# Multilayer Control Hierarchy for Water Management Decisions in Integrated Hydrologic Simulation Model

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**Abstract:** The regional simulation model (RSM) is a conjunctive groundwater surface-water hydrological model under development at the South Florida Water Management District. The model is designed to allow a flexible, extensible expression of a wide variety of natural hydrologic processes, as well as anthropogenic water resource control schemes in order to facilitate alternative management scenario evaluations. The management module of the RSM is the management simulation engine (MSE). The MSE is based on a multilayer hierarchical control architecture, which naturally encompasses the local control of hydraulic structures, as well as the coordinated subregional and regional control of multiple structures. MSE emphasizes independent abstraction of hydrological state information and managerial decision algorithms, facilitating the interoperation and compatibility of diverse management algorithms. The MSE architecture is described in this paper.

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## Introduction

The advent of numerical estimation and simulation software packages has produced a profound impact on the ability of scientists and engineers to model a wide variety of physical phenomena across a broad spectrum of disciplines. Certainly the fields of electrical and mechanical engineering have benefited enormously from the evolution and application of finite-element techniques applied to constrained field equations of the electromagnetic and mechanical stress fields. Likewise, the disciplines of hydrodynamics and aerodynamics have enjoyed significant progress owing to the development of numerical models enabling the evaluation of spatially extended flow regimes over a wide range of Reynolds numbers. The discipline of hydrology has profitably leveraged these developments to the point where there currently exists a wide proliferation of hydraulic and hydrological numerical models aimed at addressing the major engineering issues facing the hydrological community.

Although the performance and applicability of these hydrological solutions has matured considerably, there still exists room for improvement in the modeling of human intervention in the control of hydraulic structures. Indeed, it has been recognized that the need exists for comprehensive integration of management features in conjunctive hydrological models (Belaineh et al. 1999). This is not to say that the synthesis of control system and decision making software has failed to be successful in many of these models, rather, that careful design and decomposition of the hydraulic structure management algorithms (or state information-processing filters) can result in model implementations which provide a natural, flexible, and extensible architecture for the expression and implementation of complex hydraulic management scenarios. Such management scenarios include the local control of individual water control structures, the coordinated control of multiple local structures to meet local demands and constraints, as well as regional (global) management operations required to satisfy water supply, flood control, and environmental concerns.

To address these needs, the South Florida Water Management District is developing the regional simulation model (RSM), a conjunctive hydrological model composed of two primary, coupled components: the hydrological simulation engine (HSE), and the management simulation engine (MSE). The MSE consists of a multilayer hierarchical control scheme, incorporating a wide selection of control algorithms and decision making tools, each of which is integrated seamlessly with the hydrological computations of the HSE. From a hydroinformatics perspective, the RSM architecture emphasizes independent abstraction and processing of hydrological state information, and the management processing applied to the states. Given a well-defined interface between the two, this approach enables multiple information processing algorithms to execute in parallel, with higher levels of the hierarchical management able to synthesize the individual results which are best suited to the managerial objectives.

The RSM is therefore designed to provide numerical hydrological solutions incorporating complex anthropogenic control schemes in a flexible, extensible, clear, and consistent manner. The focus of this paper is to communicate the overall design structure of the MSE and illustrate the enhancements it provides in relation to the current state-of-the-art toward addressing the emerging needs of complex management scenarios applied to regional scale conjunctive hydrological models.

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## Hydrological Model Management Schemes

Even a cursory examination of the hydrological literature reveals a wealth of advanced management techniques applied to water resource models (Brdys and Ulanicki 1994; Mays and Tung 1991). For example, linear programming (Eschenbach et al. 2001), artificial neural networks (Sivakumar et al. 2002; Lambrakis et al. 2000), fuzzy control (Dubrovin et al. 2002; Shrestha et al. 1996), dynamic programming (Foufoula-Georgiou and Kitandis 1988), simulated annealing (da Conceicao Cunha and Sousa 1999), genetic algorithms (Wardlaw and Sharif 1999), hybrids of all of these, as well as others. However, these hydrological models tend to be specialized, requiring nonstandard input formats, and limited in scope to either reservoir routing or local hydrological control. Among the widely utilized commercial and governmental models such as MIKE-SHE-11 (DHI 2005) and MODFLOW-MODBRANCH (Harbaugh and McDonald 2000; McDonald and Harbaugh 1988; Prudic 1989; Schaffranek et al. 1981; Schaffranek 1987; Swain and Wexler 1996) there is generally a good resource set for modeling management policies, e.g., both of these models support optimization packages and rulecurve expressions for structure operations. However, dynamic switching of control processors or supervisory control of multiple flow structure controllers (discussed in the following) would not be straightforward. The RSM approach to these issues is presented in the following sections.

## Regional Simulation Model

Some of the distinctive features of RSM include:

**Metadata input:** Model inputs are specified in a self-describing format in which the inputs are contextually specified through use of the Extensible Markup Language (XML) (WC3 2004). An XML input specification enables implicit syntax and input value validation, coherently organizes the data into a structured hierarchy, and provides a common cross-platform and application generic input data set, among other advantages. The use of standardized metadata input represents a significant step forward in data representations when compared to the typical implementations relying on application-specific input formats based on proprietary or non-standard formatting specifications.

