The Modular Modeling System (MMS): A Toolbox for Water- and Environmental-Resources Management

George H. Leavesley, Steven L. Markstrom, Roland J. Viger, and Lauren E. Hay

U.S. Geological Survey, Box 25046, MS 412, DFC, Denver, CO 80225 USA

Introduction

Increasing demands for limited fresh-water supplies, and increasing complexity of environmental resource-management issues, present resource managers with the difficult task of achieving an equitable balance of resource allocation among a diverse group of users. Achieving such a balance is most difficult in arid and semi-arid regions. Hydrological and ecosystem models are often the tools being employed to address these resource-allocation issues.

The interdisciplinary nature of water- and environmental-resource problems requires the use of modeling approaches that can incorporate knowledge from a broad range of scientific disciplines. Selection and application of appropriate models and tools is a function of a number of evaluation criteria, including problem objectives, data constraints, and spatial and temporal scales of application. The U.S. Geological Survey (USGS) Modular Modeling System (MMS) is an integrated system of computer software that provides a research and operational framework to support the development and integration of a wide variety of hydrologic and ecosystem models, and their application to water- and environmental-resources management.

MMS supports the integration of models and tools at a variety of levels of modular design. These include individual process models, tightly coupled models, loosely coupled models, and fully-integrated decision support systems. A geographic information system (GIS) interface, the GIS Weasel, has been integrated with MMS to enable spatial delineation and characterization of basin and ecosystem features, and to provide objective parameter-estimation methods for selected models using available digital data coverages. Optimization and sensitivity-analysis tools are provided to analyze model parameters and evaluate the extent to which uncertainty in model parameters affects uncertainty in simulation results. A variety of visualization and statistical tools are also provided.

Forecasts of future climatic conditions are a key component in the application of MMS models to resource-management decisions. Forecast methods applied in MMS include a modified version of the United States National Weather Service's Ensemble Streamflow Prediction Program (ESP), and statistical and dynamical downscaling from atmospheric models.

MMS is being used to develop and apply water- and environmental-resource management models and decision support systems in several arid and semi-arid regions of the world. MMS provides a framework in which to collaboratively address the many complex issues associated with the design, development, and application of hydrological and environmental models in
these regions. The open source software design of the MMS facilitates the direct and indirect sharing of resources, expertise, knowledge, and costs among projects in these different regions. This paper presents an overview of the concepts and components of MMS and of applications in selected arid and semi-arid regions.

Levels of Modular Design

Process modules and models

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.

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. Selecting a directory in the Module Locations window will display all the modules available in the Available Modules window. Selecting a module in this window will place it in the Current Model window. As additional modules are added to the Current Model window they are linked by using the output from one module as 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.
Loosely coupled models

The module linking concept for model building applies to loosely coupled models as well. In loosely coupled models, information flow is in only one direction; output from one model is used as input to another model (Figure 2). 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 are not a component of MMS. The only requirement for the use of non-MMS models is that they can be executed in a batch mode.
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. A fully coupled model 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. Feedback is normally provided through the use of iterative computational procedures where groups of modules may be required to run multiple times to reach convergence for selected feedback processes.

A fully coupled surface-water/ground-water model is currently being developed in MMS (Figure 3). The watershed model PRMS (Leavesley et al., 1983; Leavesley and Stannard, 1995), ground-water model MODFLOW, 1-d hydraulic model DAFFLOW (Jobson, 1989), and an unsaturated zone model are being linked with the ability to simulate the interactions among these individual models. PRMS provides the spatial and temporal recharge for MODFLOW grid cells. This recharge is passed to the unsaturated zone model for routing to MODFLOW. When the water table reaches the soil surface, the unsaturated zone model disappears in the associated grid cells, ground-water exfiltration occurs from these cells, and saturated areas are developed in PRMS that will generate direct runoff from rain or snowmelt that occurs on these areas. Runoff from PRMS is delivered to the channel reaches in DAFFLOW. The water-surface elevation (head) in a DAFFLOW reach and the head in the MODFLOW grid cell adjacent to the channel reach are then used to solve for the rate and direction of water flow between the stream and the aquifer. If the head in the aquifer is below the bottom of the channel reach, the unsaturated zone model is used to route flow from the channel to MODFLOW.
**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 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-modeling 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, which 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 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 PRMS 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 Object User Interface (OUI)

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 analyzing 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 OUI are a hierarchical data tree and a map window for display of, and interaction with, one or more data-tree themes (Figure 4). 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 display and data tree provide action buttons to initiate model applications, evaluate model results using a variety of statistical and graphical tools, analyze associated spatial and temporal data, and generate a 3-D animation of simulated model states.

