Management Simulation Engine of the Regional Simulation Model: An Overview

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Abstract

The Regional Simulation Model (RSM) is a conjunctive aquifer-stream-surface hydrological model under development at the South Florida Water Management District (SFWMD). The model is designed to allow a flexible, extensible expression of a wide variety of natural hydrologies, 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 multi-level 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 the decoupling of hydrological state information from the managerial decision algorithms, facilitating the interoperation and compatibility of diverse management algorithms. The overall hierarchy and operational capabilities of the MSE are described, and compared to management capabilities of some of the leading hydrological models.

1 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. Similarly, the discipline of hydrology has profitably leveraged these developments to the point where there currently exists a nearly overwhelming proliferation of hydraulic and hydrological computational numerical models aimed at addressing the major engineering issues facing the hydrological community.

While 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 [1]. 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 multi-level 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 the decoupling of hydrological state information from the management information 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 towards addressing the emerging needs of complex management scenarios applied to regional scale conjunctive hydrological models.

1.1 Hydrological Model Management Schemes

Even a cursory examination of the hydrological literature reveals a wealth of advanced management techniques applied to water resource models [2, 3]. For example, linear programming [4], artificial neural networks [5, 6] fuzzy control [7, 8], dynamic programming [9], simulated annealing [10], genetic algorithms [11], hybrids of all of these, as well as others. However, these hydrological models tend to be specialized, requiring non-standard input formats, and limited in scope to either reservoir routing or local hydrological control. Instead, we will focus on models which incorporate the following attributes:

- Widely available and accepted by the hydrological community
- Implement stream flow & hydraulic structures
- Allow control of hydraulic structures
- Extensive body of model implementations

While there are many models which meet the above criteria to varying degrees, we have focused on the widely used and accepted models listed in Table 1. A list of the acronyms is provided in appendix 7.

Model	Source	Language
MODBRANCH	USGS	FORTRAN
MIKE SHE/11	DHI	Pascal
FEQ	USGS	FORTRAN
RSM	SFWMD	C++
HMS-RAS	HEC	C++/FORTRAN
SWMM	EPA	C
FLDWAV	NWS	FORTRAN
FLO-2D	Tetra Tech	FORTRAN

Table 1. Hydrologic models used in comparison

The primary features of each of these models, with emphasis on the hydraulic structure control and management capabilities is summarized in Appendix 6. The RSM model is described separately in section 2. Table 2 presents a synopsis of some of these primary features for each of these models. The first column lists the primary feature, each row refers to the specific model. An X entry indicates that the feature is fully implemented in the model, x denotes that the features is partially available, and * is used to represent features that do not apply, for example the coupling of ground water and stream flow in one-dimensional stream conveyance models. The reader is cautioned that the purpose of this comparison is not to argue for superiority of any one model over another. Indeed, the applicability of this diverse set of tools targets a wide spectrum of hydrological conditions for which there are disjoint functional overlaps between several of the models. Rather, the comparison focuses on the managerial capabilities of these leading applications which are well accepted in the hydrological community.

Function	MB	MS	FEQ	RSM	HEC	SM	FW	FLO
Metadata Input				X				
Non Rectangular			*	X			*	
Coupled G W/SF	X	X	*	X	X		*	*
Coupled GW/SW/SF		X	*	X	X		*	*
Rating Curves	X	X	X	X	X	X	X	X
Dynamic Control		x		X				
Arbitrary Control		x	x	X	x	x		
Multi Supervision		x		X				
Optimization		X		X				

Table 2. Comparison of Modern Hydrological Models.
MB - MODBRANCH, MS - MIKE SHE/11, FEQ - FEQ, RSM - RSM,
HEC - HEC HMS, SM - SWMM, FW - FLDWAV, FLO - FLO-2D

The primary features have the following meanings:

Metadata Input This indicates that the model inputs are specified in a self-describing format in which the inputs are contextually specified. A prime example would be the use of the Extensible Markup Language (XML) employed by the RSM [12]. An XML input specification enables implicit syntax and input value validation, coherently organizes the data into a structured hierarchy, provides a common cross-platform and application generic input dataset, 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.

Non Rectangular This refers to the shape of the spatial computational elements in the hydrological numerical representation. While this is not directly implicated in the functionality of the hydraulic structure modeling, it does represent a significant difference between the RSM and other models. The RSM operates on arbitrary triangular elements, which may provide more efficient geo-spatial matching and representation than is easily obtainable with rectangular elements. The 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.

Coupled GW/SF The groundwater and streamflow are integrated in the hydrologic solution.

Coupled GW/SW/SF The groundwater, surfacewater and streamflow are integrated in the hydrologic solution.

Rating Curves Hydraulic structures can have transfer functions specified by rating curves defined as lookup tables.

Arbitrary Control The modeler can implement an arbitrary control or management algorithm. This feature is considered fully implemented if one can write the control algorithm using standard computer code. The code is compiled into a shared library which is loaded at runtime, with I/O 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. The feature is partially implemented if the model restricts the expression of control algorithms to a set of rules, or limits the inputs to a restricted set hydraulic and temporal variables.

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 controller such as a PID may have it's 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.

Multi Supervision The management algorithms are capable of multi-input, multi-output operations. For example, a management object is capable of setting the structure flow characteristics for multiple structures simultaneously. This is strictly possible with MIKE 11, but requires careful design and PASCAL code programming to implement. 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, LP, graph flow algorithms or heuristics.

Optimization The model incorporates an optimization package able to solve constrained optimization problems directed at allocating hydraulic structure flows, water storage control, or other resource management decisions.

2 Regional Simulation Model (RSM)

The Regional Simulation Model (RSM) is designed to simulate the complex natural and anthropogenic flow of an integrated aquifer-stream flow model. It consists of two interoperative computational modules, the Hydrologic Simulation Engine (HSE) [13, 14, 15, 16, 17, 18] and the Management Simulation Engine (MSE) [19, 20, 21]. The HSE 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 it's design.

2.1 Hydrologic Simulation Engine (HSE)

HSE can simulate two-dimensional overland flow, two-dimensional or three-dimensional groundwater flow, one-dimensional canal flow, and flow in and out of reservoirs. The overland and groundwater flow domains are discretized in the horizontal 2-D 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 2-D cells. The stream flow network is discretized using piecewise linear canal segments, with variable geometry rectangular or trapezoidal cross-sections. The triangular 2-D meshes and 1-D stream networks are independent, and may overlap partially, fully, or not at all. A wide variety of local and micro-hydrologic functions associated with urban and natural land use, agricultural management practices, irrigation practices, and local routing are handled with a feature known as pseudocells. The pseudocells 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 use of the PETSC sparse linear system solver [22]. 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.

2.2 Management Simulation Engine (MSE)

The MSE design is based on the hydroinformatic principle that operational and managerial decisions applied to water control structures can be viewed as information processing algorithms decoupled from the hydrological state information on which they operate. Essentially, the HSE provides hydrological and hydraulic state information (Σ), while external policies dictate managerial constraints and objectives (Λ).

In the MSE this state and process information can be functionally transformed by an independent set of filters, which can be viewed as information pre-processors. These processors are denoted as Assessors (A) and Filters. For example, an Assessor may perform statistical filtering such as spatio-temporal expectations, amplitude or time-delay modulation, or any other suitable data filtering operation. The MSE is then tasked with appropriately processessing the assessed state information in order to produce water management control signals (χ, μ) which are applied to the hydraulic control structures in order to satisfy the desired constraints and objectives. Figure 1 illustrates this overall cyclic flow of state and management information in the RSM.