**Nonrectangular mesh:** HSE is a finite-volume formulation, consequently, the computational elements are not limited to rectangular grid cells as imposed by pragmatics of applying finite-difference formulations. The arbitrary triangular mesh elements may provide more efficient geo-spatial representation than is easily obtainable with rectangular elements.

**Arbitrary control:** The modeler can implement an arbitrary control or management algorithm by expressing the control in C or C++. The code is compiled into a shared library which is loaded at runtime, with input/output data passed between the control library and the model through a well-defined interface. The control code is able to access arbitrary hydrological state information from the model, and is able to dictate hydraulic structure control to the model.

**Multisupervision:** In the MSE, the management hierarchy defines objects which explicitly control the behavior of multiple hydraulic structures. This can be done with user-defined computer code, fuzzy rules, linear programming (LP), graph flow algorithms or heuristics. For example, a management object is capable of setting the structure flow characteristics of multiple structures simultaneously.

**Dynamic control:** This feature refers to the ability to dynamically alter or adjust the control behavior of hydraulic structures. For example, a closed loop feedback decision process such as a proportional-integral-derivative (PID) controller may have its target value, or, any adjustable parameter of the controller changed in response to a dynamic variable. Another feature is to provide for dynamic switching of management algorithms. For instance, a rule-based fuzzy algorithm optimized for flood-control operations can dynamically replace a rule curve or setpoint controller of a hydraulic structure in response to any observable state variable.

The HSE component of RSM is described briefly in the following section, one may refer to the citations for more detail. The MSE is detailed in the subsequent sections with an emphasis on the information processing characteristics inherent in its design.

## Hydrologic Simulation Engine

HSE can simulate two-dimensional (2D) overland flow, two-dimensional or three-dimensional groundwater flow, one-dimensional (1D) canal flow, and flow in and out of reservoirs (Lal et al. 1997; Lal 1998, 2001; Lal and Van Zee 2003; Lal et al. 2005; SFWMD 2005a). The overland and groundwater flow domains are discretized in the horizontal 2D domain using unstructured triangular cells. The groundwater aquifer layers may consist of any number of variable depth layers, each of which can span an arbitrary extent of horizontal 2D cells. The stream flow network is discretized using piecewise linear canal segments, with variable geometry rectangular or trapezoidal cross sections. The triangular 2D meshes and 1D stream networks are independent, and may overlap partially, fully, or not at all. A wide variety of local and microhydrologic functions associated with urban and natural land use, agricultural management practices, irrigation practices, and local routing are handled with a feature known as hydrologic process modules (HPMs). HPMs also provide various ET and rain function interactions, as well as unsaturated flow distributions.

The numerical solution is based on a semi-implicit finite-volume approximation of the diffusion flow transport equations. The computational method is unconditionally stable, and is achieved through the use of the Portable Extensible Toolkit for Scientific Computation (PETSC) sparse linear system solver (ANL 2004). The model is fully integrated. All coupled aquifer, overland, and stream flow regional components are solved simultaneously.

The RSM is an object-oriented code, which relies heavily on the features of abstraction and inheritance. Within the HSE, the abstraction "waterbody" is used to represent objects which contain conservative variables while the "watermover" class represents fluxes between waterbodies. A watermover class for each type of hydraulic structure is implemented when dictated by the model input descriptions. These hydraulic structure watermovers are the primary interface for hydraulic control signals from the MSE. In the absence of a control signal, the watermover transports the flow imposed by the hydraulic structure transfer function in response to the hydrological state variables. When a control signal is applied, some fraction of the total possible flow is allowed as specified by the control value.

## Management Simulation Engine

The MSE design is based on the hydroinformatic principle that operational and managerial decisions applied to water control

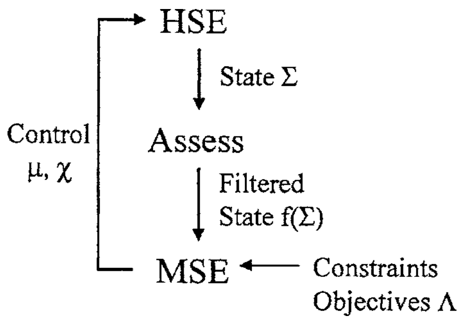


**Fig. 1.** RSM state and management information flow

structures can be viewed as information processing algorithms which are independently expressed from the hydrological state information on which they operate (Park et al. 2005; SFWMD 2005b,c). Essentially, the HSE provides hydrological and hydraulic state information ($\Sigma$), external policies dictate managerial constraints and objectives ($\Lambda$), and MSE computes water management control signals ($\chi, \mu$) in order to satisfy the desired constraints and objectives. $\chi$ represents a controller command to a hydraulic structure watermover, and $\mu$ denotes a supervisory command that regulates, activates, or deactivates controllers. Fig. 1 illustrates this overall cyclic flow of state and management information in the RSM.

