Peer Review of the Regional Simulation Model (RSM)

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Intersection of Urban Area and the Everglades, looking west from Central Broward County
Source: D.A. Chin

Submitted to

Office of Modeling
South Florida Water Management District
West Palm Beach, Florida

23 September 2005

Executive Summary

The South Florida Water Management District (SFWMD) is developing a new model to simulate regional water movement in South Florida. This model, called the Regional Simulation Model (RSM), is a significant improvement over the currently used South Florida Water Management Model (SFWMM). Key advancements include more efficient computational algorithms, better spatial resolution using irregular triangular cells instead of a regular square grid mesh, more transparency to client users, and an object-oriented programming approach that provides greater flexibility for further model development. There is currently no commercially available model that has all the features planned for the RSM, and this model should be ideally suited for regional simulation of water movement in the mixed agricultural, urban, and natural environment of South Florida. The RSM is capable of simulating a wide variety of hydrologic, hydraulic, and water-resource processes and applying the complex set of operational rules and conditions that are unique to water management in South Florida.

After reviewing the RSM model documentation, supporting references, and the SFWMD responses to a draft of this report, several recommendations for further improvement of the RSM are made in this final report. These recommendations address aspects of the RSM formulation that need to be reassessed, concerns regarding the applicability of the diffusion-wave model formulation in some parts of the water-management system (particularly in coastal areas and canals), suggested improvements in the numerical solution technique, and concerns about the formulation and validity of some hydrologic process modules. There is a particularly urgent need to validate the RSM in South Florida and include results of pending validation studies in the model documentation. As application of the model in South Florida develops, it is anticipated that inefficiency of the numerical-solution algorithms will become a major issue, giving development of more robust solution methods a heightened priority. Coupled application of the management simulation engine (MSE) to the Hydrologic Simulation Engine (HSE) appears very promising but will need to be demonstrated.

Model documentation in its current draft form needs significant improvement in organization and content, particularly in describing model assumptions, numerical solution procedures, model-calibration methods, control of numerical errors, and model-validation techniques and results. Panel discussions with SFWMD staff indicate that a plan has been developed to improve the array of overview materials, technical reference papers, user manuals, implementation application reports, and background material an better organize them into a cohesive RSM Documentation Set. The improved documentation will greatly help to highlight current features of the model and its suitability for application in South Florida.

The SFWMD is proceeding towards the development of a state-of-the-art regional water-management model that will address the needs of its clients adequately. This peer-review component provides an important quality-control step in the development of the RSM. The SFWMD is to be commended for including this formative review in the RSM development process and for responding to the questions raised during the review.

1. Introduction

Both surface water and ground water significantly influence the hydrology of South Florida. Any applicable regional-scale model must be capable of conjunctively simulating both of these hydrologic elements and their interactions. The surface-water component must account for stormwater-management systems in urban areas, crop-management and irrigation practices in agricultural areas, natural hydrologic processes in overland-flow areas, ground-water recharge or discharge, and open-channel flow in the extensive canal network. Performance curves and operational rules for canal hydraulic structures also must be considered. The ground-water component of any regional-scale hydrologic model necessarily must simulate the shallow water table that frequently rises above ground level, highly permeable aquifers, withdrawals for water supply, and seepage into and out of surface waters.

The South Florida Water Management District (SFWMD) has developed the Regional Simulation Model (RSM) to simulate the behavior of the water-management system in South Florida. The RSM is a generic regional-scale model particularly suited for simulation of the managed flow conditions in South Florida. The RSM simulates surface-water and ground-water hydrology, interaction between surface water and ground water, flow regulation at hydraulic structures, canal hydraulics, and management of the connected system. The RSM has two principal components, the Hydrologic Simulation Engine (HSE) and the Management Simulation Engine (MSE). The HSE simulates the natural hydrology, water-control features, water-conveyance systems, and water-storage systems. The MSE component is designed to use the hydrologic-state information generated by the HSE to simulate a variety of water-management options, including those presently being used and others planned for future implementation. The MSE is capable of identifying optimal water-management protocols for meeting various water-allocation and hydrologic-state objectives.

Within the HSE, hydrologic process modules (HPMs) resolve the local surface-water hydrology for each cell (or group of cells) in an irregular mesh that covers the entire model domain. Each HPM is unique to a particular type of area; HPMs have been developed for agricultural, urban, and natural systems. The inclusion of HPMs in the RSM accounts for small-scale hydrologic processes and land-use heterogeneity, without having to use an extremely fine mesh in the regional model that would make computations impractical.

The RSM is a significant improvement over the regional-scale water-management model (SFWMM) currently used by the SFWMD. Computational features of the RSM that make this model different from the SFWMM are: inclusion of object-oriented design concepts; new and more efficient computational approaches; utilization of the latest programming languages, Geographic Information Systems (GIS), and databases; improved spatial resolution using triangular instead of square grid cells; and minimization of hard-coding of hydrologic elements unique to South Florida. Compared to the SFWMM, the RSM is more complex but designed to be more understandable and transparent to users, easier to learn, and more amenable to the development of additional hydrologic modules by client users.

A review of the RSM development is provided in this report. The eight goals of this review were to: (1) assess the scientific soundness of the model; (2) assess the conceptual framework of the model; (3) identify appropriate use of the model; (4) make suggestions for modifications and improvements to the model; (5) assess the model documentation; (6) suggest validation tests for the model; (7) suggest validation tests for the HPMs in the model; and (8) assess the suitability of the model for meeting client goals. This report provides a detailed assessment of the RSM, with each review goal addressed in a separate section.