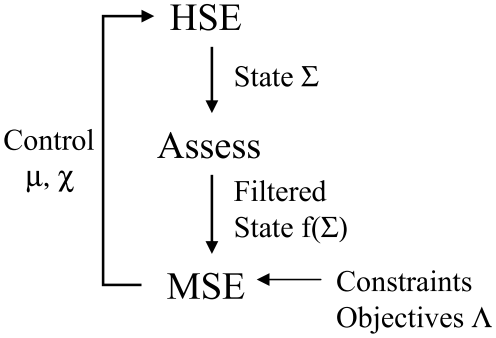

Figure 1: RSM state and management information flow

More specifically, the MSE architecture is based on a multilayered hierarchy, with individual water control structures regulated by 'controllers' while the 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 figure 2.

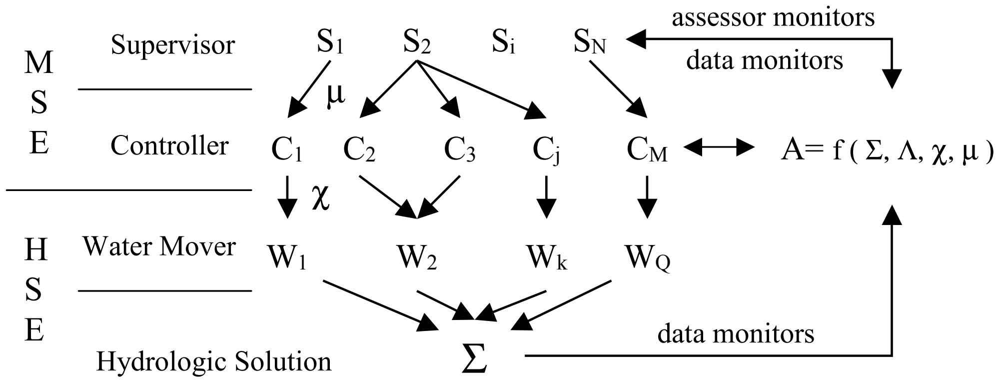

Figure 2: HSE MSE schematic

At the lowest layer is the hydrological state information (Σ) 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 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 (μ) 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 section 2.5.

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 rulecurve could be enforced during normal operations. In this manner the MSE provides for dynamic switching of hydraulic structure control functions in response to state or process information.

Once the controllers have computed their respective control values (χ), 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.

2.3 Assessors & 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 needs (WSN) assessor estimates the volumetric flow in a canal water control unit which is required to meet a downstream water supply demand. This assessor considers both upstream and downstream supply & 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. Since 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.

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 timeseries amplitude modulation consisting of the usual arithmetic operations (multiplication, division, addition, subtraction) or may compute simple timeseries 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 FIFO fashion, as exemplified by the XML fragments below and in figure 3.

```
<WcuAssessor asmtID="101" name="Reach1" mode="wsneeds">
   <target> <dss file="Reach1Target.dss"/> </target>
</WcuAssessor>

<filter type="offset">
   <offset><dss file="Reach1Offset.dss"/></offset>
   <filter type="MovingAvg" numAvg="15">
      <assessormonitor id="101" attr="flow"></assessormonitor>
   </filter>
</filter>
```

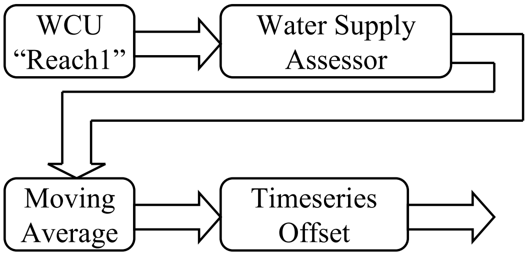

Figure 3: Unified interfacing of data preprocessors allows piped operations.

The first XML section defines a water control unit assessor (WcuAssessor) attached to the canal unit Reach1. The assessor is in water supply needs mode, which computes the flow required in the control unit to satisfy the target levels specified in the timeseries file Reach1Target.dss. The second section defines a dual-stage filter applied to the assessed flow values. An assessormonitor is used to reference the assessed flow, and serves as input to a moving average filter. The output of the moving average filter is input to an offset filter, with offset values specified by the timeseries Reach1Offset.dss. To change the data source, order, or type of operations, one simply reconfigures the XML specification. This procedure can be automated with the use of a graphical user interface software application.

A crucial aspect of effectively storing and accessing assessed state information for water resource management purposes is the maintenance of an efficient storage mechanism which associates hydrological state information with the proper managerial abstractions. In the RSM this is done by storing assessed information relevant to a particular water control unit (WCU) in a data storage object defined in the MSE network. The MSE network is an abstraction of the reservoirs, stream flow network, and water control structures dedicated to representing the managerial architecture of the model, it is discussed in section 2.6

A result of these data handling abstractions and interfaces is the desired decoupling of state variable processing from managerial decision processing based on a flexible, data driven specification which is easily modified providing a level of plug-and-play functionality not commonly found in conjunctive hydrological models.

2.4 MSE Controller Layer

The MSE controller layer is the intermediary between the hydraulic structure watermovers and the regional-scale supervisory coordinators. The controllers can operate independently of the supervisors, in fact they 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. Since the interface between a structure watermover and any controller is uniform, 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 & two dimensional rulecurves
- Piecewise linear transfer function
- Proportional Integral Derivative (PID) feedback control
- Sigmoid PI feedback control
- Fuzzy control
- User defined finite state machine

Each of these is briefly described in the following sections. Detailed information regarding the usage, applicability, and examples of model implementations are described in [20].

2.4.1 One & two dimensional rulecurves

All of the models examined in section 1.1 implement rulecurves in some fashion as a method of controlling the flow transfer function of hydraulic structures. The MSE provides for one or two variable interpolated lookup 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.

2.4.2 Piecewise linear transfer function

With the piecewise linear transfer function controller, the user specifies a control function as a combination of two or three linear segments as shown in figure 4. The upper and lower control values are C_H and C_L, with the control output determined by the value of the input state variable ϕ in relation to the upper and lower threshold values τ_H and τ_L. This controller can act as either a binary switch between the output control values of C_H and C_L, or can provide linear interpolation between the control points (τ_L, C_L) and (τ_H, C_H) along with lower and upper saturation values at C_L and C_H.

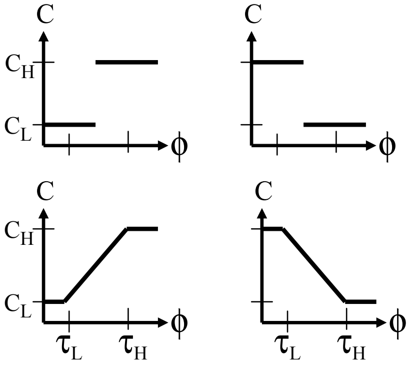

Figure 4: Piecewise linear transfer functions.

2.4.3 Proportional Integral Derivative (PID) feedback control

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

$$C(i) = \gamma_P \, \epsilon_i + \gamma_D \frac{\triangle \epsilon_i}{\triangle t} + \gamma_I \sum_{i=1}^{n} \epsilon_i \triangle t \tag{1}$$

where γ_P γ_D and γ_I represent gain factors for the proportional, derivative and integral terms, the system state variable to be controlled is $\phi(t)$ and the desired system target state is $T(t)$ at timestep t. The system error is computed as $\epsilon(t) = \phi(t) - T(t)$.