In the MSE this state and process information can be functionally transformed by an independent set of filters, which can be viewed as information preprocessors. These processors are denoted as assessors ($A$) and filters. For example, an assessor may perform statistical filtering such as spatiotemporal expectations, amplitude or time-delay modulation, or any other suitable data filtering operation. The assessed or filtered information is transparently available to any MSE processor.

More specifically, the MSE architecture is based on a multilayered hierarchy, with individual water control structures regulated by "controllers," whereas regional coordination and interoperation of controllers is imposed by "supervisors." Supervisors can change the functional behavior of controllers, completely switch control algorithms for a structure, or override the controller output based on integrated state information and/or rules. A schematic depiction of the HSE-MSE layered hierarchy is shown in Fig. 2.

At the lowest layer is the hydrological state information ($\Sigma$) computed by the HSE. This information includes water stages, flow values, rainfall, ET, hydrologic boundary conditions, or any other state variable used as input or computed as output by the HSE. All such variables are made available to the MSE and assessors through the implementation of a uniform data monitor interface. The data monitor interface extends naturally to the MSE

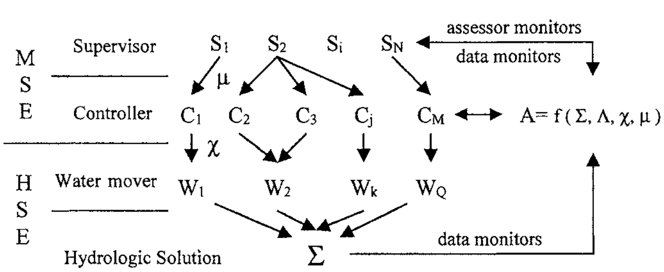


**Fig. 2.** HSE-MSE multilayer control hierarchy schematic

input/output variables. Therefore, the input state information available to a controller or supervisor is not limited to water levels or flow values, but can include control information, decision variables, constraints or any other management variable from any other controller or supervisor in the model. This transparency of state and process information throughout the model is central to the efficient synthesis and processing of heterogeneous information required to simplify and naturally express complex water management policies.

The top level of the MSE is the supervisory layer. There is no limit on the number of supervisory algorithms, or constraint on the number of controllers that a supervisor may influence. Based on state and process information, which optionally may have been filtered or assessed, the function of a supervisor is to produce the supervisory control signal ($\mu$) for a single, or collection of hydraulic structure controllers. The supervisors are therefore able to comprehensively coordinate the global behavior of multiple independent, or coupled hydraulic structures. A description of the available supervisors is given in the following.

The intermediate layer consists of the hydraulic structure watermover controllers. A controller is responsible for local regulation of structure flow. It is possible to attach multiple controllers to a structure watermover, although only one controller at a time is activated. This activation is controlled by a supervisor. For example, a fuzzy controller optimized for wet condition operations may be selected by a supervisor during significant rain events, while a standard rule curve could be enforced during normal operations. In this manner, the MSE provides dynamic switching of hydraulic structure control functions in response to state or process information.

Once the controllers have computed their respective control values ($\chi$), these signals are applied as flow constraints to the structure watermovers in the HSE. Each watermover will compute a maximum flow capacity based on the hydrological state conditions and hydraulic transfer function of the structure. The resultant controlled flow will be some fraction of the currently available maximum flow capacity.

## Assessors and Filters

The role of assessors in the MSE is to perform data preprocessing required for operational control decisions. By decoupling the conditioning and filtering of state and process information from the decision-making algorithms, the decision processors can be simplified and modularized. Therefore, an assessor is a information processor intended to provide specialized aggregation or differentiation of state variables particular to a managerial decision process.

For example, the water supply network (WSN) assessor estimates the volumetric flow in a canal water control unit (WCU) which is required to meet a downstream water supply demand. A WCU is defined as a collection of HSE canal segments that are managed as a single entity. The WSN assessor considers both upstream and downstream supply and demand from connected water control units. Once this assessment is completed, a supervisory algorithm can synthesize information from other assessors or operational constraints to arrive at a control decision. As the supervisor is not concerned with the particulars of how the assessments are made, only with their results, the management algorithms are isolated to information processing relevant to the decision process, and do not include code or rules to perform data filtering and assessment.

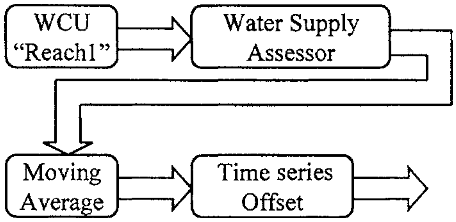


**Fig. 3.** Unified interfacing of data preprocessors allows piped operations

Related to the assessors, are MSE filters. Filters are generic information processors implemented to perform simple, often redundant data filtering operations. For example, a filter may apply a scalar or time series amplitude modulation consisting of the usual arithmetic operations (multiplication, division, addition, subtraction) or may compute simple time series or spatial variable statistics such as arithmetic, geometric, or other expectations, or may act as an accumulator.