Figure 4. The Object User Interface (OUI)

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). An MMI is a set of Java code that provides the ability to pre- and post-process data and to 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.

Optimization and sensitivity analysis tools

Optimization and sensitivity analysis tools are provided to analyze 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). 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 Evolution algorithm (Yapo et al., 1998), which is capable of solving
multi-objective optimization problems, are currently being incorporated into the MMS tool set.

Sensitivity-analysis components allow the user to determine the extent to which uncertainty in the parameters results in uncertainty in the predicted runoff. Two methods of sensitivity analysis are currently available. One is the method developed for use with the original PRMS, the output of which includes measures of the relative sensitivity, error propagation, joint and individual standard errors, and correlation among user-selected model parameters. 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. Other sensitivity analysis methods to address the questions of parameter and prediction uncertainty are being evaluated for incorporation in MMS. Currently the Generalized Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992) is being added to the MMS tool set.

**Forecasting**

*Ensemble Streamflow Prediction*

Forecasting capabilities are provided by the Ensemble Streamflow Prediction (ESP) procedure (Day, 1985). ESP uses historic or synthesized meteorological 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 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 user can view all the forecast traces and then select all or a subset of the traces for use in an associated water management model (Figure 5). In the example shown the user selected the traces that represent the 10, 50, and 90 percent 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 also 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. Years associated with El Nino, La Nina, ENSO neutral, Pacific Decadal Oscillation (PDO) less than -0.5, PDO greater than 0.5, and PDO neutral have also been identified in the ESP procedure. The years in these groups 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.
Downscaling Atmospheric Model Output

Procedures to dynamically and statistically downscale atmospheric model output for use as input to watershed models have been developed and coupled with the MMS (Wilby et al., 1999; Hay et al., 2000, 2002). The dynamical downscaling procedure applies a bias correction directly to the atmospheric model grid-scale temperature and precipitation outputs. The statistical method uses 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.

Applications

The component tools in the MMS can be used individually or in various combinations to address a wide range of water- and environmental-resource management needs. A selected set of example applications in arid and semi-arid regions is presented to provide an overview of the types of resource-management issues being addressed.

Watershed and River System Management Program (WARSMP)

MMS is being used as the hydrological modeling and forecast component of the WARSMP (Leavesley et al., 1996a). WARSMP is a cooperative effort between the USGS and the Bureau of Reclamation (BOR) to develop an operational, database-centered, DSS for application to complex, water and environmental resource-management issues (Figure 6). 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 modeling framework developed to provide tools for evaluating and applying optimal water-allocation and management strategies.

![Diagram of database-centered decision support system](image)

Figure 6. Database-centered decision support system

MMS and RiverWare are linked using a common hydrologic database (HDB). The database used varies among the basins, with Oracle and HEC-DSS being currently supported. Real-time hydrologic and meteorological data are provided to HDB every 6 hours. HDB is also the database of record and so all model results and forecasts are stored there as well.

A typical exchange between RiverWare and MMS would be for RiverWare to request all inflow predictions for reservoirs in a basin. A watershed model in MMS would simulate these forecast streamflows and write them to HDB. RiverWare would read these results and evaluate alternative reservoir-management strategies. The associated reservoir releases for each strategy are written to HDB. These strategies may have implications for environmental or flood issues. MMS could be called again to run one or more hydraulic and/or ecosystem models to evaluate the effects of the reservoir releases on selected river reaches. These results would then be written to HDB for use by RiverWare in selecting a specific management alternative.