The assessment described in this report is based on model and support documentation provided to the peer-review panel prior to 22 June 2005, an interactive workshop with SFWMD staff and RSM developers in West Palm Beach on 22-23 June 2005, a helicopter and airboat tour of the SFRSM area, and follow-up correspondence between the model developers, SFWMD staff, and the peer-review panel until 23 September 2005. Draft version 1.3 of this review report was submitted to the SFWMD on 15 July 2005. The SFWMD subsequently reviewed the draft report and provided a response to the Panel on 19 August 2005. The SFWMD staff is to be commended for their thorough and forthright consideration and assessment of Panel recommendations in the draft review report. The Panel evaluated the Draft District Response Document and revised their draft review report to produce this final version. This final report, submitted to the SFWMD on 23 September 2005, reflects responses to Panel questions raised at the interactive workshop and responses to Panel recommendations contained in the Draft District Response Document. This peer-review report is intended to provide formative input to assist the SFWMD in development of the RSM. The comments in this report do not necessarily apply to later versions of the model, documentation, and subsequent applications.

2. Scientific Soundness of Model Approach

The goal of this section is to assess whether proper and sound scientific approaches were used in the development of the RSM, and to verify that there is a self-correcting open process in place for continued assessment of scientific development.

2.1 General

It was difficult to assess conclusively the scientific soundness of the RSM from the vast amount of information provided by the SFWMD. The draft documentation, referred to as the Theory Manual, did not present a complete cohesive description of the model. The current draft of the model documentation does not provide adequate coverage of the equations solved by the model and the numerical techniques used to obtain their solutions. The descriptions of validation examples for the current version of the RSM were insufficient. However, a significant amount of supporting information in the form of journal articles, unpublished papers, online documents, and written responses to both pre-workshop peer-review comments and a draft of this report were provided to the Panel. Based on this information, the Panel has attempted to assess the scientific soundness of the model.

The excellent proposal by the SFWMD to add a figure illustrating the RSM Documentation Set to the inside front cover of all RSM-related documents should help apprise potential client users of all available references and direct users to the correct information source for insight beyond that provided in the Theory Manual. An integrated illustration that identifies the array of published journal papers, unpublished "white" papers, and electronic documents describing the conceptual development, formulation, and use of the RSM will better serve the SFWMD in representing the model formulation to the South Florida scientific community and client users. The interim draft status of the RSM Theory Manual provided to the Panel and the variety of separate reference documents spanning the multi-year model development period, identified for use by the Panel, presented unnecessary review distractions and complications, making it difficult for the Panel to readily assess the model formulation and determine the precise model status. Potential client users likely would suffer the same frustrations given the identical draft of the Theory Manual and collection of RSM reference documents. These shortcomings of the RSM documentation should be corrected upon implementation of both the Panel recommendations for improving the Theory Manual, presented below in the Documentation section and the SFWMD action plan to compile, revise, and illustrate the full RSM Documentation Set. A major improvement in the quality of the RSM Theory Manual will be achieved upon removal of the six journal and white papers reproduced in Appendix C, with pertinent content incorporated directly into appropriate chapters and linked together in the Theory Manual.

2.2 Basic Equations and Formulation

The ground-water component of the RSM assumes that the subsurface geology is isotropic. The validity of this assumption throughout the model domain in all applications of the model is questionable. For example, secondary solution cavities certainly will be oriented in the direction of historical flows, leading to anisotropic hydraulic conductivities and transmissivities. It is recognized that the assumption of isotropy is usually necessary due to lack of data, and might be a reasonable assumption in many applications of the model. However, if anisotropy cannot be incorporated into the model, then the validity and limitations of assuming isotropy should be stated clearly in the Theory Manual. The SFWMD modelers are aware of the potential limitations of assuming isotropic properties and plan to explore the inclusion of anisotropy in a future version of RSM.

The canal seepage watermover is based on the following linear relationship between seepage rate per unit length of the canal, q_l, and the difference between the water-surface elevation in a canal, H_i, and the water table elevation adjacent to the canal, H_m (Equation 2.40 in the Theory Manual):

$$q_l = \frac{k_m p}{\delta}(H_i - H_m)$$

where k_m is the sediment-layer conductivity, p is the perimeter of the canal, and δ is the sediment-layer thickness. This equation is applicable for describing canal seepage only where a sediment layer exists, and only in the case of a very fine grid will the adjacent grid cell provide a reasonable estimate of H_m. In most canals in South Florida, a sediment layer does not exist on the sides of the canal and this is where most of the seepage occurs. In such cases, canal seepage in numerical models is best estimated using a reach transmissivity (Chin, 1991). In the reach transmissivity formulation, canal seepage, q_l, is expressed in the form

$$q_l = \Gamma(H_i - H_m)$$

where Γ is the reach transmissivity, H_i is the water-surface elevation in the canal segment, and H_m is the water-table elevation in the adjacent grid cell. Since the reach transmissivity, Γ, is a function of where H_m is measured, then Γ necessarily must be a function of the grid size.