The RSM implements a unified design approach for monitors, filters, and assessors based on object oriented design principles. As a result, the interfacing of these constructs from the user's perspective is particularly simple, and powerful. Assessor and filters operate in a piped first-in/first-out fashion, as exemplified in Fig. 3.

Fig. 3 depicts the flow of information starting with a water control unit denoted Reach1. A water supply assessor is attached to Reach1 and computes the flow required in the control unit to satisfy a target level. Following the assessor is a dual-stage filter, first a moving average, then a time series offset filter. To change the data source, order, or type of operations, one simply reconfigures an XML specification.

## MSE Controller Layer

The MSE controller layer is the intermediary between the hydraulic structure watermovers and the regional-scale supervisory coordinators, although the controllers can operate without supervision. In fact controllers are not required at all for uncontrolled operation of a hydraulic structure. The essential purpose of a controller is to regulate the maximum available flow through a structure to satisfy a local constraint. A controller may take as an input variable any state or process information which can be monitored within the RSM. As the interface between a structure watermover and any controller is uniform, as well as the interface between the supervisors and controllers, it is possible to change controllers dynamically with a supervisory command, or manually with a simple XML input change. The unitary interface also allows for the modeler to mix and match controllers in a particular model application so that the local control schemes are a hybridization of any of the available control algorithms.

The currently available controller modules in the RSM include:

- One- and two-dimensional rule curves;
- Piecewise linear transfer function;
- PID feedback control;
- Sigmoid activated PI feedback control;
- Generic fuzzy control; and
- User defined finite state machine.

Detailed information regarding the usage, applicability, and examples of model implementations for the controllers are described in the MSE User's Manual (SFWMD 2005b), brief descriptions are given in the following.

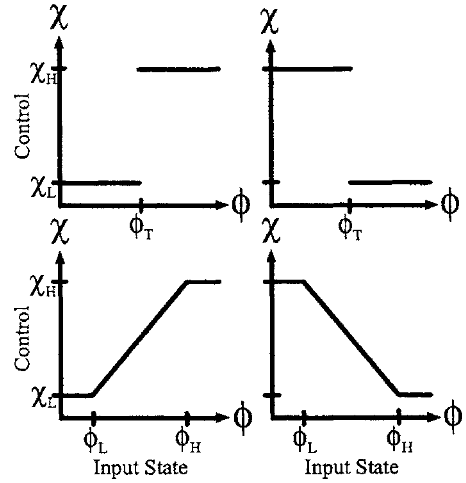


**Fig. 4.** MSE controller piecewise linear transfer functions

Rule curves are routinely implemented as a method of controlling the flow transfer function of hydraulic structures. The MSE provides for one or two variable interpolated look-up tables as a means of structure control. Notable in the MSE implementation is that the selected variables can be taken from any HSE or MSE variable which can be monitored, not just water level or flow variables.

The piecewise linear transfer function specifies a control function as a combination of two or three linear segments as shown in Fig. 4. The maximal upper and lower control values are $\chi=\chi_H$ and $\chi_L$, with the control output determined by the value of the input state variable $\phi$ in relation to the upper and lower threshold values $\phi_H$ and $\phi_L$, or the trigger threshold $\phi_T$. This controller can act as either a binary switch between the output control values of $\chi_H$ and $\chi_L$ switched at the threshold $\phi_T$, or can provide linear interpolation between the control points $\chi_L=(\phi_L,\chi_L)$ and $\chi_H=(\phi_H,\chi_H)$ along with lower and upper saturation values at $\chi_L$ and $\chi_H$.

MSE implements a standard closed-loop feedback PID controller based on the time-difference approximation

$$\chi(i)=\gamma_P\epsilon_i+\gamma_D\frac{\Delta\epsilon_i}{\Delta t}+\gamma_I\sum_{i=1}^{n}\epsilon_i\Delta t \qquad (1)$$

where $i$=model timestep; $\Delta t$=timestep length; $\gamma_P$, $\gamma_D$, and $\gamma_I$ represent gain factors for the proportional, derivative, and integral terms, respectively; the system state variable to be controlled is $\phi$, the desired system target state is $T$; and the system error is computed as $\epsilon(i)=\phi(i)-T(i)$. Implementation of PID controller requires a parameter tuning of the gain factors appropriate to a specific set of state variable bounds (SFWMD 2005b).

