciplines. Selection of a model to address these problems is difficult given the large number of available models and the limited information available with which to compare models objectively. A modular approach provides a framework in which to focus the multidisciplinary research and operational efforts needed to facilitate the selection and application of the most robust distributed modelling methods to address these complex problems.

This argument is based on the premise that there are no universal models. Models developed for different purposes require different levels of detail and comprehensiveness. The appropriate levels of detail and comprehensiveness are a function of problem objectives, data constraints, and spatial and temporal scales of application. One or more models, that satisfy a given set of these criteria, can be created by coupling the appropriate process conceptualizations. This concept requires that we change the question of 'which model is most appropriate for a specific set of criteria?' to 'what combination of process conceptualizations is most appropriate?' The measures used to define 'most appropriate' remain to be defined by further research.

The term *modular* has been used to indicate a variety of model features and capabilities. These range from the use of programming structures such as subroutines or functions, termed 'modules', for simulating individual processes, to larger model-system components where modules represent system functions such as

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input, model, output, graphics, and analysis capabilities. Variations in the interpretation and use of modular approaches can be seen by examining many of the models described in the compilation of watershed models by Singh (1995). Some of the earliest research and development of modular concepts and systems was done for the Système Hydrologique Européen (SHE) model (Abbott *et al.*, 1986a,b). One focus of more recent research has been how to deal with the increases in model complexity and uncertainty in model parameters and output that are associated with the wide range of hydrological and environmental processes that can be coupled in modular systems. Systems and tools to address these issues are being developed using multi-criteria optimization, sensitivity analysis, and generalized likelihood uncertainty analysis techniques (Beven and Binley, 1992; Yapo *et al.*, 1998; Wagener *et al.*, 1999; Wheater and Lees, 1999).

Though there has been a major focus on modular model and tool development, little or no consideration has been given to compatibility among modular concepts and systems. Several systems are also proprietary, which further limits the possibility of sharing concepts and software. To facilitate the collaborative research, development, and application of modular concepts to distributed hydrological and environmental models, the US Geological Survey (USGS) modular modelling system (MMS) has been developed (Leavesley *et al.*, 1996b). The MMS is an integrated system of computer software developed to: (1) provide the research and operational framework needed to enhance development, testing, and evaluation of physical-process modules; (2) facilitate integration of user-selected modules into operational physical-process models; (3) facilitate the coupling of models for application to complex, multidisciplinary problems; (4) provide a wide range of analysis and support tools for research and operational applications.

These concepts are not new or unique. However, the open source software system approach (DiBona *et al.*, 1999) of the MMS, in which all members of the scientific community can participate and share in the design and development of the system framework, process modules, and analysis and support tools, separates the MMS from most other modelling systems. The MMS provides a framework in which to address collaboratively the many complex issues associated with the design, development, and application of distributed hydrological and environmental models. This paper presents an overview of the concepts and components of the MMS and provides an example application to demonstrate the use of selected system components and tools.

LEVELS OF MODULAR DESIGN

Process modules and models

The MMS has a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. The library may contain several modules for a given process, each representing an alternative conceptualization to simulating that process. The different conceptualizations are functions of a variety of constraints that include the types of data available and the spatial and temporal scales of application. A model for a specified application is created by coupling appropriate modules from the library. If existing modules cannot provide appropriate process algorithms, new modules can be developed and incorporated into the library.

Criteria and rules for good module design have been given by Reynolds and Acock (1997), as modules should:

- relate directly to real world components or processes;
- have input and output variables that are measurable values;
- communicate solely *via* these input and output variables.

Though not discussed explicitly in the paper, it is assumed that the input and output variables are 'hypothetically' measurable, given the associated spatial, temporal, and instrumental limitations on the measurement of some process variables. A good discussion of modular concepts and their application to plant and ecosystem models is also provided by Reynolds and Acock (1997). One could substitute or include

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the term 'hydrological models' in their discussions and reach similar conclusions regarding the applicability and benefits of modular concepts to distributed hydrological models.

Model building in the MMS is accomplished using an interactive model builder interface termed Xmbuild (Figure 1). Xmbuild enables the user to select and link modules to create a model. Modules are designed so that the output from one module is the input to other process modules. Xmbuild enables users to view inputs and outputs for each module and to search the module library for all modules that provide the necessary inputs for each module. Using this search and select procedure, a user-defined model can be constructed. Module inputs and outputs include a units attribute that can be checked to ensure module compatibility. Plans include the development of an expert system to assist users in module selection based on future research to identify the most appropriate modules for various problem objectives, data constraints, and spatial and temporal scales of application.

Fully coupled models

The concept of linking modules to create a model can also be applied to the linking of models to create a larger integrated model. Fully coupled models refers to the coupling of individual models where there is a two-way flow of information between the models. These typically are developed to provide feedback among related processes in the linked models.