2.4.4 Sigmoid PI feedback control

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 equation 1 without the derivative term. Once a preliminary PI control output is available C_{PI}, the output is processed by a nonlinear sigmoidal activation function commonly known as the logistic or sigmoid function which is specified by

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

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→0) to one of a unit step function ($c \rightarrow \infty$). This function serves to limit the possibly unbounded control outputs to the interval [0,1], while also providing an adjustable derivative for the linear portion of the activation function. Finally, the processed control signal is scaled by a constant scale factor α. The resultant sigmoid control signal is therefore given by

$$C(i) = \alpha \, S \left(C_{PI}(i) \right) \tag{3}$$

The sigmoid controller has been shown to increase stability and tolerance of closed loop feedback PI control to large variations of input state variables [19].

2.4.5 Fuzzy control

The MSE incorporates a generic fuzzy controller as defined by the International Electrotechnical Commission (IEC) standard for Fuzzy Control Programming [23]. The fuzzy controller constitutes a rule-based expert system utilizing an inferencing engine coupled with multiple constraint aggregation. Fuzzy control can be useful in cases where there exists an experiential reference base that can be expressed in terms of rules. In contradiction to many canonical control processors, fuzzy control doesn't require knowledge of the system transfer function, that the transfer function be expressible in closed form, or that the system has to be linear. An additional advantage is that the rule base is expressed in a linguistically natural format and can be easily understood by non-specialists.

The definition of a fuzzy controller is expressed in the Fuzzy Control Language (FCL) [23]. 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 figure 5.

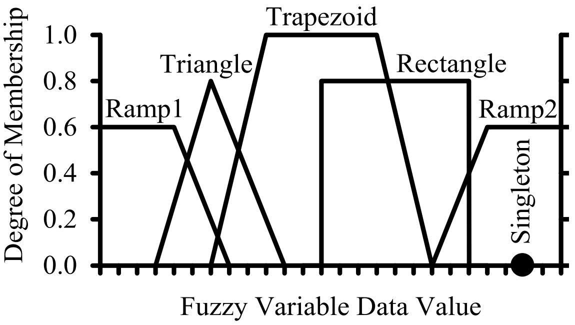

Figure 5: MSE fuzzy I/O terms

An example FCL excerpt for a simple pump station controller is shown below.

```
// Fuzzy Controller for Pump Station
VAR_INPUT
        CanalStage : REAL;
END_VAR
VAR_OUTPUT
        PumpOut : REAL;
END_VAR
FUZZIFY CanalStage
        TERM low    := (9, 1) (10, 0);
        TERM medium := (9, 0) (10, 1) (12, 1) (13, 0);
        TERM high   := (12, 0) (13, 1);
END_FUZZIFY
DEFUZZIFY PumpOut
          TERM off        := 0.;
          TERM mediumLow  := (0.3, 1) (0.6, 0);
          TERM mediumHigh := (0.4, 0) (0.7, 1);
          TERM on         := 1.;
END_DEFUZZIFY
RULEBLOCK No1
          RULE 1: IF CanalStage IS high THEN PumpOut IS on;
          RULE 2: IF CanalStage IS medium AND CanalStage IS high
                  THEN PumpOut IS mediumHigh;
          RULE 3: IF CanalStage IS medium AND CanalStage IS low
                  THEN PumpOut IS mediumLow;
          RULE 4: IF CanalStage IS low THEN PumpOut IS off;
END_RULEBLOCK
```

The corresponding fuzzy input/output terms for this example are shown in figure 6.

To completely implement this fuzzy controller, the XML specification read by the RSM must specify the structure watermover to which the controller is applied, the source of the input state variable(s), and the name of the output variable exemplified below. As with the other controllers, the input state variables can be obtained from any monitored data source in the RSM. Although only one input variable is demonstrated in this example, multiple inputs are supported.

```
<fuzctrl cid="101" wmID="1" fcl="pump.fcl">
   <varIn name="CanalStage">
     <segmentmonitor id="34" attr="head"></segmentmonitor>
   </varIn>
   <varOut name="PumpOut"> </varOut>
</fuzctrl>
```

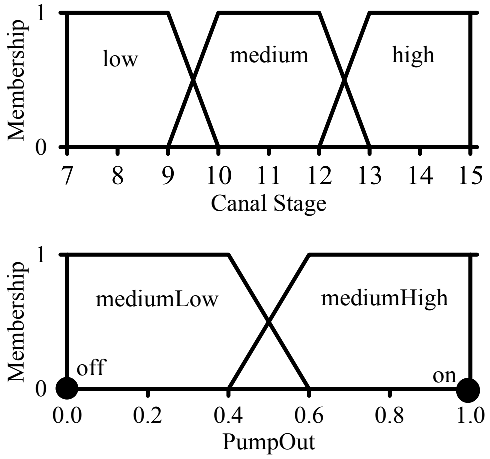

Figure 6: Fuzzy input output terms for pump example

2.4.6 User defined finite state machine

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 it's 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 [20].

An example of the RSM XML specification for a user defined controller is shown below. To manually replace this controller with the previously mentioned fuzzy controller, or any other controller, a simple edit of the XML input file is all that is required.

```
<userctrl cid="102" wmID="2" module="./UserCtrl.so" func="myControl">
   <varIn name="Canal1">
      <segmentmonitor id="25" attr="head"></segmentmonitor>
   </varIn>
   <varOut name="GateOpen"> </varOut>
</userctrl>
```

2.5 MSE Supervisor Layer

An MSE supervisor is effectively a meta-controller, a controller of controllers. The addition of this supervisory layer considerably simplifies the control expression of multiple, coordinated hydraulic structures. In addition to the organizational simplification of control algorithms, it is likely that the additional layer enables representation of management functions which are not realizable with a single control layer. This assertion is based on analogy with the universal approximation theorem for artificial neural networks (ANN).

The universal approximation theorem states that any real valued (linear or nonlinear) continuous function can be approximated arbitrarily closely by an artificial neural network having only two adjustable weight layers which are processed by sigmoidal activation functions. The proof of this theorem [24, 25] builds on seminal work of Kolmorogorov concerning the decomposition of continuous functions [26].

In relation to the multi-level control hierarchy of the MSE as depicted in figure 2, the computational architecture can be viewed as an analog of the universal approximation artificial neural network as follows. Consider that the MSE control signal outputs μ and χ are analogous with the adjustable weight matrix of an artificial neural network. In an ANN the weights are adjusted in a learning or evolution process based on the optimization of an error metric in relation to a desired goal. In the MSE control scenario, the control signals converge on values dictated by optimization of the system response in relation to the desired control objectives. Concerning the MSE control and supervisory processors $\mathrm{S_i}$ and $\mathrm{C_j}$, it is clear that the control signal output for physically based control structures is stable and finite. Therefore, the processor transfer function of these stable and bounded control processors must also be stable and bounded. Such process functions are functionally analogous to the sigmoidal functions which are inherently stable and bounded process functions (equ. 2). Based on this analogy, it is expected that the multi-layered control hierarchy of the MSE provides a computational architecture capable of modeling the majority of water resource management policies.

In relation to the controllers, which are multi-input, single-output (MISO) processors, the supervisors are multi-input, multi-output (MIMO) 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
- 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 common to have a hybrid selection of different supervisors, each one regulating a specific sub-regional 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
- Heuristic Object Routing Model

The fuzzy supervisor is derived from the same fuzzy library modules as the fuzzy controller described in section 2.4.5. It's operational characteristics and fuzzy control language usage are the same. The user defined supervisor is an extension of the user defined controller described in section 2.4.6 from a multi-input, single-output controller, to a multi-input, multi-output supervisor. The multi-outputs 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 sections. Detailed information regarding the usage, applicability, and examples of model implementations for all supervisors are described in [21].