The modeling capabilities of MMS and RiverWare include simulating watershed runoff, reservoir inflows, and the impacts of resource-management decisions on municipal, agricultural, and industrial water users, environmental concerns, power generation, and recreational interests. The WARSMP DSS is currently operational in the Gunnison River Basin, Colorado; Yakima River Basin, Washington; Rio Grande Basin in Colorado and New Mexico; and Truckee River Basin in California and Nevada.

The Upper Gunnison River Basin provides a typical example of the modeling issues that need to be considered in applying MMS. The basin is about 10,000 km² in size. The GIS Weasel was used to partition it into subunits or MRUs, using characteristics such as slope, aspect, elevation,
vegetation type, soil type, and precipitation distribution (Figure 7). Each unit is assumed to be homogeneous with respect to its hydrologic response and to the characteristics listed. Each unit is termed a hydrologic response unit (HRU), which is just a specific type of MRU. More than 1000 HRUs were defined. The HRUs were then grouped into 15 major subbasins and 24 streamflow forecast nodes were defined. However, only five of the 15 subbasins had observed streamflow data. 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.

![Figure 7. Gunnison River basin delineation into HRUs, subbasins, and forecast nodes.](image)

The distributed-parameter watershed model PRMS was selected for application. A set of spatial parameters was estimated for each subbasin and HRU using the GIS Weasel. An objective parameter estimation and calibration procedure has been developed and is being tested in the MMS for the PRMS applications. 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. Parameters calibrated on the five gauged basins were then transferred to the 10 ungauged basins.

For streamflow simulation purposes, an MMI was created in OUI 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 the 24 river forecast
nodes. In PRMS, 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 subbasin streamflow. The user can view the routed streamflow at any node by activating the routing-node data layer in the OUI data tree and then clicking on the desired node in the OUI map display.

A second MMI was created to implement the ESP procedure in OUI. 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 5). 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 HDB 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.

A major goal of the WARSMP DSS program is to effectively integrate scientific understanding into the water- and environmental-resource decision-making process. The database-centered DSS approach that combines MMS and RiverWare provides a flexible framework that can be used by scientists, resource managers, and stakeholders in this process. This approach is generic and applicable to a wide variety of basins and resource-management issues in arid and semi-arid regions.

River Drâa, Morocco

GLOWA is a program initiated by the German Federal Ministry of Education and Research (http://www.glowa.org/eng/home/home_objectives.htm) to focus on problems of water availability. One aim is the development of simulation-tools and instruments that will aid in the development of strategies for sustainable water management at a regional level (river basins of approx. 100,000 km²), while considering global environmental changes and socioeconomic conditions. IMPETUS is program within GLOWA to investigate all aspects of the hydrological cycle in two river catchments in North West and West Africa: the wadi Drâa in the south east of Morocco and the river Ouémé in Benin. MMS is being used in IMPETUS study of the wadi Drâa. The Drâa basin forms a large transboundary catchment (115 000 km²) stretching across Algeria, Mauretania and Western Sahara, but the Drâa river itself is restricted to the upper parts of the catchment (34,609 km2) located in Morocco and no longer reaches the Atlantic ocean (Figure 8).
The River Drâa drains from the High Atlas Mountains to Lac Iriki and feeds a large dam for irrigation purposes. In order to address a number of imminent problems limiting the availability and allocation of water along the wadi Drâa, 12 measurement sites were installed along a gradient of elevation and aridity. Monitoring of the thickness and the extent of snow cover in the High Atlas mountains is essential to enable the competing water users (power generation, irrigation, domestic consumption) to have adequate supplies. In addition to seeking a better understanding and prediction of the geospheric, atmospheric, and biospheric components of the hydrological cycle, the IMPETUS activities centre around the questions of the influence, risks and resulting conflicts of human activities in the context of the specific social and economical structures encountered in the area.