The ability to create fully coupled models in the MMS is currently being developed through the introduction of control modules. Control modules provide the communication paths and feedback links among the coupled

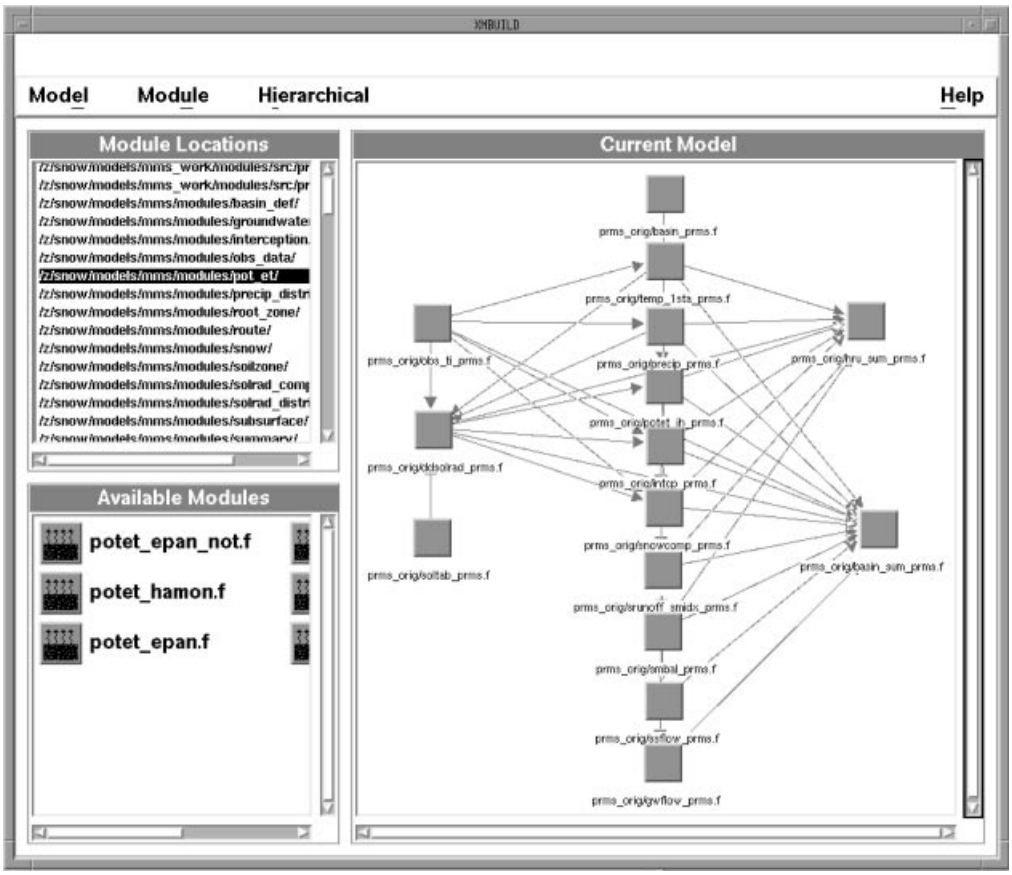

Figure 1. The model builder interface Xmbuild. Reproduced by permission of the US government

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models, and provide support for iterative computational procedures where groups of modules may be required to run multiple times to reach convergence for selected feedback processes. Where convergence is not assured, alternative strategies are being evaluated to handle these cases. For complex coupled models that require large amounts of processing time, work is ongoing to provide the capability to run such models in the MMS using multi-processor or parallel processing systems. Initial work is being conducted to integrate the parallel application work space (PAWS) software (Beckman *et al*., 2000) with the MMS.

Loosely coupled models

The module linking concept for model building applies to loosely coupled models as well. In loosely coupled models, however, information flow is in only one direction; output from one model is used as input to another model. An example of a series of loosely coupled models might begin with a watershed model that simulates hillslope runoff volume and timing for input to a channel hydraulics model. Output from the channel hydraulics model can then be input to a fish model. The link between models is accomplished using a common database and a software component termed a 'data management interface' (DMI).

A DMI reformats model output and writes it to the database and reads data from the database and reformats it for input to a given model. Each DMI is unique for the database being used and for each model being applied. Writing a DMI is currently the responsibility of the user, but a library of DMIs for selected databases and models is being developed. Numerous combinations of models are possible using the loosely coupled approach. Models can be those created from the module library as well as off-the-shelf models that have not been modularized.

Decision-support systems (DSSs)

DSSs are the top level of complexity for model coupling and integration. Various combinations of models from all levels of modular design can be integrated with resource management and decision-support models to create a resource management DSS. For example a resource management DSS might include: (1) watershed models for simulating reservoir inflows and streamflow from unregulated basins; (2) one-dimensional and two-dimensional hydraulic models for application to selected river reaches where channel-flow characteristics may affect channel morphology or biological habitats; (3) sediment-transport and chemical-transport models to address a variety of water quality issues at the basin or reach scale; (4) agricultural models to address land-management and irrigation practices and the fate and transport of nutrients and pesticides; (5) biological and ecosystem models that address critical habitat issues; and (6) reservoir management models to control the volume, timing, and distribution of water within a basin.

The ability to couple and integrate models for DSS development and application are provided in the MMS by the object user interface (OUI) tool set. A variety of analytical, statistical, and graphical support tools are also provided to aid in the decision-support process. The capabilities of OUI and the other support tools are described in the next section.

ANALYSIS AND SUPPORT TOOLS

The GIS Weasel

The GIS Weasel 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-modelling approaches. It is composed of ArcInfo (ESRI, 1992) GIS software, C language programs, and shell scripts. Distributed basin features are typically described using a concept of 'model response units' (MRUs). MRUs 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. MRUs can be characterized using these attributes. The GIS Weasel also delineates a drainage network and

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computes the connectivity of MRUs with this drainage network. The location of data-collection sites can also be overlaid with the MRU map to define associations between MRUs and the data sites.