2.5.1 Linear Programming supervision

MSE provides an interface to the GNU Linear Programming Kit (GLPK) [27]. The GLPK package is intended for solving large-scale linear programming (LP), mixed integer programming (MIP), and other related optimization problems. GLPK supports the GNU MathProg language, which is a subset of the AMPL language. AMPL is a comprehensive and powerful algebraic modeling language for linear and nonlinear optimization problems, in discrete or continuous variables. AMPL lets you use common notation and familiar concepts to formulate optimization models and examine solutions.

The MSE GLPK supervisor is defined by a MathProg model definition file which specifies the parameters, variables, and optimization function of the supervisor. The model definition file may also contain a data section which defines parametric values, and initial values for variables. If the data section is not included in the model definition file, then a separate data definition file must exist. The MSE GLPK supervisor reads these files, creates the GLPK problem objects, and calls the appropriate GLPK API routines to solve the supervisory constrained optimization problem.

2.5.2 Graph flow supervision

From the perspective of mathematical graph theory, there is a well developed body of work regarding the assessment of flows in interconnected networks [28, 29]. Graph representations of flow networks for water distribution and stream flow networks are common, and useful [30, 31]. The MSE maintains a graph theory based representation of the managed canal network as described in section 2.6. The MSE Graph supervisor implements the maxflow, feasible flow, and mincost feasible flow algorithms. These algorithms are essentially minimal 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 explicitly. The constraints consist of the canal arc capacity, the hydraulic structure capacity, demand and supply flows at the structures, and flow cost weights assigned to the canal arcs.

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

2.5.3 Heuristic Object Routing Model supervision

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 [32] which incorporates many years of 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.

2.5.4 Supervisor XML

Several of MSE supervisors require external information dictating the information processing model of the particular supervisor. For example, the fuzzy supervisor requires an FCL file, the user supervisor a C or C++ algorithm and the LP supervisor a MathProg file. However, all supervisors share a common input/output interface with the RSM state variables, and are described in the RSM model input with an XML entry. An example XML excerpt is shown below. In this example, two watermover controllers have their lower trigger threshold value adjusted according to the control algorithm coded in the user defined C++ function `SetTrigLow`. This supervisor accepts two input variables, and sets two output variables.

```xml
<user_supervise id="804" module="./UserSprv.so" func="SetTrigLow">
   <ctrlID> 103 104 </ctrlID>
   <varIn name="segment1Head">
      <segmentmonitor id="1" attr="head"></segmentmonitor>
   </varIn>
   <varIn name="segment4Head">
      <segmentmonitor id="4" attr="head"></segmentmonitor>
   </varIn>
   <varIn name="season">
      <tkprmonitor attr="month"></tkprmonitor>
   </varIn>
   <varOut ctrlID="103" func="triglow" name="103_TrigLow"> </varOut>
   <varOut ctrlID="104" func="triglow" name="104_TrigLow"> </varOut>
</user_supervise>
```

2.6 MSE Network

A central feature of the MSE which enables decoupling of the hydrological state information maintained by the HSE and the operational process information of the MSE is the MSE network. The MSE network is an abstraction of the stream flow network and control structures suited to the needs of water resource routing and decisions. It is based on a standard graph theory representation of a flow network comprised of arcs and nodes [29]. The MSE network data objects serve as state and process information repositories for management processes. They maintain assessed and filtered state information, parameter storage relevant to WCU or hydraulic structure managerial constraints and variables, and serve as an integrated data source for any MSE algorithm seeking current state information. It also provides a mathematical representation of a constrained, interconnected flow network which facilitates the efficient graph theory solution of network connectivity and flow algorithms.

From the hydrological perspective, the HSE stream network is composed of an interconnected network of flow segments, with each segment maintaining parameters relevant to aquifer-stream interaction, flow resistance, spatial coordinates and other physical properties. The spatial representation of HSE segments are typically dictated by topographic and physical parameters. From the water resource management viewpoint of the MSE, the important features of the flow network are it's connectivity, flow capacities, flow regulation structures, and assessed state information relevant to managed sections of the network. The MSE network maintains a mapping between these two representations.

The primary stream object in the MSE network is the Water control unit (WCU). A WCU maps a collection of HSE stream segments that are operationally managed as a discrete entity to a single arc in the MSE network. WCU's are typically bounded by hydraulic control structures, which are represented as nodes in the MSE network. Each WCU includes associative references to all inlet and outlet hydraulic flow nodes. Some of the variables stored in a structure (node) object include:

1. current flow capacity
2. maximum design flow capacity
3. reference to hydraulic watermover
4. reference to structure controller
5. operational policy water levels
6. supply
7. demand

while the WCU (arc) objects incorporate:

1. flow capacity
2. seasonal maintenance levels
3. inlet flow
4. outlet flow
5. water depth
6. water volume

Each WCU in the MSE network is referenced by a unique label, and has an associative data storage object which dynamically allocates storage for assessment results. This allows multiple, independent assessments of the WCU state. For example, one assessment of WCU inlet structure flows might come from a graph algorithm, while another could be stored from a LP model.

This abstraction from hydrological objects to managerial objects condenses the network representation facilitating the organization and storage of relevant assessed state and process information. As an example, figure 7 depicts an HSE stream network consisting of 63 nodes and 62 segments. Some of the nodes correspond to locations of hydraulic control structures, though the association is not apparent from examination of the HSE network. Each stream segment has a unique identifier which allows the modeler or MSE processor to monitor state information of the segment. However, as pointed out earlier, it may be appropriate to make water management decisions based on some assessed or filtered version of aggregated stream segment states.

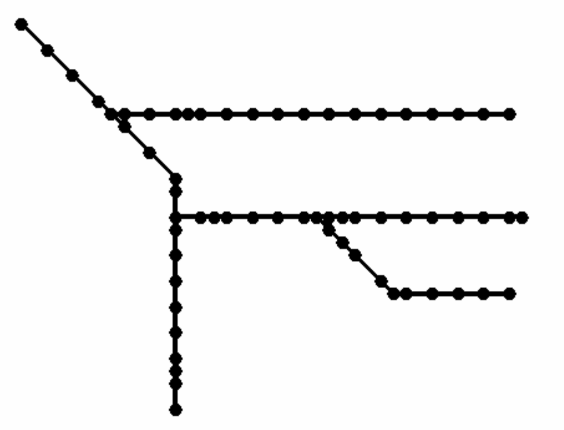

Figure 7: Example HSE stream network segments and nodes.

Consider now an abstraction of the HSE network into 10 WCU's, regulated by 11 hydraulic structures. An example of such a MSE network is presented in figure 8. In the MSE network each line segment represents a WCU, while each node represents a hydraulic structure which regulates a WCU. The modeler or MSE processor is able to directly monitor information stored in any of these object data containers, information which has already been assessed and automatically stored in the appropriate WCU data object at each timestep.

As with other RSM model inputs, the WCU mapping from the HSE stream network is performed with an input XML entry. The excerpt below shows basic elements in the construction of an MSE network. The `mse_arc` establishes a collection of HSE stream segments as a single entity, and defines the nodes which connect to this arc. The `mse_node` supplies optional parameter and data values for nodes, while the `mse_unit` aggregates the `mse_arc` into WCU's.