Coupling of overland and ground-water flow in the RSM currently assumes continuity of head for the overland and ground-water domains, since there is only one head value computed for each waterbody. Other approaches exist to couple surface and subsurface flow, for example by assuming that the head in the overland and subsurface-flow domains can be different in a single finite-difference cell (which is the analogue of a waterbody in the RSM). In that case, the overland and ground-water domains are linked by a fluid-flow term, similar to that currently used in the RSM to link a canal and a cell (see Equation 2.40 of the Theory Manual). The SFWMD modelers could explore the need for modifying the RSM to use this other coupling approach. Coupling the overland and ground-water domains with this linking term, and computing two different head values, can produce simulations in which the overland domain is recharging the ground-water domain, ground water recharges the overland domain, or where there is ponding of surface water on top of an unsaturated zone. The documentation does not provide evidence that such exchange of flow between domains can be as readily simulated with the current head continuity assumption in the RSM. Discussions with the SFWMD modelers indicate that HPMs could be used to allow the simulation of ponding conditions, but that capability has not been demonstrated. Another potential advantage of solving for two head values per waterbody is that different time steps could be used to solve the overland and ground-water flow equations, if needed.

The SFWMD states that part of the reason overland and ground-water head discontinuity was not considered in the RSM development was to maintain compatibility with the previous application of the SFWMM. Progress in RSM development and the SFRSM application appears to be hampered by the constraint to maintain SFWMM compatibility. Moreover, the justification presented in the SFWMD response to Panel concerns about the continuity of overland and ground-water head assumption seems to overemphasize the need for improved computational speed potentially at the expense of RSM generic utility and/or proper replication of potential head differences in the SFRSM application.

The RSM Theory Manual does not discuss explicitly how the RSM accounts for conservation of momentum in the transition between surface and subsurface flow. For example, this should be analyzed in cases where one cell has overland flow and an adjacent cell does not, how is the conservation of momentum considered? The panel understands that there is an option to provide a plot of the transmissivity and the conveyance with water level as input to the RSM. However, the need for such input and its implications should be clarified in the Theory Manual.

Many of the watermovers in the Hydrologic Simulation Engine (HSE) are formulated in terms of the Manning equation, which strictly is applicable only to fully developed turbulent flow. In some cases in the HSE, the Manning equation likely will be used to describe overland flows that are either mixed turbulent-laminar or laminar. In practice, the term "effective roughness parameter for overland flow" is often used, and N is substituted for n to indicate that the flow is not fully turbulent. Since many of the potential overland-flow applications of the model are not fully turbulent flow, it is recommended that N be used instead of n. The SFWMD agrees to adopt the Panel recommended terminology and variable notation.

In the formulation of the linear form of Manning's equation, the square root of the energy slope is moved inside the denominator of the matrix coefficient and a minimum value of this slope is required to prevent numerical instabilities. The Panel understands this and agrees that it is a reasonable approach. However, there is concern about the wide range of values for this minimum, which ranges from 10^{-7} to 10^{-13}. This artifact of the linearization process requires an expanded explanation of why that range was chosen and the practical implications of this restriction.

2.3 Diffusion-Wave Approximation

Local and convective acceleration (inertia) terms are neglected in watermover equations that simulate overland and canal flow. These watermovers use a special type of diffusion-wave approach where the volume flux is proportional to the head gradient. Omission of the local acceleration term limits RSM to the simulation of slowly varying transients, and neglecting the convective acceleration term limits the ability of RSM to simulate spatial variability in flow conveyance accurately. The diffusion-wave approach is suited for overland flow in steep to mild slopes, making it compatible for use in most inland flow systems and water bodies in South Florida under most conditions. Exceptions arise where and when inertial effects are significant. Flows in coastal areas influenced by tides cannot be simulated by the diffusion-wave approximation, due to the importance of the local and convective acceleration terms. The Panel recognizes that tides are limited to coastal zones and the time step of one day currently used in the RSM is incompatible with treating tidal stresses. The panel further recognizes that there is a natural check against using diffusion-flow models (such as the RSM) under dynamic conditions where the model is not applicable, since such applications tend to become unstable when the diffusion-wave approximation is violated. Inertial effects in flows through structures also could be significant, depending on the structure-discharge rate, the converging and diverging channel geometry at the structure, and the nonlinear behavior of the structure. This condition is of less concern when inertial effects at structures are incorporated in structure flow equations and in cases where local high-flow velocities have limited effects on regional flows.

The diffusion-wave applicability criteria used in the RSM (Ponce et al., 1978) should be qualified as an extension from one-dimensional to two-dimensional flow. Although the convective and diffusive properties of one-dimensional surface flow are well known, the same is not true for two-dimensional surface flows. For instance, how the diffusivity in one dimension (Ponce, 1989) is resolved in two dimensions is uncertain.

In one-dimensional canal flow, the use of lookup tables in the RSM renders the simulation kinematic and, therefore, not subject to physical diffusion. Any hydrograph diffusion manifested in the simulation would necessarily be a function of grid size (Cunge, 1969). Therefore, an assessment should be made of how the use of lookup tables is reconciled with the diffusion-wave assumption, which has built-in physical diffusion through hysteresis in the rating. This is not likely to be an issue for South Florida applications of the RSM, where the SFWMD does not plan to implement the lookup-table option.

In summary, adopting the diffusion-wave approach for RSM development imposes some limitations on the use of RSM in South Florida. However, this concern must be balanced with experience, which suggests that the diffusion-wave assumption is reasonable for simulating regional overland flows in South Florida under most conditions. Nonetheless, potential client users must be cautioned about limitations of the RSM stemming from the diffusion-wave approximation. The RSM model developers agree with the Panel recommendation to caution potential client users about diffusion-wave assumptions, and the Panel welcomes their proposal to state these clearly under RSM Limitations and Assumptions in the RSM documentation.