Parameter estimation methods are implemented using ARC macro language (AML) functions. Keeping with the modular concept, a library of parameter estimation methods is maintained in a similar fashion to the library of process modules. For a given model, a recipe file of AML functions can be created and executed to estimate a selected set of spatial parameters. This recipe file can also be modified to change the parameter estimation method associated with a selected parameter, thus enabling the evaluation of alternative parameter estimation methods.

Currently, methods to estimate selected spatially distributed model parameters have been developed for the USGS precipitation-runoff modelling system (PRMS) (Leavesley *et al.*, 1983; Leavesley and Stannard, 1995) and TOPMODEL (Beven *et al.*, 1995). 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.

The OUI

The OUI is a Java-based, multi-purpose MMS component developed jointly by the Friedrich-Schiller University, Jena, Germany, and the USGS. OUI is a map-based interface for acquiring, organizing, browsing, and analysing spatial and temporal data, and for executing models and analysis tools. OUI is the key component of the MMS for developing loosely coupled models and DSSs.

The functional components of the OUI are a hierarchical data tree, a map window for display of one or more data-tree themes, and pull-down menus across the top of the window (Figure 2). The data tree provides users access to a variety of data layers that typically include basin boundaries, model response units, stream reaches, meteorological and streamflow gauge sites, and other map-based features of interest for model application and analysis. These spatial data layers are stored in an ESRI shape-file format. The pull-down menus provide action buttons to initiate model applications, evaluate model results using a variety of statistical and graphical tools, and analyse associated spatial and temporal data.

The contents of the data tree and pull-down menus are specified using the eXtensible markup language (XML). OUI is easily applied by creating or modifying a control file called tree.xml. This file contains a variety of information, including the locations and names of all data files, format of all data, database connection parameters, locations and names of all models, and the locations and names of all associated DMIs and model management interfaces (MMIs). A DMI, as introduced above with loosely coupled models, is a small piece of Java code that reads data from and writes data to a database.

An MMI is a set of Java code that provides the ability to pre- and post-process data and execute models for a user-defined set of simulations and analyses. It is, in effect, a script that creates and executes a sequence of models and analytical tools based on an established set of interface rules. MMIs are executed *via* the OUI pull-down menus. A library of MMIs is available for selected models and procedures. New MMIs are the responsibility of the user.

Optimization and sensitivity analysis tools

Optimization and sensitivity analysis tools are provided to analyse model parameters and evaluate the extent to which uncertainty in model parameters affects uncertainty in simulation results. Two optimization procedures are available to fit user-selected parameters. One is the Rosenbrock technique (Rosenbrock, 1960), as it is implemented in the PRMS. The second is a hyper-tunnel method (Restrepo and Bras, 1982). The Shuffle Complex Evolution Optimization algorithm (Duan *et al.*, 1993) and the Multi-Objective COMplex

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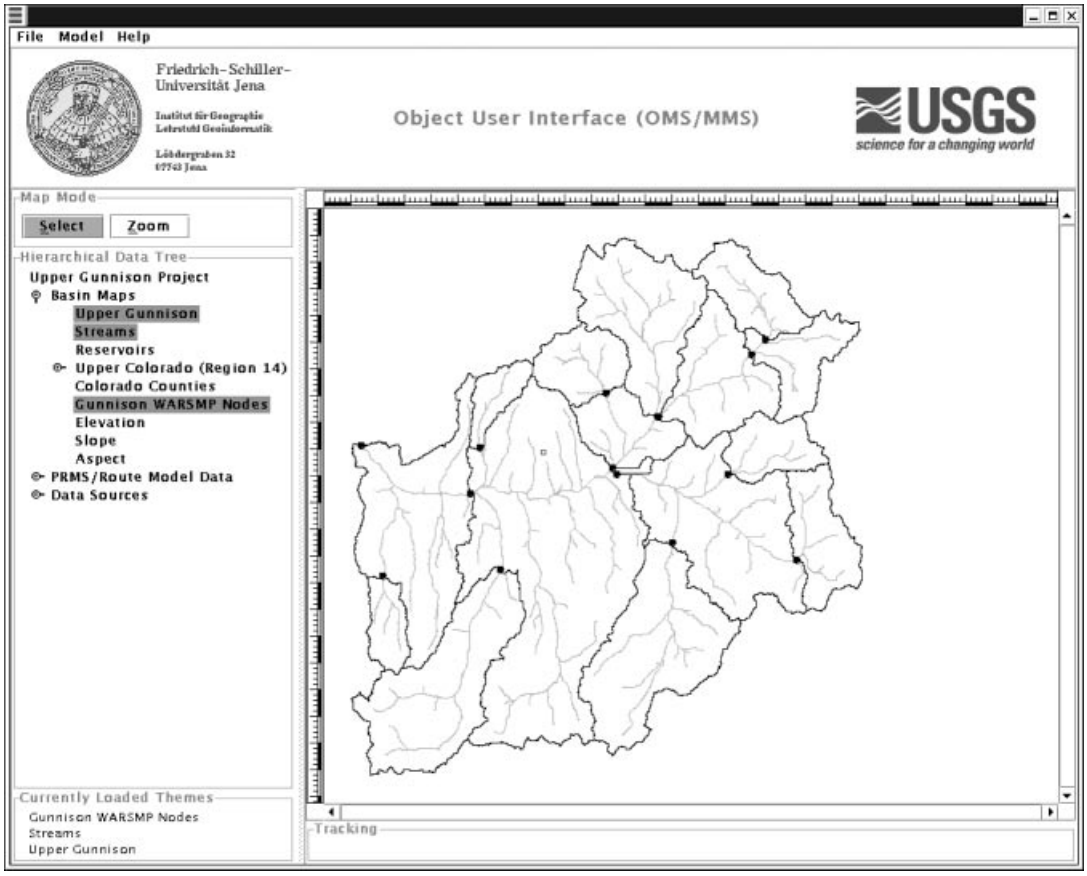

Figure 2. The object user interface (OUI). Reproduced by permission of the US Government

Evolution algorithm (Yapo *et al.*, 1998), which is capable of solving multi-objective optimization problems, are currently being incorporated into the MMS tool set.