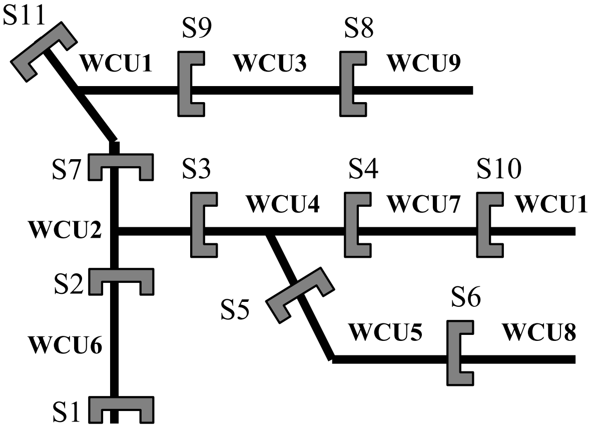

Figure 8: Example MSE network abstraction of HSE network into WCU's and structures.

```
<mse_network name="Test Network">
  <mse_arcs>
    <mse_arc name="Reach_1" capacity="1400">
      <hse_arcs> 100 101 102 103 </hse_arcs>
      <node_source> "S11"    </node_source>
      <node_sink>   "S11_A"  </node_sink>
    </mse_arc>
    <!-- more mse_arc entries.... -->
  </mse_arcs>
  <mse_nodes>
    <mse_node name="S11" purpose="WaterSupply" designCap="3000.">
      <supply name="S11 Supply"> <const value="100"> </const> </supply>
      <open   name="S11 Open">   <rc id="2"></rc> </open>
      <close  name="S11 Close">  <const value="5.5"> </const> </close>
    </mse_node>
    <!-- more mse_node entries.... -->
  </mse_nodes>
  <mse_units>
    <mse_unit name="WCU1">
      <unit_arcs> "Reach_1" "Reach_1S" "Reach_1E" </unit_arcs>
      <maintLevel name="maint"> <const value="5.5"> </const> </maintLevel>
      <inlet  name="S11 inlet">  "S11" </inlet>
      <outlet name="S7 outlet" > "S7"  </outlet>
      <outlet name="S9 outlet" > "S9"  </outlet>
    </mse_unit>
    <!-- more mse_unit entries.... -->
  </mse_units>
</mse_network>
```

3 RSM Integrated Example

In this section we demonstrate some basic MSE operational controls applied to a RSM model application which represents the Florida lower east coast. This model covers roughly the area from Lake Okeechobee in the northwest to southern Miami-Dade county in the southeast. The HSE model consists of 1124 mesh cells representing a single layer aquifer and ground surface, coupled with a stream network consisting of 455 canal segments. The model period of record is from January 1 1998 to March 31 1999, this period encompasses the May-September rainy season, as well as an exceptional rain event from a tropical storm which passed over the area on October 5, 1988. Figure 9 illustrates the HSE mesh and canal network.

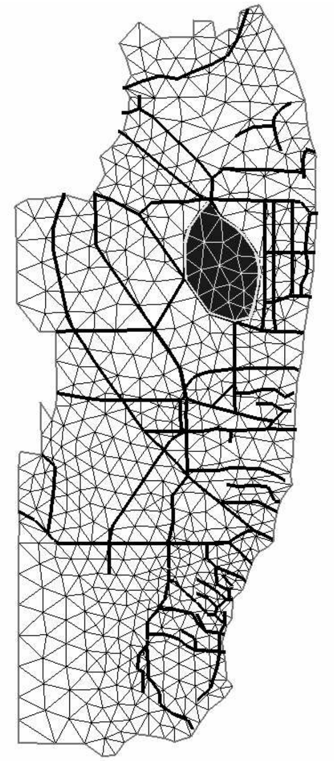

Figure 9: Example RSM application mesh and canal network, WCA1 is highlighted.

Regarding the MSE implementation of this model, there are 192 hydraulic structure watermovers, with a controller assigned to each watermover. The MSE implements 12 supervisors to control coordination of multiple controllers. The HSE canal network has been aggregated into 56 water control units (WCU's) forming the MSE network. Figure 10 shows a graphic comparison of the HSE and MSE networks.

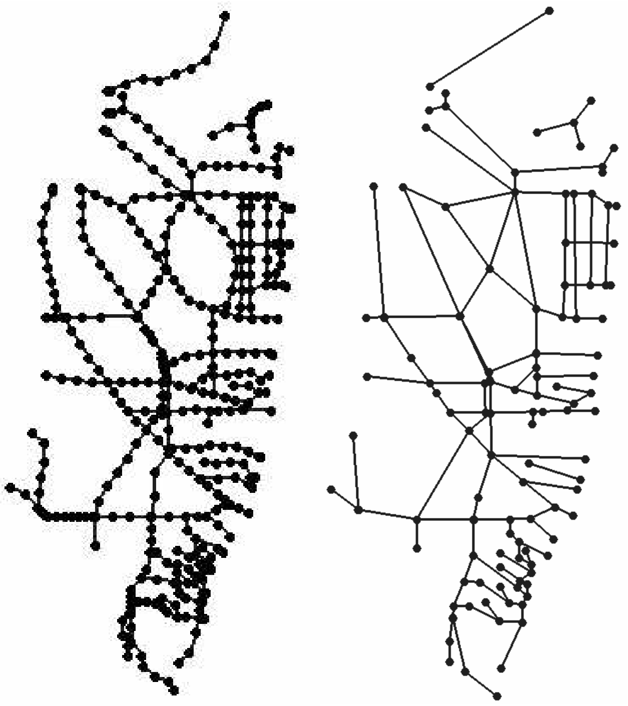

Figure 10: Comparison of HSE (left) and MSE networks (right).

The highlighted area in figure 9 corresponds to the northernmost extent of the Everglades. It is a federally protected wetland, the Arthur R. Marshall Loxahatchee National Wildlife Refuge. The refuge is commonly referred to as Water Conservation Area 1 (WCA1). The refuge is surrounded by a canal and levee system which effectively isolates it from the adjacent lands. Water levels inside WCA1 are controlled through a series of inlet and outlet hydraulic structures located on the perimeter canals of the basin. Figure 11 depicts a schematic representation of the WCA1 model representation with the major flow control structures indicated as arrows.

The primary outlet flow structures from WCA1 are the series of S10 structures along the lower left canal rim. These structures discharge into the

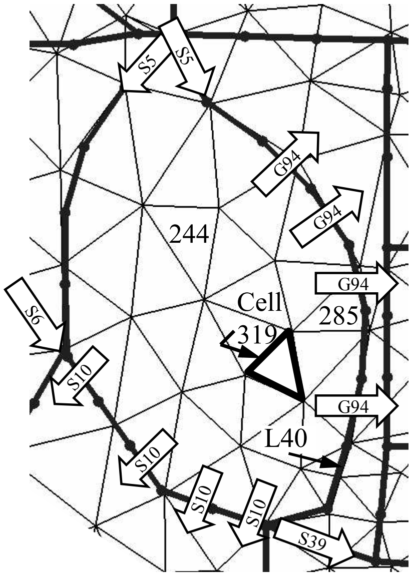

Figure 11: WCA1 model conceptualization.

adjacent Everglades referred to as Water Conservation Area 2 (WCA2). The hydraulic structure S39 controls the flow from the southern rim canal into a coastal outlet canal. Additionally, the series of G94 structures are capable of discharging from WCA1 into the adjacent drainage district (though these structures are usually controlled by the drainage district into which they discharge.) In the model, the controllers for the S10 and G94 structures are piecewise linear transfer functions while the S39 controller is a user defined (C++) finite state machine module. When the supervisor is not in effect, these controllers regulate the flow through the structures.