2.4 Numerical Methods

The solution of all watermover and waterbody equations in the HSE is integrated into one global matrix as opposed to sub-matrix solutions coupled by boundary fluxes. According to the SFWMD modelers, the Petsc matrix solver used in the model is very efficient in solving the global matrix for current applications. Although it does not appear to be the case currently for regional simulations in South Florida, there is concern that this approach could cause the model to grow too numerically intensive as the mesh size is refined or the size and complexity of the model domain increases. The diagonal dominance of the global matrix likely will be diminished as the number of canal segments increases and a greater number of sophisticated water-control structures are added, potentially requiring an increased number of iterations for convergence. Sixty percent of the processing time in the RSM application to South Florida (SFRSM) is expended in matrix inversion and 40-60 iterations are required for convergence. The numerically intensive computational performance of the SFRSM, which is still under development, appears excessive and is likely a symptom of increasing system complexity and/or linear assumptions made in the RSM. Typically, the factors that increase the computational run times of numerical models are the nonlinear terms, which are not included in the diffusion-wave approximation of the RSM. The SFWMD model developers respond that a global solution requires a very good sparse matrix solver, such as the Petsc solver presently used, and that HPMs are designed to deal with some of the complexities and nonlinearities in the system. The developers indicate that other approaches for dealing with nonlinearities are under consideration, including HSE iterations. The SFWMD action plan also calls for the development of implementation strategies. The Panel views these proposed actions as vital to addressing the numerical solution run-time issue.

The use of an implicit versus explicit numerical solution scheme is a tradeoff that needs to be assessed judiciously. Implicit schemes ($0 < \alpha \leq 1$) are usually unconditionally stable, whereas explicit schemes ($\alpha = 0$) are not. Therefore, if stability is an issue, an implicit scheme is preferred. However, in numerical modeling, stability is usually achieved at the expense of convergence (O'Brien et al., 1950). Once the focus shifts from stability to convergence, an explicit scheme can compete effectively with an implicit scheme. An explicit scheme usually will achieve convergence at the same time as stability, whereas an implicit scheme might be stable throughout a wide range of grid resolutions, while remaining nonconvergent for some subrange. Therefore, it should not be assumed a priori that implicit schemes are altogether better than explicit schemes. The objective in the RSM numerical solution technique should be to seek a balance between stability and convergence, and not to pursue one at the expense of the other. This balance should be obtained through the simultaneous minimization of round-off and truncation errors (O'Brien et al., 1950). The use of a fully-implicit model ($\alpha = 1$) as the default case for numerical solution is justified only when results of sensitivity analysis clearly show improved stability without undue sacrifice of convergence. This problem is not unique to the RSM, and can be found in other widely-used models such as MODFLOW. It is recommended that the tradeoffs between the use of $\alpha = 1$ and that of more convergent values ($\alpha < 1$) continue to be investigated and reported by the RSM developers.

The Panel acknowledges and recognizes that Manning's n and α values are not fixed in the RSM code, which is the typical approach used in model design and development. Considerable open discussion occurred in the Interactive Workshop held 22-23 June 2005 during which appropriate and reasonable Manning's n values were suggested for wetland sheet-flow conditions in South Florida (refer to Meeting Notes of 2:34 PM June 23, 2005). Interactive Workshop discussion also occurred on the topic of the α weighting factor and its affects on simulation behavior (refer to Meeting Notes of 1:54 PM June 22 and 4:47 PM June 23, 2005), during which time sensitivity testing with the α factor was recommended by the Panel. The Panel did not imply that SFWMD model developers used Manning's $n = 1$ and a weighting factor of $\alpha = 1$ to hide numerical instabilities in the model as suggested in the Draft District Response Document. The greater energy dissipation effects of large resistance values and the wave suppression effects of weighting factors approaching a value of one are well known in engineering practice, as acknowledged in the Draft District Response Document. The Panel's recommendation to the SFWMD model developers was that sensitivity testing on both conditions be conducted so that effects on model results could be investigated, demonstrated, and reported for the benefit of potential client users. Moreover, the observation made in the SFWMD's response summary that structure nonlinear equations are more likely the cause of numerical instabilities than overland flow equations should be discussed and illustrated in the RSM documentation. In the Draft District Response Document, contradictory comments are made regarding the issue of α in controlling stability. One comment indicates that an increase in α had limited success in controlling instability or oscillations as more complicated nonlinear equations were added because the diffusion flux terms were not the source of the instability, while another comment states that the α value was left at almost 1.0 to keep the model non-oscillatory. Some discussion, explanation, and clarification about this are needed in the RSM documentation.

There should be an option in the model to evaluate waterbody mass-balance matrices with updated H values, which does not appear to be possible in the current version of the RSM. As described in Equation 2.47 of the Theory Manual, it appears that matrices A and M on the left-hand side of the equation are evaluated with previous head values at time n, rather than updated values at time n+1. The latter approach has the potential to introduce numerical difficulties in the simulation when the MSE is coupled to the HSE. Undocumented analyses conducted by the RSM developers indicate that the error generated by the use of previous head values was smaller than the discretization error. Their proposed action plan calls for revisiting this issue when addressing rapidly varying diffusion flows and dynamic flows.

2.5 Hydrologic Process Modules

The panel is satisfied that the runoff curve number method is being used in a continuous-simulation mode by adjusting the value of maximum potential retention (S) based on the available soil-moisture storage. While the method's developers did not intend it to be used outside of event modeling (see http://mockus.sdsu.edu), it is correct to state that the method has been extended, by default and by practice, to the continuous simulation arena. The key is to do it carefully and transparently.