The issues and needs for water management DSS tools are described by de Jong, et al. (2004, 2005). One of the most severe problems affecting the Drâa in terms of the natural physiography is its water shortage and drought over the last 5 years. According to the world water poverty index, Morocco has an index of below 45 and the Drâa belongs to the world’s ten driest catchments (Ravenga et al., 1998). Population, settlements, infrastructure and agriculture are concentrated around the rivers and oases. The catchment is also subject to highly variable rain- and snowfall regimes and extremely sporadic and variable discharge. The downstream reservoir Mansour Eddahbi situated near Ouarzazate, the regional capital, is strongly dependant on water input from the mountain catchments. Over the past few years, there have been large fluctuations in water input into the reservoir and its minimum capacity is often no longer reached. The
Mansour Eddahbi dam has also been subject to substantial infill by sediments and consequently rapid capacity loss. If this trend continues, the reservoir will have lost half of its capacity by the year 2030 and will require intensive study of sediment delivery to predict its entire lifetime and economical function.

MMS is currently being used to develop a DSS for the whole Drâa catchment for operational discharge forecasting. A number of physical and hydrological characteristics have been identified as having major effects on the ability to make such forecasts. These include the spatial and temporal distribution of precipitation and the determination of its form as rain or snow. Evapotranspiration and snow sublimation also play a significant role. Surface and subsurface runoff and springs are controlled by complex geomorphology and geology including limestone and basalt. Wadi river beds are highly porous and discharge is sporadic and highly variable depending on precipitation inputs and river bed characteristics.

The initial modeling efforts are focused on the implementation of the model PRMS to selected headwater catchments. HRU delineation and parameterization using the GIS Weasel has been based mainly on geomorphological and hydrogeological characteristics. Analysis of model results are being used to identify additional process models required to meet the water- and environmental-resource management needs on the basin. These modeling needs include the processes of snow ablation, erosion and sedimentation, channel transmission loss, surface-water/ground-water interactions, and oasis formation and use.

Heihe River, China

A collaborative research program has been recently (2004) established between the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (CAREERI/CAS) in Lahzhou, China and the USGS for the development of integrated models and a modeling environment for inland river basins. A case study for this effort is being conducted in the Heihe River basin, Northwest China (Figure 9). The Heihe is the second largest inland river watershed in China with an area of 140,000 km². The basin runs from the Qilian mountains in the south to the Alxa high plain in the north. There is a diverse set of hydrological and geological conditions in the basin that include alpine glacial, snow, grassland, forest, plain, oasis, and desert regions. River flows originate as rainfall and snowmelt in the Qilian mountains and gradually disappear as the river flows north due to irrigation use, evapotranspiration, and channel transmission losses to ground water.
Research is being conducted on water resource allocation and utilization, and the integrated management of water resources, ecosystems, and economic systems in the Heihe River Basin. These research efforts include the investigation of 1) sustainable utilization of water resources in inland river basins in arid regions under a changing environment, 2) heat and water transfer in the soil-vegetation-atmosphere system and land surface process studies in inland river basins, 3) studies on water cycle and water resource capacity in northwest China, and 4) the development of a basin-scale climate model for the region.

Initial collaborative research and development using MMS will focus on surface-water/ground-water issues and the development of a DSS for the Heihe Basin. The interaction of surface and ground water in the middle and lower reaches of the Heihe River Basin is very complex, and is an obstacle for good water management. An integrated model that can quantitatively describe the spatial and temporal fluxes of surface and ground water will be developed. Models to be evaluated include SWAT and MODFLOW. The coupled model will be further linked with a water management model. These integrated models will be part of the overall spatially explicit DSS for the Heihe River Basin. Additional models and tools will be added to the DSS as they become identified by research results and operational needs.

Summary

MMS provides a toolbox approach to model and system development. It supports multidisciplinary model integration and the development of decision support systems. Open source software design allows many to share resources, expertise, knowledge, and costs. Individual modules, models, and tools can be developed by those with the relevant expertise and added to the common toolbox for use by others. 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. MMS is being developed as a flexible framework in which to integrate these activities and to provide improved knowledge of hydrological and environmental processes to advance the art and science of water- and environmental-resource modeling.

MMS, the GIS Weasel, selected models and tools, and additional information on MMS can be downloaded at:

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

References