In this demonstration, a supervisor has been created from a user defined C++ module to coordinate the operation of the S10, S39 and G54 structures in an attempt to lower the canal and aquifer levels in WCA1 in response to stage and rainfall state information. The input stage information is an assessed spatial average of watertable levels in the three mesh cells 244, 285 and 319 (figure 11). The input rainfall is a spatio-temporal moving average assessed over the same three cells and a 24 hour period. The assessor XML for these inputs is shown below, the resultant assessed stage and rainfall is depicted in figure 12.

```
<statassessor asmtID="2" attr="ave" name="WCA-1 3-gage avg">
  <cellmonitor id="244" attr="head"/>
  <cellmonitor id="285" attr="head"/>
  <cellmonitor id="319" attr="head"/>
</statassessor>

<statassessor asmtID="3" attr="ave" name="WCA-1 rain avg">
  <filter type="movingavg" numAvg="4">
     <cellmonitor id="244" attr="rain"/>
  </filter>
  <filter type="movingavg" numAvg="4">
     <cellmonitor id="285" attr="rain"/>
  </filter>
  <filter type="movingavg" numAvg="4">
     <cellmonitor id="319" attr="rain"/>
  </filter>
</statassessor>
```

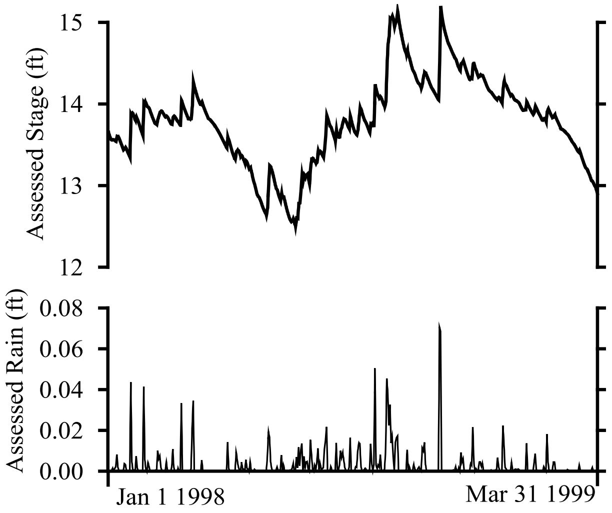

Figure 12: Assessed stage and rainfall in WCA1.

The user defined supervisor receives the assessed stage and rainfall information as input state variables, and then assigns structure control outputs to the S10, G94 and S39 structures based on two modes of operation. In the default mode the control outputs are set for each structure based only on the assessed stage values decomposed into four ranges of average stage s: ($s < 12$), ($12 <= s < 13$), ($13 <= s < 14$), ($s >= 14$) ft. The supervisor also computes a threshold comparison on accumulated values of the assessed rainfall. A sliding accumulator stores assessed rainfall over a three day moving window. If the sum of the accumulated rainfall exceeds a threshold (0.01 ft) and the assessed stage is greater than 12 ft, then an alternate set of control values are applied to the structures intended to increase the outflow from WCA1. This algorithm is not patterned after an actual water management policy for WCA1, but serves to illustrate some of the possibilities afforded with the combination of assessors and supervisors.

The model was run in two modes. In the first run the supervisor which controls the WCA1 outlet structures was switched off. In this mode the local controllers for each WCA1 outlet structure are regulating the flow according to their operational criteria. In the second mode, the supervisor is activated, and overrides the control function of the individual structure controllers as described above. The control signals and resultant structure flows for one of the S10 and G94 structures, and for the S39 are shown in figures 13 and 14 respectively.

The second model run was conducted with the WCA1 outflow supervisor activated. Control signals and selected structure flows for this case are shown in figures 15 and 16 respectively. Comparison of the unsupervised and supervised control and flow graphs shows a significant behavioral difference, where as expected, the supervisory control provides significantly increased outflow.

A comparison of the modeled canal stage in the L40 canal segment with and without supervision is depicted in figure 17. The lower portion of figure 17 plots the model input observed rainfall applied to cell 319, which was used as one of the inputs to the assessed rainfall. The supervisory control has lowered the L40 canal stage by approximately 18 inches. The model output of water levels in the mesh cell 319 are presented in figure 18. The effect of the supervisory control is clearly evident in the lower water levels achieved with the coordinated outlet flows.

This simplistic demonstration is by no means comprehensive in terms of utilizing the wide spectrum of tools and capabilities available in the RSM. Rather, it serves to illustrate a simple coordinated structure control scenario which makes use of assessors, filters, controllers and supervisors.

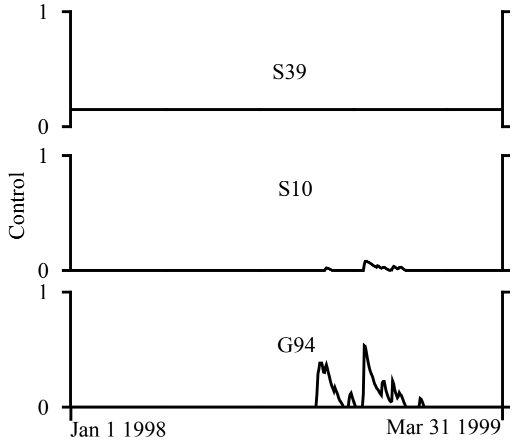

Figure 13: WCA1 outlet structure control signals without supervision.

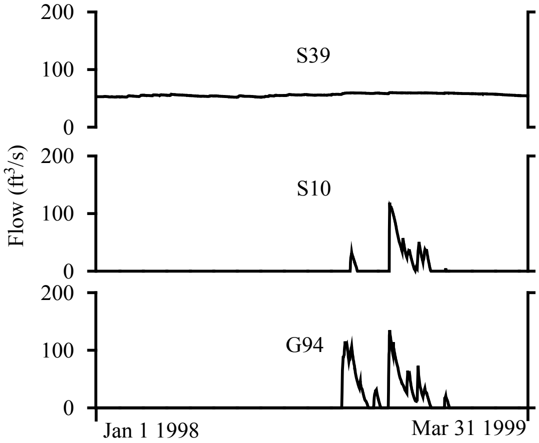

Figure 14: WCA1 outlet structure flows without supervision.

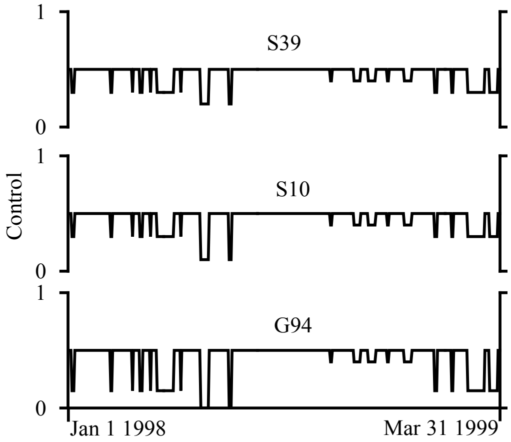

Figure 15: WCA1 outlet structure control signals with supervision.

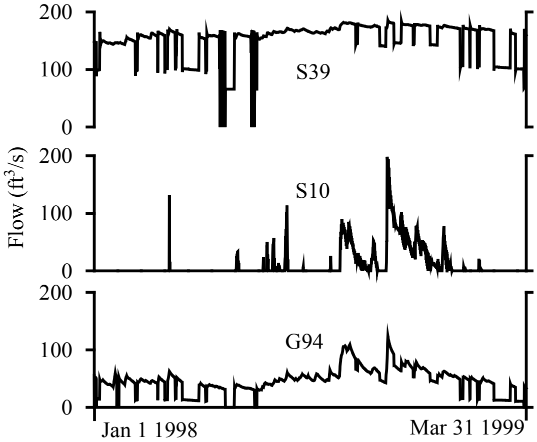

Figure 16: WCA1 outlet structure flows with supervision.