The <agimp> module uses the V-notch weir equation to calculate the angle of the V-notch weir to be used in the compound-weir equation. The module should place limitations on the calculated notch angle, since the assumed relationship is not valid for all angles and heads and some weir angles might not be practical. In cases where an impractical V-notch weir is selected by the <agimp> module, a circular orifice might be a better selection. The Panel understands that the SFWMD plans to modify the <agimp> module to check impoundment discharges and select the appropriate discharge structure.

The <unsat> module assumes that evapotranspiration (ET) is zero when the water depth is greater than the root depth (Equation 13). This formulation is questionable since it has been demonstrated that evaporation can still be significant well below the root depth (Chin and Patterson, 2005).

3. Conceptual Framework

The goal of this section is to assess whether the conceptual framework of the model contains all of the important hydrological processes necessary to do regional-scale modeling in South Florida.

In most regional-scale models, it is commonplace for the potential evapotranspiration (PET) to be calculated based on climatic input such as maximum and minimum temperature. The SFWMD should consider incorporating the calculation of PET into the RSM, rather than specifying it as input data, especially since there are fairly simple relationships currently in use to estimate PET. PET might vary temporally in a long-term model application, particularly as land-use changes and ecosystem-restoration practices are implemented. Furthermore, the inclusion of PET calculations in the model would allow the simulation of climate-variability scenarios. If historical PET estimates were derived using different methodologies than those incorporated in the RSM, then it would be appropriate to include the historical PETs as input. In addition, if computation of PET within the model significantly increases the run time or it is desirable to apply a fixed PET to several models, then calculation of the PET outside of the RSM would be justified. The Panel concurs with the SFWMD response to consider PET calculation inside the model as a future enhancement.

The Management Simulation Engine (MSE) is essential for developing management protocols for the complex operations of the main hydraulic structures in South Florida. This well-documented component of the RSM is designed to optimize operation of hydraulic structures to achieve some desired outcome. Given the constraint of a daily time step in the SFRSM implementation, it is problematic to translate the MSE-recommended daily-averaged operation of hydraulic structures to their sub-daily operation. The MSE is still under development and its effectiveness in achieving water-management objectives will need to be demonstrated. Operational features of the hydraulic structures could potentially be modified to incorporate the MSE algorithms, thereby producing a much more efficient water management system in South Florida.

The shear-stress effects of winds on surface flows are not accounted for in the RSM. Slowly varying flows are potentially subject to wind forcing that could cause setup, particularly in sparsely vegetated wetland sloughs, in lakes and reservoirs, and in canal segments between water-control structures. Given that wind forcing is not accounted for in reservoirs and lakes, this omission could be particularly problematic in the SFRSM implementation, as Lake Okeechobee is treated as a reservoir. Wind effects on Florida Bay are an important forcing mechanism, producing backwater effects along the coast. The present conceptual framework of the RSM excludes treatment of wind-stress forcing in all watermovers. The Panel recognizes that the effects of wind stress on regional-scale water surface elevations is likely to be small, and that the RSM provides the same wind stress functionality as the currently used model, the SFWMM. The SFWMD should remain open to including wind stress in the RSM if future experience indicates that such a refinement is necessary.

Conveyance in sloughs traversing overland-flow cells is not accounted for; sloughs are treated simply as surface depressions in the storage-volume relationship of the RSM. Representation of the ridge and slough wetland landscape needs to be factored into the mesh-generation and flow-simulation processes. Similarly, patchiness in vegetation density can lead to heterogeneity and anisotropy in conveyance. The SFWMD plans to conduct research into implementing transmissivity and conveyance as tensors or design detailed HPMs to capture resistance heterogeneity.

The RSM simulates hydrologic responses to a time-varying climate in a static physical system. Although this approach might adequately address a variety of water-management objectives at the present time, historical trends indicate that land use constantly changes as agricultural land is converted to urban use, marshes, or reservoirs. Such land-use changes should be accounted for in future versions of the RSM, in which case the following RSM capabilities would be desirable:

- The land-surface mesh configuration and definition in the HSE of RSM are dynamically adjustable to account for topographic and physical changes during the course of a simulation.

- Physical changes due to natural catastrophic events such as wetland fires and hurricanes are treated by dynamically varying the RSM mesh configuration and applicable parameters.

- Structure, levee, and canal configurations are dynamically adjustable during long-term simulations.

It is relevant to note that there have been a number of the above-mentioned physical changes to the system during the 1965-2000 simulation period.

The SFWMD plan to clarify the purpose and scope of the RSM in the Theory Manual and Fact Sheet should aid in representing the model's capabilities to the South Florida scientific community and client users. According to the Draft District Response Document, the RSM was originally envisioned to simulate hydrologic responses, e.g. changes in water levels and flows, in a static physical configuration, using a time-varying climatologic input (rainfall and ET) and to a limited extent, time-varying structure operating rules over a 36-year simulation period. The fact that the RSM is not a succession model, capable of incorporating dynamic changes in the physical configuration, is an important distinction to note in the Theory Manual and other RSM documentation as appropriate. Moreover, it might be appropriate to recognize that one of the primary purposes of the RSM in the SFRSM application is to conduct regional long-term scenario testing for hydrological and ecological assessment of restoration design and operational system modifications.

4. Use of Model in South Florida

The goal of this section is to identify appropriate use of the RSM in South Florida.