The sigmoid controller is essentially a PI controller with a single nonlinear activation function (the sigmoid) filtering the controller output. The PI portion of the controller is implemented as specified in Eq. (1) without the derivative term. Once a preliminary PI control output is available $\chi_{PI}$, the output is processed by a nonlinear sigmoidal activation function commonly known as the logistic or sigmoid function which is specified by

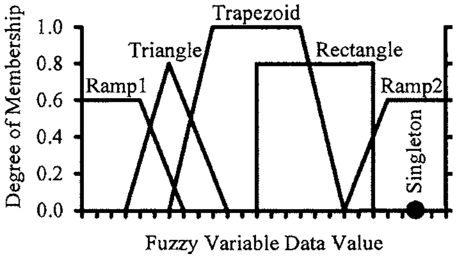


**Fig. 5.** MSE fuzzy controller and supervisor input-output terms

$$\sigma(cx) = \frac{1}{1 + e^{-cx}} \tag{2}$$

with $c > 0$. The value of $c$ determines the slope of the activation function at the origin, and can change the functional behavior from that of a slowly rising transition ($c \to 0$) to one of a unit step function ($c \to \infty$). Finally, the processed control signal is scaled by a constant scale factor $\alpha$. The resultant sigmoid control signal is therefore given by

$$\chi(i) = \alpha\sigma[\chi_{\mathrm{PI}}(i)] \tag{3}$$

The sigmoid controller has been shown to increase stability and tolerance of closed-loop feedback PI control to large variations of input state variables (Park et al. 2005).

The MSE incorporates a generic fuzzy controller as defined by the International Electrotechnical Commission (IEC) standard for fuzzy control programming (IEC 2000). The definition of a fuzzy controller is expressed in the fuzzy control language (FCL) (IEC 2000). The FCL specifies the input/output variables, fuzzy membership functions, and rule base. The fuzzy controller supports five types of input/output terms for fuzzification and defuzzification illustrated in Fig. 5.

In certain cases, a canonical fixed transfer function or rule-based expert system controller may not best suit the needs of a hydraulic structure watermover controller. To accommodate this, the MSE allows the user to develop arbitrary finite state machine algorithms through the development of C or C++ shared libraries. MSE implements a dynamic shared library loader and function pointer interface which calls the user-defined control function(s) at each timestep. Each controller maintains its own shared object and function pointer information, allowing the user to define multiple control functions inside a single shared object. The control functions can receive multiple input state variables from any data source that can be monitored within the RSM. The input-output interface to the user functions are detailed in the MSE User's Manual (SFWMD 2005b).

## MSE Supervisor Layer

A MSE supervisor is effectively a metacontroller, a controller of controllers. The addition of this supervisory layer can considerably simplify the control expression of multiple, coordinated hydraulic structures. In relation to the controllers, which are multiinput, single-output processors, the supervisors are multiinput, multioutput processors. Supervisors have the ability to change individual response characteristics of controllers, or, in the case of multiple controllers attached to a watermover, to dynamically select and activate a specific controller for a watermover. Specifically, the supervisory functions include:

- Synoptic assessment of state and process information;
- Controlling multiple parameters of multiple controllers;
- Dynamic switching of multiple controllers; and
- Flow regulation override for controller(s).

This is done through a uniform interface to the controllers ensuring interoperability between different supervisory processors and any controller.

There is no practical limit on the number of supervisors allowed in a model, or on the number of controllers that a supervisor may affect. It is possible to have a hybrid selection of different supervisors, each one regulating a specific subregional collection of hydraulic structures. The ability to selectively tailor management control algorithms, as well as the flexibility to easily reconfigure them in a plug-and-play fashion lends considerable power to the implementation of diverse and complex operational management scenarios.

The currently available supervisor modules in the MSE include:

- Fuzzy supervision;
- User-defined finite state machine;
- Linear programming;
- Graph flow; and
- Heuristic object routing model.

The fuzzy supervisor is derived from the same fuzzy library modules as the fuzzy controller. It's operational characteristics and FCL usage are the same. The user-defined supervisor is an extension of the user defined controller from a multiinput, single-output controller, to a multi-input, multioutput supervisor. The multioutputs allow for the coordinated operation, or behavioral changes to multiple watermover controllers. The user supervisor allows one to define arbitrary supervisory algorithms in dynamically loaded shared libraries.

The remaining supervisory modules are briefly described in the following section. Detailed information regarding the usage, applicability, and examples of model implementations for all supervisors are described in the MSE User's Manual (SFWMD 2005c).

MSE provides an interface to the GNU's Not Unix (GNU) linear programming kit (GLPK) (GNU 2005). The GLPK package is intended for solving large-scale linear programming, mixed integer programming (MIP), and other related optimization problems. GLPK supports the GNU MathProg language, which is a subset of A Modeling Language for Mathematical Programming (AMPL).

From the perspective of mathematical graph theory, there is a well developed body of work regarding the assessment of flows in interconnected networks (Ford and Fulkerson 1962; Ahuja et al. 1993). Graph representations of flow networks for water distribution and stream flow networks are common, and useful (Diba et al. 1995; Ostfeld 2005). The MSE maintains a graph theory representation of the managed canal network in an abstraction known as the MSE network. The MSE network couples the interconnection and flow control structures of the canal network with management data objects. For example, a network node is associated with a hydraulic structure, the node object maintains operational information relevant to the structure such as maximum flow capacities, gate opening trigger levels, etc. Likewise, canal maintenance levels and regulation schedules can be attached to the network arcs (canals or other waterbodies.)