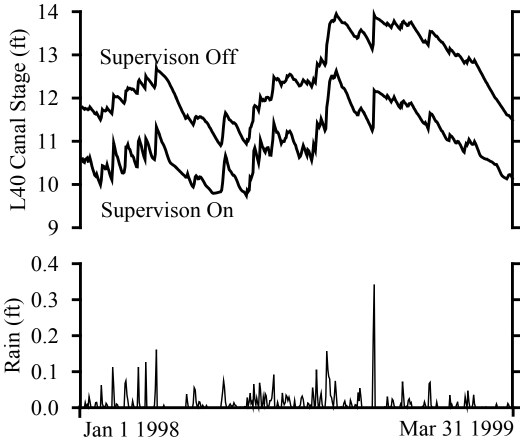

Figure 17: L40 canal stage comparison with and without supervision.

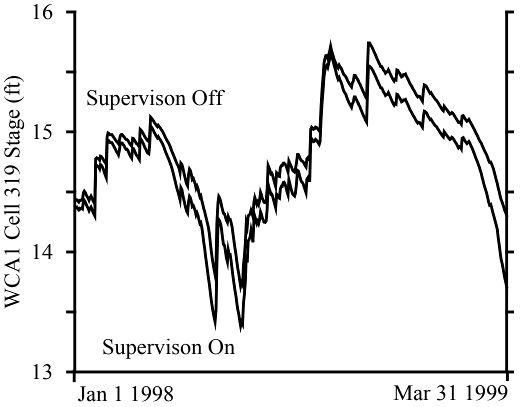

Figure 18: Cell 319 aquifer stage comparison with and without supervision.

4 Future work

To continue progress towards the comprehensive integration of management features in conjunctive hydrological models, there are several areas of continuation relevant to the RSM that deserve attention. At the controller level, there are plans to extend the controller library to include canonical state estimation filters. In the linear domain with Gaussian statistics this includes the addition of a Kalman filter, while for nonlinear transfer functions and non-Gaussian statistics the extended Kalman filter and artificial neural networks.

In the supervisory realm 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, while a competing supervisor for the same basin might be computing optimal solutions for a 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 information processors (LP, fuzzy, finite state machine) could all be extended 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 an LP optimization, through the aggregation and inferencing of a fuzzy processor, or with the use of a knowledge base and case-based or model-based reasoning inference processor, or artificial intelligence processor.

Another useful extension would be the development of scenario management tools. These would provide the ability to comprehensively specify alternative predefined supervisory or control schemes based on user defined, or state variable information.

5 Conclusion

This paper has explored the general features and capabilities of the Management Simulation Engine component of the Regional Simulation Model. The MSE has been designed based on principles of interoperability of control algorithms, decoupling of hydrologic state and managerial process information, and a multi-level control hierarchy. The combination of these features results in a powerful, extensible methodology to express a wide variety of anthropogenic water resource control policies.

This level of functionality is not typical of some of the leading hydraulic routing, hydrological, and conjunctive aquifer-stream models in use today. Most of these models provide a limited set of water resource management expressions, such as the use of rulecurves based only on hydraulic or hydrological state variables. One notable exception to this is the MIKE SHE suite of modeling tools. MIKE SHE implements a mature and expansive set of management features, arguably the most comprehensive set available in commercial conjunctive models. The RSM and MSE extend this functionality and provide a new set of tools and features not previously available. A list of the essential features of the RSM and MSE which highlight this level of functionality is presented below.

XML input:

Data driven, industry standard XML input specifications

Multilayer control hierarchy:

Local control algorithms for individual hydraulic structures, supervisory control of multiple controllers for synoptic and coordinated structure operations

Integrated structure control algorithms:

1. Closed loop feedback PID control
2. Sigmoid activated closed loop feedback PID control
3. Piecewise linear transfer function
4. Fuzzy logic
5. User defined finite state machine

Integrated supervisory structure coordination algorithms/models:

1. Fuzzy logic
2. User defined finite state machine

3. LP
4. Graph flow
5. Heuristic

Stream flow network abstraction:
Management objects are defined in terms of hydrological entities aggregated into Water Control Units and their associated hydraulic structures, which are internally represented using graph theory. Necessary aggregation and assessment of hydrological state variables is implicit.

Network dynamic data store:
Assessed hydrologic state variables, operational control parameters, and other water resource management variables are dynamically stored and updated in the stream flow network abstraction providing a central data store for managerial algorithms.

Decoupled hydrologic state and management information:
Enables isolation of hydraulic control algorithms from hydraulic and hydrological state algorithms.

Control process interoperability:
Decoupled state and process information with a uniformly designed interface allows compatibility between various control algorithms.

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.

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.

Suite of assessors:
Provides specialized quantification of hydrological state variables, freeing managerial algorithms from data preprocessing.

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.

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6 Appendix A: Review of commonly used models

6.1 MODFLOW MODBRNCH

The modular finite-difference ground-water flow model (MODFLOW) [33, 34] is a three dimensional finite-difference groundwater model capable of simulating steady and nonsteady flow in an irregularly shaped boundary in which aquifer layers can be confined, unconfined, or a combination of both. The ground-water flow equation is solved using the finite-difference approximation wherein the flow region is subdivided into blocks in of uniform medium properties. The MODFLOW spatial domain is discretized into variably spaced rectangular blocks which must constitute a grid of mutually perpendicular lines. Currently, MODFLOW is the most widely used program in the world for simulating ground-water flow [35].

Surface and groundwater interactions can be simulated by the coupled BRANCH and USGS modular, three dimensional, finite- difference groundwater flow (MODFLOW) models, referred to as MODBRNCH [37].

The Branch-Network Dynamic Flow Model BRANCH [38, 39] is used to simulate steady or unsteady flow in a single open-channel reach (branch) or throughout a system of branches (network) connected in a dendritic or looped pattern. BRANCH uses a weighted four-point, implicit, finite- difference approximation of the unsteady-flow equations. The effects of hydraulic control structures within the model domain are treated by a multi-parameter rating method.

6.2 MIKE SHE

MIKE SHE is a modeling tool that can simulate the entire land phase of the hydrologic cycle encapsulated in an integrated modeling environment that allows components to be used independently and customized to local needs [40].

MIKE SHE includes a traditional 2D or 3D finite-difference groundwater model, which is very similar to MODFLOW. MIKE SHE's overland-flow component includes a 2D finite difference diffusive wave approach using the same 2D mesh as the groundwater component. Overland flow interacts with the river, the unsaturated zone, and saturated groundwater zone.

MIKE SHE's river modeling component is the MIKE 11 modeling system for river hydraulics. MIKE 11 is a dynamic, 1-D modeling tool for the design, management and operation of river and channel systems. MIKE 11 supports any level of complexity and offers simulation engines that covers the entire range from simple Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations. MIKE 11 is the most widely used hydraulic modeling system in the world [41].