A calibrated and validated version of the RSM should be appropriate for simulating the current water-management system in South Florida. However, considerable work remains to be done at the SFWMD to successfully transition from the SFWMM to the SFRSM. A thoroughly calibrated and validated SFRSM should be more useful than the SFWMM in simulating various alternatives for restoration of the Everglades and for assessing water-supply and flood-control measures in South Florida. This increased utility is due to improved process and hydraulic-structure representations and increased spatial resolution. The success and validity of the RSM in South Florida (SFRSM) will need to be demonstrated in a subsequent peer review planned for 2006, upon full implementation of the SFRSM.

For canals of nearly zero bed slopes, such as those in South Florida, the only way to induce flow is to force a depth gradient mechanically, which might incorporate some inertia. This flow is unsteady, and the Manning equation is not able to account for the unsteadiness and associated convection and diffusion properties of such a wave. There is an urgent need for a theoretical analysis to identify the convective and diffusive properties of such waves and to build the canal model on these premises. Barring this analysis, an alternative is to implement full dynamic-wave modeling in the canals with all the attendant nonlinearities, which will likely impose associated additional data requirements and numerical computations. The RSM model developers propose additional benchmark and field tests to determine if full dynamic-wave capability might become necessary to implement.

The computational domain of the RSM in the SFRSM application includes the tidally dominated mangrove ecotone along the southwest Gulf coast between Cape Sable and Ten Thousand Islands. Use of the RSM in coastal areas is not justified within the context of the diffusion-wave assumption, and the computational domain of the SFRSM should not be publicized as including the tidal transition zone. The SFWMD response to the Panel's objection to inclusion of the coastal mangrove ecotone in the SFRSM domain identified two options for treatment of the boundary interface between overland flow with the tidal transition zone. The two options were to either terminate the SFRSM domain at the boundary interface, which would require development of a suitable boundary condition at the interface, or to extend the SFRSM domain through the tidal transition zone, which requires determination of a suitable boundary condition at the coastline. The option chosen was the extension of the SFRSM domain to include the tidal transition zone. In this approach, erroneous model results in the tidal transition zone must not be published and presentations illustrating the SFRSM domain should not include the mangrove ecotone, as agreed in the Draft District Response Document.

The approach used by the SFWMD to develop the coastal boundary condition in the SFRSM application is unknown and undocumented. One approach to developing the coastal boundary condition could be to subtract tides from a local (NOAA or other) long-term tidal record using either a tidal decomposition technique or a simpler 24-hour running average filter. Whatever approach is used in the SFRSM application to accommodate flow computation up to the overland/tidal boundary interface should be thoroughly documented and restrictions on RSM use in tidal areas should be clearly identified in all model documentation.

5. Modifications and Improvements

The goal of this section is to suggest modifications and future improvements to the RSM, including suggestions for improved computational methods and future model-expansion ideas.

With such a large number of canals in South Florida, and given the long simulation period, both rainfall and ET should be included in the canal water balance. This is simple to implement, and it should improve model accuracy slightly. The necessity of implementing rainfall and ET in the canal water balance certainly increases as the model domain size decreases yielding increased resolution. This is likely in future applications of the generic RSM.

If an objective of the RSM is to simulate the extent of surface flooding, consideration should be given to using a GIS model component to improve spatial resolution of the distribution of water on the land surface. The water-surface elevation calculated for each cell by the RSM could be combined with more detailed sub-cell GIS land-surface elevation coverage to refine estimates of the spatial extent of flooding.

The RSM solves all equations for regional flow simultaneously. The formulation of the surface-water, ground-water, and canal-flow equations into a coupled-matrix solution forces the simulation to be conducted at a unique time step for all waterbodies within the system. Ideally, flow conditions in the most dynamic waterbody should govern the choice of time step. Otherwise, unnecessary flow computations might be carried out for other waterbodies. For instance, ground-water flow solutions are typically required much less frequently (daily stress periods) than surface-water flow solutions (hourly or smaller time steps). Given that reduced computational run time is a high priority issue for RSM development, decoupling the ground-water and surface-water solutions could be advantageous. The RSM model developers assert that, at present, the use of an efficient sparse matrix solver diminishes the impact of excessive computations associated with using a common time step for the overland and ground-water flow equations. However, RSM model developers note that decoupling techniques might be considered should excessive computation times become an issue in the future.

Consideration should be given to making the time step dynamically variable. It is more computationally efficient and accurate to adjust the simulation time step dynamically to closely match the flow conditions. For example, it might make sense to use longer time steps ($\Delta t > 24$ hours) in dry seasons and shorter time steps in wet seasons ($\Delta t < 24$ hours) and during periods of extreme weather, flow, and control events. During the Interactive Workshop, SFWMD model developers stated that dynamic time stepping was used in the RSM before a recent change in the matrix solver. The model developers indicated that dynamic time stepping might need to be re-implemented (refer to Meeting Notes of 5:13 PM June 22, 2005).

Other numerical enhancements to be considered for future development of the RSM include sub-timing and domain decomposition. Sub-timing has been described in Bhallamudi et al. (2003) for subsurface flow and transport simulation. The objective of sub-timing is, for a single global time step, to take smaller time steps for regions of the domain where flow processes are faster (say the surface) and larger time steps for slow flow regions (for example, the subsurface). Domain decomposition is also attractive for large-scale simulations of coupled surface and subsurface flows that potentially require very long simulation times. It consists of splitting the total flow domain into several pieces or sub-domains (sub-watersheds, for example), solving for flow in each sub-domain individually, and then iteratively linking all sub-domains.