The MSE graph supervisor implements the maxflow, feasible flow, and mincost feasible flow algorithms. These algorithms are numerical procedures which solve constrained optimization problems on the network flow by taking advantage of the network properties, rather than solving a set of simultaneous equations

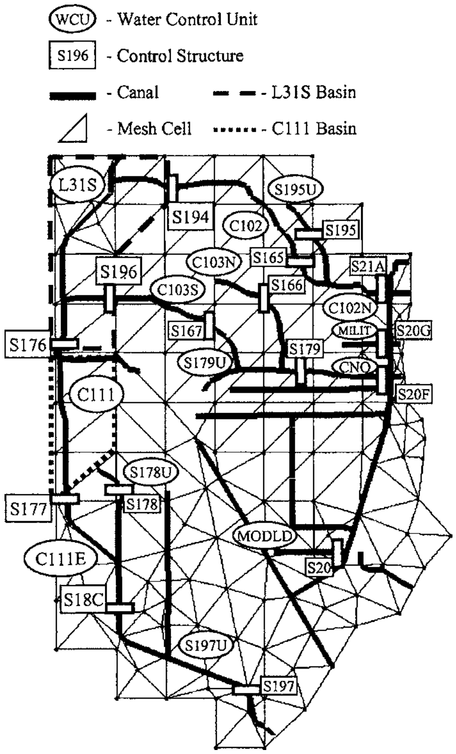


**Fig. 6.** Example RSM application mesh and canal network

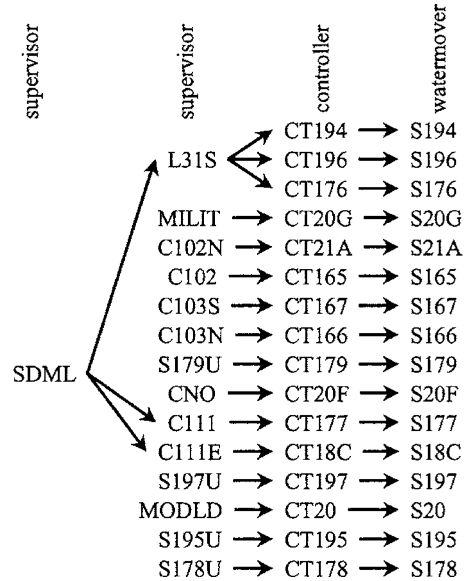


**Fig. 7.** Example RSM application MSE schematic

explicitly. The constraints consist of the canal capacity, the hydraulic structure capacity, demand and supply flows at the structures, and flow cost weights assigned to the canals.

Each supervisor solves the network flow based on its own MSE network representation, however, this can be degenerate with other supervisor network representations. As a result, a supervisor can solve the flow for the entire network, or for any subset of the network for which a MSE network has been defined.

In addition to the generic supervisory information processors described above, there is also a heuristic operational management module specific to the South Florida region. This module is termed the object routing model (ORM) and was derived from the longstanding legacy application known as the South Florida water management model (SFWMM) (SFWMD 1999) which incorporates many years of regional water resource management and numerical hydrological experience. The ORM is a basin routing model that follows a binary decision tree in the determination of hydraulic structure flow settings. Assessors quantify the water supply and flood control needs of a basin which are to be resolved by basin flow transfers. Management objectives are expressed as policies which dictate the structure of the decision tree.

## RSM Integrated Example

In this section we demonstrate basic MSE operational management in a RSM model application of southeastern Miami-Dade County, Fla. This area is primarily an agricultural zone, with water supply deliveries routed into the L31 canal from the regional water supply network. A schematic of the HSE model is shown in Fig. 6. Generally, water flows north to south (top to bottom) and west to east (left to right) with the structures along the eastern boundary discharging to coastal tidewater. The RSM groundwater domain contains 227 cells, with minimum, average, and maximum areas of 0.28, 3.42, and 6.63 km$^2$. The canal network consists of 297 canal segments with an average length of 0.8 km. Boundary conditions are taken from the SFWMM (SFWMD 1999). This includes levee seepage for the L31 and C111 canals, overland flow and groundwater flow boundary input, as well as canal leakage coefficients. Model calibration and implementation details are available by contacting the authors. Here, we will discuss features of the model implementation as it relates to the MSE control hierarchy.

### Model Description

The HSE model incorporates 16 hydraulic structure watermovers indicated by the labeled rectangles in Fig. 6, for example, S194 at the top. The MSE implementation consists of 16 controllers, one for each structure watermover, and 15 supervisors. Fourteen of the supervisors provide structure flow commands, while one supervisor provides modification of WCU maintenance levels. The WCUs are depicted in Fig. 6 with the labeled ovals. For example, in the upper left of Fig. 6 the canal segments upstream of structures S194, S196, and S176 constitute WCU L31S.

A schematic of the MSE implementation is shown in Fig. 7. The right-hand column represents the hydraulic structure watermover layer in the HSE. The second column from the right depicts the controller layer, one controller for each of the water control structures. In this model implementation, the controllers are configured as "setflow" controllers, which means they are expecting a structure flow command from a supervisor. The setflow controller will ensure that flows greater than the structure capacity are not allowed. The third column from the right represents the 14 WCU supervisors. Each of these supervisors is responsible for setting the flow of the WCU outlets such that the management criteria of the WCUs are fulfilled. The management criteria consist of flood control water levels above which water is released, and water supply maintenance levels which are minimum levels for WCUs. These levels are listed in Table 1 for the WCUs manipulated in the example.