MIKE 11 provides for hydraulic analysis/design of structures including bridges, as well as optimization of river and reservoir operations. A wide range of structures can be represented with native computational methods and user defined functions. The structures are included in the MIKE 11 hydrodynamic module (HD), which provides computational formulations applicable to flow over a variety of structures that include:

- Broad-crested weirs
- Culverts
- Bridges
- Pumps
- Regulating structures
- Control structures
- Dam-break structures
- User-defined structures
- Tabulated structures

Further, operational control strategies for a number of different standard structures are included in the structure operation (SO) module for the following structures:

- Sluice gates
- Overflow gates
- Radial gates
- Pumps
- Reservoir releases

Control strategies for gate operations can be defined in the following ways:

1. A direct determination of the gate operation by description of the gate level as a function of time or as a function of hydraulic or species concentration variables at specified locations inside the model area.
2. The gate is determined by PID operation. The set-point for this can be chosen on the basis of hydraulic variables and concentrations within the model area.

3. An iterative determination of the gate level. With this approach iteration is performed on the gate level until a requested set-point value is obtained. This facility is ideal for flood control purposes.

The functional representation of the control strategy can be specified by rating curves, a binary decision tree which selects alternative strategies, or by user- defined functions developed in the Pascal programming language and compiled into a dynamic load library (DLL).

6.3 EPA SWMM

The EPA Storm Water Management Model (SWMM) [42] is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM also contains a flexible set of hydraulic modeling capabilities used to route runoff and external inflows through the drainage system network of pipes, channels, storage/treatment units and diversion structures. These include the ability to apply user-defined dynamic control rules to simulate the operation of pumps, flow dividers, orifice openings, and weir crest levels. The SWMM model allows the user to specify control functions based on a user specified set of rules, where the rules are decomposed into condition-action components. The conditions evaluate to boolean expressions composed from an if-and-or syntax. The correspondingly selected actions are specified in terms of then-else constructs, with optional priority fields assigned to each potential action.

6.4 HEC HMS-RAS-RESSIM

The Hydrologic Engineering Center (HEC) [43] Hydrologic Modeling System (HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. Several hydraulic structures can be modeled including bridges, culverts, weirs or other hydraulic control structures. Hydraulic structures are simulated by user specified discharge rating curves or rating tables assigned to either channel or floodplain elements. Culvert flow can occur between grid elements that are not contiguous. Reference elevations for headwater depth and tailwater effects can be considered.

A variety of hydrologic routing methods are included for simulating flow in open channels. Routing with no attenuation can be modeled with the lag method. The traditional Muskingum method is also included. The modified Puls method can be used to model a reach as a series of cascading, level pools with a user-specified storage-outflow relationship. Channels with trapezoidal, rectangular, triangular, or circular cross sections can be modeled with the kinematic wave or Muskingum-Cunge method. Channels with overbank areas can be modeled with the Muskingum-Cunge method and an 8-point cross section.

The HEC River Analysis System (HEC-RAS) is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regimes water surface profiles. The effects of various structures such as bridges, culverts, weirs, pump stations, navigation dams, and culvert flap gates may be considered in the computations.

Special features of the steady flow component include:

- multiple plan analyses
- multiple profile computations
- multiple bridge and/or culvert opening analyses
- split flow optimization

The HEC-RAS modeling system is also capable of simulating one-dimensional unsteady flow through a full network of open channels. The unsteady flow equation solver was adapted from Dr., Robert L. Barkau's UNET model [44].

The HEC Reservoir System Simulation program, HEC-ResSim is dedigned for reservoir operation modeling at one or more reservoirs for a variety of operational goals and constraints. A network of rivers and streams, called a stream alignment, is created in the watershed setup module, This stream alignment is used as a back bone on which the reservoir network schematic is developed. The network schematic elements include reservoirs, routing reaches, diversions, and junctions. The reservoirs are complex elements that are made up of the pool, the dam, and one or more outlets.

The criteria for reservoir release decisions is called an operation set which is made up of a set of discrete zones and rules. The zones divide the pool by elevation and contain a set of rules that describe the goals and constraints that should be followed when the reservoir's pool elevation is within the zone.

6.5 NWS FLDWAV

The U.S. National Weather Service Flood Wave (FLDWAV) program [45] is a generalized flood routing program capable of modeling single stream or a an interconnected system of flow channels. A four-point finite-difference approximation of the one-dimensional St. Venant equations is the basis of the formulation. Boundary conditions include dams, bridges, weirs and other common flow controls. FLDWAV can model time-dependent gate controls, and has the ability to read generic rating curves applied to control structures. The model incorporates equations for spillway flows, bridge and embankment effects, tidal flap gates, dams, tributary inflows, river sinuosity, and tidal effects. The user may specify multiple routing techniques (dynamic-implicit/ explicit, diffusion, level-pool) throughout the stream system.

6.6 FLO-2D

FLO-2D [46] is a dynamic flood routing model that simulates channel flow, overland unconfined flow and street flow. It predicts the progression of a flood hydrograph over a system of square grid elements while conserving volume. The model uses the full dynamic wave momentum equation and a central finite difference routing scheme to distribute the flow. The potential flow surface topography is represented in a FLO-2D simulation by a square grid format.

The model has number of components that enhance flood routing detail including channel-floodplain discharge exchange, loss of storage due to buildings, flow obstructions, rill and gully flow, street flow, hydraulic structure controls, levee and levee failure, mud and debris flow, sediment transport, rainfall and infiltration. Hydraulic structures can represent bridges, culverts, weirs or other control structures. Structures are simulated by user specified discharge rating curves or rating tables assigned to either channel or floodplain elements. Culvert flow can occur between grid elements that are not contiguous. Reference elevations for headwater depth and tailwater effects can be considered.

6.7 FEQ

The Full Equations model (FEQ) [47] simulates flow in a stream system by solving the full, dynamic equations of motion for one-dimensional unsteady flow in open channels and through control structures. FEQ stream systems are subdivided into three broad classes of flow paths:

1. stream reaches (branches)
2. stream segments for which complete information on flow and depth are not required (dummy branches)
3. level-pool reservoirs

These components are connected by special features or hydraulic control structures, such as junctions, bridges, culverts, dams, waterfalls, spillways, weirs, side weirs, pumps, and others. The hydraulic characteristics of channel cross sections and special features are stored in function tables calculated by the companion program FEQUTL. The FEQ model uses keyword and format-specific input files.

7 Appendix B: List of Acronyms

AMPL - A Modeling Language for Mathematical Programming
ANN - Artificial Neural Network
API - Application Programming Interface
DHI - Danish Hydraulic Institute Water & Environment
EPA - United States Environmental Protection Agency
FCL - Fuzzy Control Language
FLDWAV - Flood Wave
FLO-2D - FLO-2D Software
FEQ - Full Equations model
GLPK - GNU Linear Programming Kit
GNU - GNU's not Unix
GW - Ground Water
HEC - Hydrologic Engineering Center
HSE - Hydrologic Simulation Engine
HMS - Hydrologic Modeling System
LP - Linear Programming
MODFLOW - Modular finite-difference ground-water flow model
MODBRANCH - Coupled MODFLOW & BRANCH model
MIKE - Anecdotally attributed to Michael B. Abbott [48]
MIP - Mixed Integer Programming
MSE - Management Simulation Engine
NWS - United States National Weather Service
ORM - Object Routing Model
RSM - Regional Simulation Model
RAS - River Analysis System
RESSIM - Reservoir System Simulation
SF - Stream Flow
SFWMD - South Florida Water Management District
SFWMM - South Florida Water Management Model
SHE - Systeme Hydrologique Europeen
SW - Surface Water
SWMM - Storm Water Management Model
USGS - United States Geological Survey
WCA - Water Conservation Area
WCU - Water Control Unit
XML - Extensible Markup Language