Two methods of sensitivity analysis are currently available. One is the method developed for use with the PRMS, which allows the evaluation of up to ten parameters at one time. The second method evaluates the sensitivity of any pair of parameters and develops the objective function surface for a selected range of these two parameters. To address the question of parameter and predictions uncertainty, the generalized likelihood uncertainty estimation procedure (Beven and Binley, 1992; Beven, 2001) is being added to the MMS tool set.

Forecasting tools

Distributed models are typically identified as the most appropriate approach for simulating the effects of land-use and climate change. These types of application require meteorological data time series for selected forecast periods. Forecast methods available for use in the MMS include a modified version of the National Weather Service's extended streamflow prediction (ESP) procedure (Day, 1985) and statistical downscaling procedures using output from atmospheric models.

ESP. 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

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point in time. Typically, multiple hydrographs are simulated from this point in time forward, one for each year of available historic 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 then 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 give equal weight to all years. El Niño and La Niña 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.

Statistical downscaling. Procedures to downscale atmospheric model output statistically for use as input to watershed models have been developed and coupled with the MMS (Wilby *et al.*, 1999). These methods use a regression-based statistical downscaling model to simulate point values of daily precipitation and temperature from atmospheric-model output of grid-scale synoptic measures. The point estimates of climate variables are then spatially distributed across a basin using lapse rates and topographic information.

EXAMPLE APPLICATION

The component tools in the MMS can be used individually or in various combinations to address a wide range of distributed modelling needs. An example application that demonstrates the use of most of the capabilities of the MMS is its use as the hydrological modelling and forecast component of the Watershed and River System Management Program (WARSMP) (Leavesley *et al.*, 1996a). WARSMP is a cooperative effort between the USGS and the Bureau of Reclamation (BOR) to develop an operational, database-centred, DSS for application to complex, water and environmental resource-management issues. The MMS has been coupled with the BOR RiverWare software (Fulp *et al.*, 1995) using a shared relational database. RiverWare is an object-oriented reservoir and river-system modelling framework developed to provide tools for evaluating and applying optimal water-allocation and management strategies. The application of the MMS described here is to the Upper Gunnison River Basin, in Colorado.

The Xmbuild tool was used to construct a modular version of the PRMS. Distributed-parameter capabilities in the PRMS 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.

Simulation of the spatial and temporal distributions of precipitation (PRCP) and maximum and minimum air temperature (TMAX, TMIN) to each HRU are critical components in the PRMS. Recent research has resulted in the development of an improved distribution methodology for daily values of measured PRCP, TMAX, and TMIN (Hay *et al.*, 2000). These values are distributed using monthly multiple linear regression (MLR) relations developed for each dependent climate variable using the independent variables of measurement station latitude (x) and longitude (y) coordinates and elevation (z). The daily mean value of PRCP, TMAX, and TMIN and the corresponding mean x, y, and z for a selected set of stations are used with the monthly XYZ MLR relations to distribute PRCP, TMAX, and TMIN according to the mean x, y, and z of the individual HRUs of a basin. Taking advantage of the modular structure of the PRMS, new process modules were written for the XYZ procedure and used to replace the original precipitation and temperature distribution modules in the PRMS.

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With a model built, the basin was then delineated, characterized, and parameterized using the GIS Weasel. The Upper Gunnison Basin was divided into 15 major subbasins and 24 streamflow forecast nodes (Figure 2). Each subbasin was further divided into 50 to 200 HRUs. A set of spatial parameters was estimated for each subbasin and HRU using the GIS Weasel. The GIS Weasel recipe file for the PRMS parameter estimation was modified to include the additional parameter estimation procedures needed for the XYZ methodology. Non-spatial parameters were estimated from previous model applications in this region, guidelines provided in the PRMS user's manual, and user's knowledge of the region.

An objective parameter estimation and calibration procedure has been developed and is being tested in the MMS for the PRMS applications in the mountainous regions of the western USA. In this procedure no changes are made to the spatial parameters estimated by the GIS Weasel. Calibration is focused on the water balance parameters affecting potential evapotranspiration (ET) and precipitation distribution, and on the subsurface and ground-water parameters affecting hydrograph shape and timing.

Only five of the 15 subbasins had historic streamflow data with which to test and fine tune the estimated parameter sets (Figure 3). The model was run on each of the five subbasins using the initial parameter estimates. Simulated potential ET was compared with estimates of potential ET for this region based on published values. ET parameters were adjusted manually and the model was rerun. This procedure was repeated until the simulated potential ET values were in agreement with those reported. Subsurface and ground-water parameters were also adjusted manually to improve hydrograph shape and timing. A Monte Carlo procedure was then applied to select the best subset of climate stations in the XYZ procedure for each subbasin and to determine the magnitude of a gauge catch correction factor to account for the undercatch of snow. The best subset was the one that minimized the sum of the absolute values of the difference between measured and simulated streamflow. Three to four climate stations were selected for each subbasin and gauge catch corrections ranged from 10 to 30%.