Preliminary applications of the RSM in South Florida have focused primarily on two-dimensional ground-water flow. Intended future applications include more three-dimensional models, particularly in certain regions of the aquifer system. The U.S. Department of Defense Groundwater Modeling System (GMS) software http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=Software!1 is currently used to construct the triangular meshes for the ground-water component of the RSM. As three-dimensional components are constructed in the future, the subsurface characterization will become more challenging. There are new tools in version 6.0 of GMS (released in July 2005) that should work well with the RSM. These tools are associated with the GMS "Horizons" feature, which makes it possible to use user-defined and interpolated surfaces, in the form of triangulated irregular networks (TINs), to create three-dimensional representations of the complex geologic layering present in some parts of the aquifer system. In addition, Horizons includes tools for incorporation of boreholes and hand-sketched cross-sections between boreholes.

The very nature of South Florida and the complexity of the RSM make this application a classic example of a highly parameterized system. A new parameter-estimation algorithm called SVD-Assist (Single Value Decomposition – Assist) is available to work with highly parameterized systems. Applications of this algorithm have shown remarkable success. SVD-Assist is able to calibrate systems with thousands of parameters in a stable relatively quick fashion. The algorithm can be accessed in the most recent version of the parameter estimation utility PEST (http://www.sspa.com/pest/).

In calibrating the ground-water model, the hydraulic conductivity (K) array is broken into multiple polygons, resulting in abrupt discontinuities in the K values along the polygon boundaries. This method of dividing the K array into subsections seems arbitrary. This is a problem because the original interpolation for K values was performed across the entire model domain. If the RSM developers wish to use a zonal approach, they should first divide the area into polygons and then perform interpolation on a zone-by-zone basis, using only the K point data within each zone. At that step, the multipliers could be applied to zones without violating the integrity of the original interpolation. Another approach to consider is the "pilot point" method in which the modeler defines a series of points in the model area where the K values are allowed to vary during the parameter estimation process. An interpolation algorithm is used at each step to interpolate the K values in the remainder of the grid. Assuming the K values in an aquifer vary continuously, the pilot point method is a simple and convenient way to parameterize a model. If the purpose of the model zonation used by the RSM developers is simply to obtain a low residual rather than to represent specific geologic features, the pilot point method would seem appropriate. This method can be constrained within zones and therefore the interpolation of pilot points can be performed on a zone-by-zone basis during the parameter estimation process. The PEST parameter-estimation program provides a number of tools for performing pilot-point-based parameter estimation.

The eXtensible Model Data Format (XMDF) and Application Programming Interface (API) (http://www.wes.army.mil/ITL/XMDF/) could be used to replace the NetCDF portion of the RSM input/output file format. Based on current experience with XMDF, it is likely that this would result in much smaller file sizes than the currently used NetCDF data format. It would be easy to test this assertion by simply downloading the XMDF library and implementing some function calls in the RSM code. Sample source code is provided in the XMDF documentation.

6. Documentation

The goal of this section is to make suggestions about the model documentation, including whether the level of detail is sufficient, and whether the conceptual framework is clear.

6.1 Organization and Content

The primary documentation for the RSM model is the Theory Manual, which is currently organized into three sections: Introduction, HSE Theory and Concepts, and MSE Theory and Concepts. In addition to the Bibliography, there are three appendices: Appendix A: Regional Simulation Model Philosophy, Appendix B: Governing Equations Using the Traditional Approach, and Appendix C: Selected Publications for Further Reading. The panel recommends the following modifications to the layout of the Theory Manual:

- A “Purpose and Scope” section should be added to the documentation, wherein limitations and restrictions on use of the model, imposed by assumptions in the model formulation, are identified. Potential users should be advised of the types of analyses that can be appropriately conducted with the model and cautioned about inappropriate uses. The SFWMD acknowledges the need for a “Purpose and Scope” section and will incorporate one into the RSM Theory Manual.

- Descriptions of the HSE and HPM should be in separate chapters. The SFWMD agrees that the importance of HPMs warrants their treatment in a separate chapter rather than in an appendix. The discussion of HPMs in chapter 2 (HSE Theory and Concepts) of the Theory Manual will be limited to their conceptual framework and interaction with other HSE objects.

- Appendix A (Regional Simulation Model Philosophy), particularly A.2 (Scope of the RSM), should be included in Chapter 1 (Introduction). The SFWMD intends to remove this material entirely or retain it in Appendix A.

- Appendix B (Governing Equations Using the Traditional Approach) should be part of Chapter 2 (Hydrologic Simulation Engine Theory and Concepts). The SFWMD feels that discussion of the traditional approach is not vital and intends to remove it entirely or retain it only in Appendix B.

- Reference papers should be listed as references rather than reproduced in entirety in the Appendix. The Theory Manual suffers significantly by having technical papers describing critical aspects and concepts related to RSM development summarily attached as report appendices. Concepts vital to documenting the model formulation, guiding use of the model, and investigating potential numerical errors should be excerpted and incorporated directly into the Theory Manual for emphasis, continuity and clarity. The SFWMD agrees with Panel recommendation that refereed journal papers C.1, C.2, C.3, and C.4 should not be appendices in the Theory Manual, but that instead appropriate content should be incorporated into separate chapters in the manual.

  In naming the "References" section, it should be noted that there is a difference between "Bibliography" and "References." "Bibliography" is a list of published works that are related to the topic, but not necessarily quoted in the text. "References" is the list of published works that have been specifically referred to in the text. The Theory Manual would be expected to have only a list of references. If a bibliography is deemed necessary, it should be contained in a separate appendix. The SFWMD agrees that "Bibliography" should be changed to "References".