The left-most entry in Fig. 7, the South Dade maintenance level (SDML), represents the supervisor responsible for raising

**Table 1.** WCU Maintenance Levels Applied in RSM Example Model

| WCU | Default | Supervised |
|---|---|---|
| L31S | 1.2 m (4.0 ft) | 1.2 m (4.0 ft) |
| C111 | 0.9 m (3.0 ft) | 1.0 m (3.3 ft) |
| C111E | 0.6 m (1.8 ft) | 0.7 m (2.3 ft) |

water supply maintenance levels in the C111 and C111E WCUs to allow for additional agricultural water demands when antecedent rainfall and upstream water levels allow.

### Assessors and Supervisors

The supervisors depend on 16 assessors, one WCU assessor for each of the 14 WCUs, one WSN assessor for accumulation of water supply volumes across all WCUs, and one rainfall and canal stage assessor for the SDML canal maintenance supervisor. The WCU assessor estimates the volume of water needed to raise (or lower) a WCU water level to the target maintenance level. This computation includes all sources and sinks of water from the WCU, such as groundwater, overland flow, and stream flows. The resultant value of water supply need (or excess) volume is stored in the WCU object of the MSE network. Once the individual water supply needs are assessed, the WSN assessor processes the WCUs from downstream to upstream in order defined by the MSE network interconnection structure. The cumulative water supply needs are thereby computed for each WCU, and are available for the respective WCU supervisor which sets WCU outlet structure flow commands to the controllers. In the event that there are multiple outlet structures for a WCU, the WCU supervisor applies structure flow capacity weighting to apportion the flows.

The SDML supervisor makes WCU water supply maintenance level decisions based on assessed rainfall in the L31S and C111 WCU basins. The basins are a collection of HSE mesh cells, illustrated in Fig. 6. The SDML assessor first computes a spatial average of rainfall in the L31S and C111 WCU basins. These values are filtered through a 7-day moving average for each basin. The resultant assessed rainfall for each basin in shown in Fig. 8. The SDML supervisor receives these spatio-temporal averages as input, as well as the water levels of the L31S and C111 WCUs. If the sum of assessed rainfall in the two basins exceeds a threshold of 5.0 cm, and the upstream water level is above the upstream maintenance level, the SDML supervisor raises the WCU water supply maintenance levels from the default values to higher values specified in Table 1.

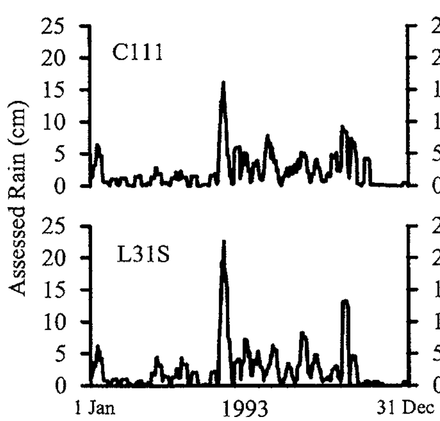


**Fig. 8.** Assessed rainfall in WCUs L31S and C111

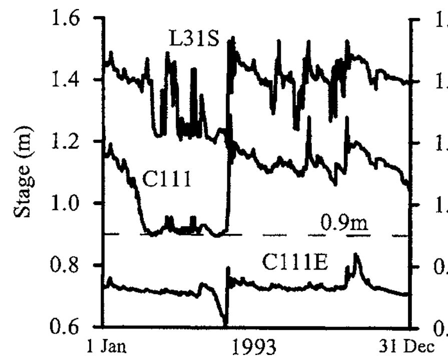


**Fig. 9.** WCU L31S, C111, and C111E water levels with WCU supervisors, no SDML supervisor

### Model Results

The model period of record is January 1, 1991 to December 31, 1995. This five-year simulation requires approximately 20 min to execute on an Intel Pentium 4 computer (2.0 GHz processor). Model results are shown for the period from January 1 to December 31, 1993. During this period, the dry season water levels were low enough to require water supply maintenance level operations. Fig. 9 plots the simulated water levels at the downstream end of the L31S, C111, and C111E WCUs with the 14 WCU supervisors and associated assessors managing the flows, the SDML supervisor is not active. During the dry season months of March–May, the lowest L31S levels are maintained near the prescribed level of 1.2 m, C111 levels are maintained close to 0.9 m.

Fig. 10 presents model results for the L31S, C111, and C111E WCUs with the SDML supervisor adjusting maintenance levels. The activation of the SDML supervisor only required a simple XML input change. It is observed that during the dry season the SDML is successful in raising the maintenance levels in C111 from 0.9 to near 1.0 m with no adverse impact on the upstream L31S WCU maintenance levels.