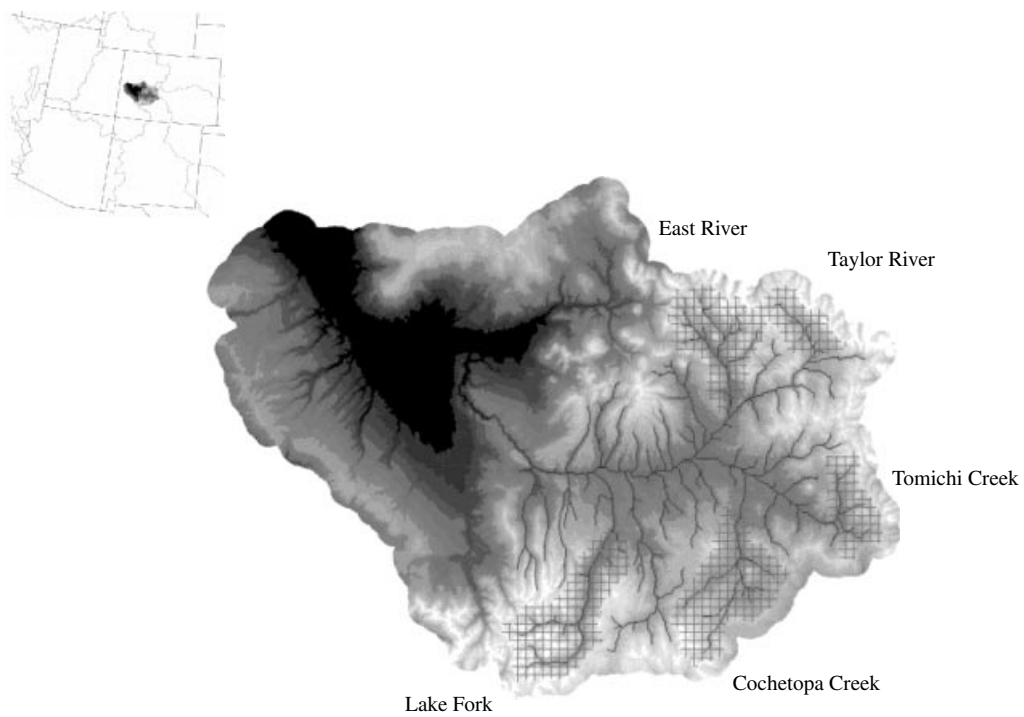

Figure 3. Subbasins of the Upper Gunnison River with measured streamflow

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The simulated and observed streamflow for the five subbasins are shown in Figure 4. With the exception of Cochetopa Creek, all the simulations are quite good. The flow from Cochetopa Creek is about an order of magnitude less than that of the other subbasins and has trans-basin diversions above the stream gauge that have not been included in the measured hydrograph shown.

The good agreement between simulated and measured streamflow provides some measure of confidence in the parameters estimated by the GIS Weasel for the five subbasins. This also provides a measure of confidence in the use of the GIS Weasel-derived parameters in the ungauged subbasins as well. However, streamflow integrates the spatial and temporal variations in hydrologic response of each HRU and provides no measure of the distributed performance of the model. To provide this distributed measure, a set of tools has been

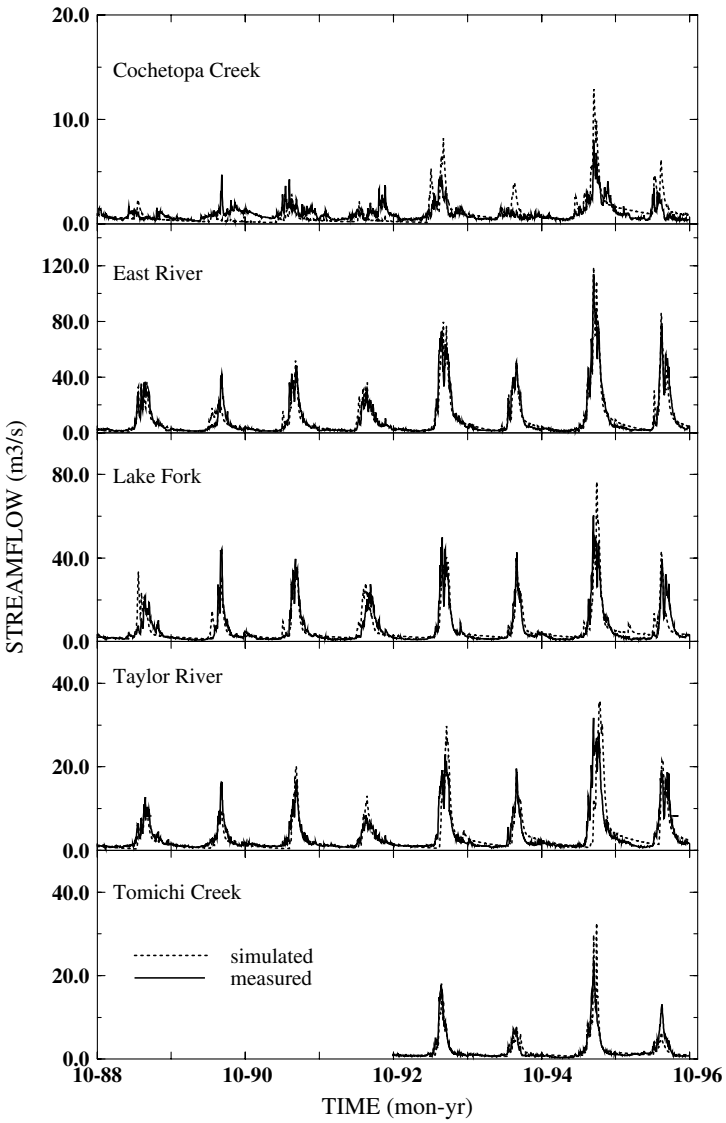

Figure 4. Simulated and measured streamflow for Cotchetopa Creek, East River, Lake Fork, Taylor River, and Tomichi Creek for water years 1988–96. Note that measured flow on Tomichi Creek begins in water year 1993

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developed to compare modelled snow-covered area with that measured from satellite. Remotely sensed snow-covered area data are available for the period 1990–99 from the US National Weather Service's National Operational Hydrologic Remote Sensing Center (http://www.nohrsc.nws.gov).

An example of model performance on the East River and Lake Fork basins is shown in Figure 5. Comparing the simulated snow-covered area for various dates on each basin shows that for most years the simulated and observed values are quite similar. The reasonable agreement between simulated and measured streamflow timing and volume and the associated general agreement between simulated and observed snow-covered area provide independent measures of the performance of the estimated distributed parameters and the validity of the parameter estimation methodology. Similar results were obtained on all the basins except Cochetopa Creek for the years remotely sensed data were available. Evaluation of the difference in simulated and measured snow-covered area for Cochetopa Creek will be used to make improvements in the precipitation-distribution and snowmelt modules.

Tools and techniques for the inclusion of remotely sensed data in the MMS are being developed in collaboration with the Southwest Regional Earth Science Application Center (http://resac.hwr.arizona.edu/), which is funded by NASA. The objective of this centre is the development of tools and techniques to support the integration and application of remotely sensed data in natural resources management. Additional tools are currently being developed in the MMS to enable the real-time updating of basin snow-covered area and snowpack water equivalent to improve runoff forecasting capabilities.

The subbasin configuration, HRU delineations, and other data layers were specified to the OUI through the tree.xml file for use in organizing the display and analysis of data and model results. For streamflow simulation purposes, an MMI was created to execute the PRMS separately on each of the 15 subbasins and then to execute a channel routing model that routes the subbasin outflows to produce a simulated streamflow hydrograph at 24 river forecast nodes. The user can view the routed streamflow at any node by activating the routing-node data layer in the data tree and then clicking on the desired node in the OUI map display.

A second MMI was created to implement the ESP procedure. Here, forecast hydrographs are simulated for each subbasin, one hydrograph for each of the 24 years in the historic data record. A routed hydrograph through the entire basin is then generated for each of the 24 forecast periods. The suite of 24 hydrographs at any forecast node can then be viewed using the ESP Tool, which is a Java-based GUI in which all or a subset of the forecast hydrograph traces can be viewed (Figure 6). For each node, a frequency analysis is computed on the suite of traces and the probability of exceedance for each trace is provided as well. The ESP Tool MMI contains the procedure to write operator-selected hydrographs to the central database for use by RiverWare. The river basin manager typically selects the hydrographs with a 10, 50, and 90% probability of exceedance for analysis in RiverWare. The ESP procedures are typically run a few times a week to aid resource managers in making reservoir and river system management decisions.

Additional modelling and management options can be added to the OUI by developing the appropriate MMIs that contain the required suite of models and DMIs. New MMIs to be added for the Gunnison River include a stream temperature model and a hydraulic and sediment transport model for use in the management of endangered fish species in the basin. Other MMIs will be added as new issues arise regarding the management of water and ecosystem resources in the basin.

The Gunnison River application of the MMS is only one of several basins being treated by WARSMP. The MMS tools described above are currently operational on the Gunnison River basin, and the Yakima River Basin in Washington. Similar systems are being completed for the Rio Grande Basin in Colorado, New Mexico, and Texas, the Truckee River Basin in California and Nevada, and the San Juan River Basin in Colorado, New Mexico, Arizona, and Utah. Water-management issues in these basins include efficiency of water-resources management, environmental concerns such as meeting flow needs for endangered species, ground-water/surface-water interactions, water-quality issues related to irrigated agriculture, and optimizing operations within the constraints of multiple objectives such as power generation, irrigation, and water conservation.