These results illustrate a specific implementation of coordinated control in response to synoptic state information based on multiple supervisory management processes within the framework of the MSE. However, the main thesis of this work is not one of specific implementation, but a generalization that the expression of water resource management decisions through the use of a flexible, modular command, and control topology enables alternative management scenario evaluation with minimal impact

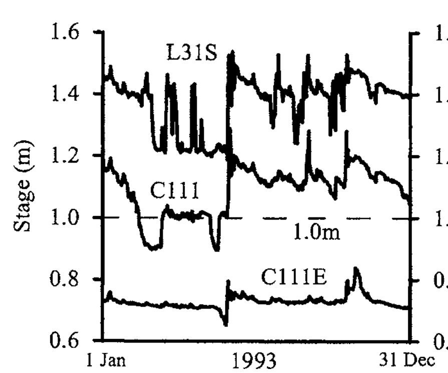


**Fig. 10.** WCU L31S, C111, and C111E water levels with WCU and SDML supervisors

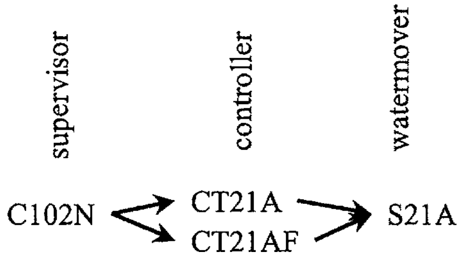


**Fig. 11.** Alternative management for WCU C102N based on flexible MSE topology

on the hydrological model, and on the overhead required to reconfigure the managerial decision processors of the model.

### *Model Flexibility*

As an example of the flexibility of the MSE topology, it can be noted that the SDML supervisor is applied at a higher layer in the multilayer hierarchy than the WCU supervisors, it is supervising other supervisors. This natural extension to higher layers is enabled by the multiinput/multioutput design of the supervisors coupled with a uniform interface between supervisors, assessors, and controllers. Further, the modular abstraction and flexible topology support reconfiguration of an implementation. Consider a situation where it is desired to evaluate alternative flood control management for the C102N WCU (in the upper right of Fig. 6). The C102N supervisor can be configured to supervise both the original setflow controller, and a new flood control function denoted S21AF. The supervisor selects activation of the alternative flood control in response to appropriate state information, such as rainfall and WCU water levels. The new MSE configuration is shown in Fig. 11. To execute this change in the simulation, the hydrological model is not impacted, only simple XML input changes are required.

## Conclusion

The MSE has been designed based on principles of interoperability of control algorithms, independent abstraction of hydrologic state and managerial process information, and a multilayer control hierarchy. The combination of these features results in a powerful, extensible methodology to express a wide variety of anthropogenic water resource control policies. The multilayered control scheme allows for the specification of local water control policies at individual water control structures, with the ability to coordinate, activate, or override the control function of multiple water control structures in a natural way. Some notable management features enabled by this architecture include the following.

1. **Multilayer control hierarchy:** Local control algorithms for individual hydraulic structures, supervisory control of multiple controllers for synoptic and coordinated structure operations
2. **Control process interoperability:** Independently expressed state and process information with a uniformly designed interface allows compatibility between various control algorithms.
3. **Independent abstraction of hydrologic state and management information:** Enables isolation of hydraulic control algorithms from hydraulic and hydrological state processing algorithms.
4. **Dynamic switching of control processors:** Multilayered control hierarchy with management process interoperability allows dynamic switching of control algorithms based on hydrological state or management process variables.
5. **Integrated state and information variable monitoring:** Input and output variables for both hydrologic state, and managerial process variables are accessed with a uniform interface known as monitors, allowing MSE objects to access any needed state information.
6. **Suite of assessors:** Provides specialized quantification of hydrological state variables, freeing managerial algorithms from data preprocessing.
7. **Generalized data filtering:** Common statistical and mathematical functions are implemented as a series of piped filters, enabling simple, yet powerful and flexible modulation of state variables.

Concerning development of the MSE, it would be useful to enact a form of arbitration between supervisors. For example, a basin might have one supervisor defined to optimize public water supply deliveries based on synoptic rainfall and aquifer levels, whereas a competing supervisor for the same basin might be computing optimal solutions for an ecological conservation area or estuarine water quality. One way to address potential conflict resolutions is to extend the control layer hierarchy to include another layer above the supervisors, a managerial layer. This top level would have access to all raw and assessed state information, as well any external constraints required to resolve the conflict by selecting a “winner” supervisory algorithm at a particular time. The available supervisory information processors (LP, fuzzy, finite state machine) could all be implemented for this function.

An alternative would be to implement an arbitration processor below the supervisory layer. This processor would take the multiple supervisory inputs, and based on external constraint information will compute which supervisory functions will be applied. An advantage of this approach is that it would be possible to synthesize a supervisory control signal from disparate supervisors to produce an effective supervisory signal. This could be done by a LP optimization, through the aggregation and inferencing of a fuzzy processor, or with the use of a knowledge- and case-based or model-based reasoning inference processor, or artificial intelligence processor.

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