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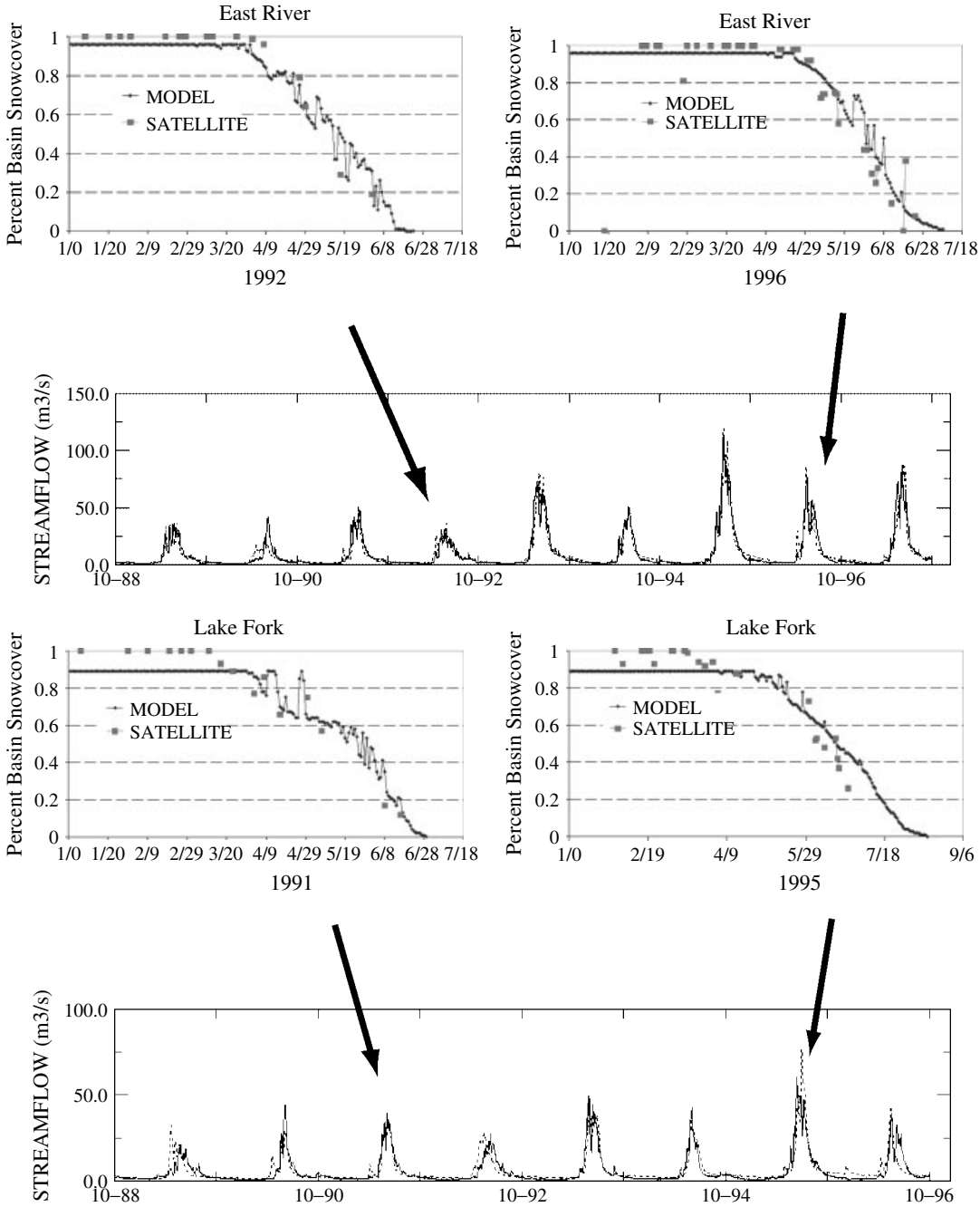

Figure 5. Comparison of simulated snow-covered area with measured snow-covered area determined from satellite observations for selected water years on East River and Lake Fork

MODELS, MODULES, AND THE MMS COLLABORATION

Though the authors have played a large role in the development of the MMS, it has been the input from a large number of collaborators, in terms of funding, human resources, ideas, and software that has brought

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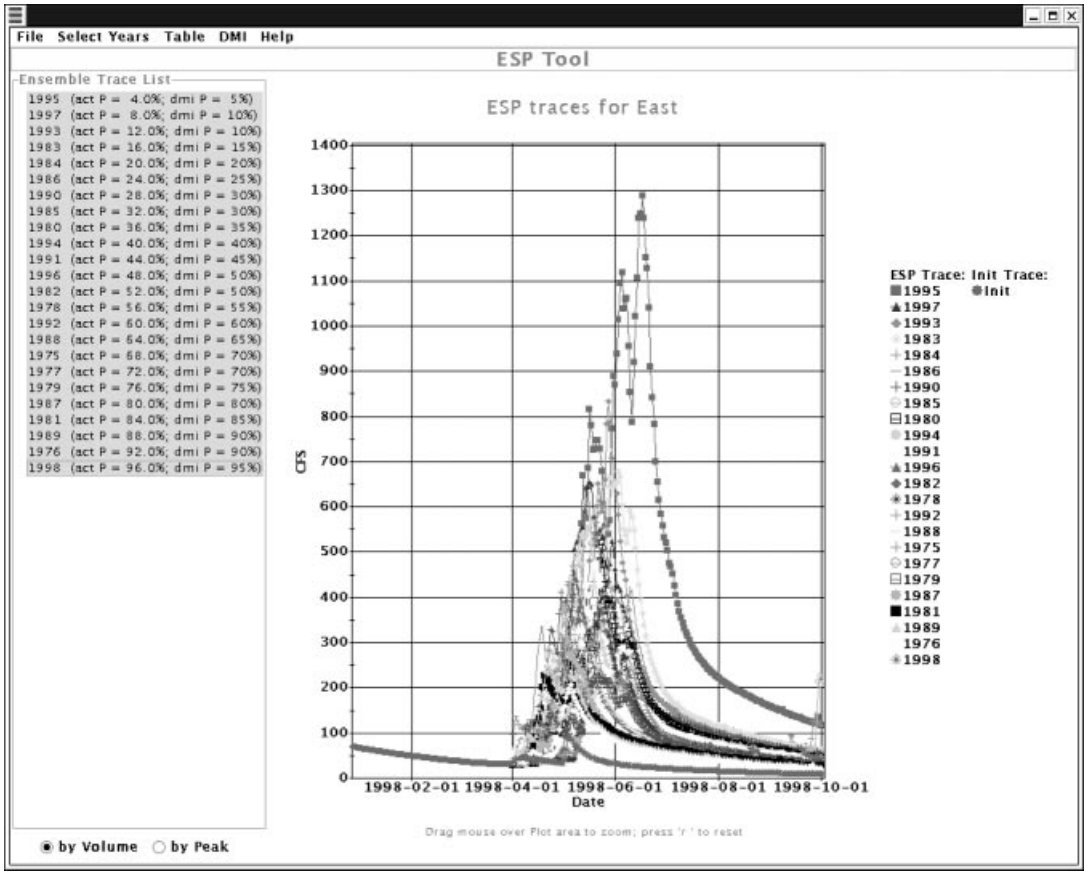

Figure 6. The ESP Tool used to display forecast streamflow hydrographs and their probability of exceedance as determined by use of the ESP procedure. Reproduced by permission of the US Government

the design and development of the MMS to its current state. Individual contributions are too numerous to mention. However, Table I presents a list of the major groups that have provided these inputs and guidance.

Module and model development using the MMS framework is being conducted by a number of individuals within the groups listed in Table I, as well as individuals in other government agencies, universities, and private industry, both nationally and internationally. The USGS has modularized and currently distributes versions of the PRMS, TOPMODEL, and Hydro-17 (Anderson, 1973). Another USGS model currently being modularized is DAFLOW (Jobson, 1989). The USGS-supported models are distributed on the internet from the MMS home page (http://wwwbrr.cr.usgs.gov/mms/). Modules and models developed by other groups will be linked to the MMS home page when developers approve their work for release.

SUMMARY AND CONCLUSIONS

As pointed out by Reynolds and Acock (1997), experimental science builds on hypothesis testing and interpretation, based on earlier published hypotheses and results. However, modellers tend to prefer to build new models from the ground up, typically because existing models are not well designed for incremental improvement by others. Model comparison studies have attempted to compare alternative modelling strategies to identify the 'best' performing modelling approaches. However, these typically have been limited to

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Table I. Major groups that have provided resources and guidance to the development of the MMS

US Government
Department of Interior
USGS
Bureau of Reclamation
Bureau of Land Management
Department of Agriculture
Agricultural Research Service
Natural Resources Conservation Service
Forest Service
Department of Energy
NASA
University
University of Colorado
University of Arizona
International
Friedrich Schiller University, Germany
Public Works Research Institute, Japan

comparisons of simulated hydrographs, with little or no insight developed as to the causes of the differences among models. A modular approach to model development facilitates model process comparisons by enabling detailed analysis of individual processes and their interactions. It provides a framework in which to conduct hypothesis testing and analysis and to make incremental model improvements based on these results.

The problems of model design, scale, and parameter estimation associated with the development and application of distributed models reflect the limitations in our current methods and knowledge. The modular approach facilitates the multidisciplinary research needed to address these complex problems. The recent collection of papers addressing the combined use of tracer, remote sensing, and new hydrometric techniques to develop an integrated approach to catchment hydrology (Leibundgut *et al*., 1999) demonstrates the value in the multidisciplinary approach. It provides improved process understanding not achievable with the tools of a single discipline. Extending this integrated approach and knowledge to model development is a focus of the MMS. Multidisciplinary research among atmospheric and hydrologic scientists is being fostered by a Community Hydrometeorological Laboratory that has been established at the National Center for Atmospheric Research in Boulder, Colorado (Warner *et al*., 2000). The MMS is a centrepiece of this laboratory, and the issues of model design, scale, and parameter estimation are some of the many issues that will be addressed.

To obtain maximum benefit from the modular concept, participation by the hydrologic modelling community is needed. This participation comes with the costs of a willingness to share in the design and acceptance of a modular coding structure, the willingness to develop and share module code, and the willingness to share data for the development of distributed data sets in a wide range of climatic and physiographic regions of the world. Loss of model name recognition, for example the PRMS or TOPMODEL, is also a possible cost when process modules from a number of different models are combined to create a new model. The new model name may not reflect any of the original models from which the modules where obtained. However, the model description will identify the source of all the modules, thus giving credit to the original developers.

The benefits of participation include the ability of modellers to share resources and be part of a larger multidisciplinary research effort where individual modules can be developed by those with the relevant process expertise and be provided in a common toolbox with a wide range of analytical and support tools. Implementation of a common modular concept is not a trivial task, given the current knowledge of hydrological processes and distributed modelling technology. However, it would bring the resources of a larger community

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to bear on the problems of distributed modelling, provide a framework in which to compare alternative modelling strategies objectively, and provide a means of sharing the latest modelling advances.

Continued advances in physical and biological sciences, GIS technology, computer technology, and data resources will expand the need for a dynamic set of tools to incorporate these advances in a wide range of interdisciplinary research and operational applications. The MMS is being developed as a flexible framework in which to integrate these activities with improved knowledge of hydrological and environmental processes to advance the art and science of distributed hydrological modelling.

Further information on the MMS can be found at:

http://wwwbrr.cr.usgs.gov/mms
http://wwwbrr.cr.usgs.gov/weasel
http://wwwbrr.cr.usgs.gov/warsmp

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