- The HPM white paper (Appendix C.5) should be assimilated into the main body of the Theory Manual as a separate chapter. According to Draft District Response Document, Appendix C.5 will be incorporated as a separate chapter in the Theory Manual.

- The MSE white paper (Appendix C.6) should be assimilated into the main body of the Theory Manual as a separate chapter. The SFWMD agrees with the Panel recommendation to incorporate Appendix C.6 into the Theory Manual as a separate chapter.

  In the MSE white paper, it should be noted that the models used for comparative analyses with the RSM were not developed with the same purpose and scope as the RSM. Most of the models listed in Tables 1 and 2 of the MSE white paper can be classified as hydrodynamic-simulation models rather than hydrologic-management models. Although these other models are capable of simulating all or part of the South Florida ecosystem, they might not be as efficient and easy to use for water management as the RSM since the main purpose for their development was quite different.

- Uniform document standards should be applied to all parts of the Theory Manual. This would include using the same word processor for all parts of the document. The LaTex typesetting program is clearly superior to other programs when used for large, high-technical-content documents such as the Theory Manual. The SFWMD intends to use uniform document standards in developing future versions of the Theory Manual and the document set supporting the RSM.

- A list of symbols with units of measure would significantly improve the Theory Manual. Defined variables could be limited to those used in equations. The SFWMD intends to add a list of symbols and variables used in the equations to the Theory Manual.

- Consistent terminology should be used throughout the Theory Manual and supporting documentation. A glossary would make the Theory Manual easier to understand and unambiguous. The SFWMD agrees to add a glossary and an index to the Theory Manual.

- A consistent set of units should be used throughout the Theory Manual, either "English units" (which should properly be called U.S. Customary units) or "metric units" (which should properly be called SI units). If both systems are used in the RSM, the Fact Sheet should state so. Both systems of units should be used if the model is going to be applied outside of South Florida. According to the SFWMD, "SI" and "U.S. Customary" units will be used throughout the documentation.

The Panel commends the SFWMD for developing plans to reorganize the Theory Manual in response to most of the above recommendations. Furthermore, the SFWMD has proposed a RSM document set that should provide adequate supporting information for users to understand the formulation and application of the model.

6.2 Hydrologic Process Modules

Many of the equations used as a basis for the HPMs are heuristic and have not been validated in the field. Although this does not rule out using these equations, the lack of validation and references to validation studies should be made clear in the documentation. In general, HPM validation experiments should be reported in the section where the basis of the HPM is described.

Many of the parameter values suggested for use in the HPMs are presented without references describing the contexts in which the parameters were derived. All tabular presentations of suggested parameter values should have a "References" column.

6.2.1 <unsat>

This HPM uses different equations depending on the elevation of the water table relative to ground surface. Whereas the equations appear to be reasonable approximations to reality, the documentation and assigned variable names indicate that “water depth” is being compared to “surface elevation”. Variable names and document terminology should be changed to differentiate between depth and elevation.

6.2.2 <layer5>

The symbols Θ_{cap} and Ew are both used to represent the extractable water in the soil column. To avoid confusion, one or the other variable should be used.

6.2.3 <prr>

The suggested values for the maximum infiltration rate, K_{0inf}, in Table 4 of the HPM white paper are off by at least an order of magnitude. The results of Chin and Patterson (2005) for Miami-Dade could be used as one reference for estimating this parameter.

Several parameters given as “typical values” in Table 4 of the HPM white paper depend on local conditions within individual cells; guidance should be provided for selecting these variables. Specifically, the variable Lmax depends on depth to the water table and soil type, and the variables CKOL, CKIF, and CKBF depend on local surface and subsurface conditions. Guidance in selecting these variables, preferably based on their functional relationship to other variables, should be presented in the documentation.

6.2.4 <pumpedditch>

The documentation states that a “throwout” pump can remove water from a farm at a rate as high as six inches per day. Expressing maximum pumping rates in terms of inches per day is questionable; m^3/s or cfs seems to be more appropriate. This doubt is reinforced in Table 6, where the pump rates for wsPump and fcPump are expressed in m^3/s.

6.2.5 <agimp>

The NRCS curve number method is given as a basis for calculating the runoff (Q) from the 25-year 3-day rainfall amount (r25y3d), with the available soil storage denoted by S. The documentation further states that S is determined from the soil series. In South Florida, S is sometimes taken to be a function of the depth to the water table, not a function of the soil series.

6.2.6 <mbrcell>

The documentation provides a range of values and a typical value for the time of concentration (3600 seconds, typically) and the water content at field capacity (20 cm, typically). Both of these values depend on local conditions and cell dimensions, and are best expressed as functional relationships. Specifically, the time of concentration could be given as a function of cell dimension and ground slope, and the water content at field capacity could be given as a function of the depth to the water table.

6.3 Need for Additional Materials

The current draft version of the Theory Manual asserts that a challenge in modeling complex hydrologic systems is to maintain an acceptable level of numerical error. However, no guidance is given on what is an acceptable level of numerical error and where to expect error in applying the RSM. In addition, there is no clear statement on the sources of numerical error in the RSM. Identification of suspicious numerical behavior and manifestations of numerical error in RSM simulations should be provided in the documentation. Any numerical errors specific to the RSM theory assumptions should be identified and their manifestations in model simulations should be discussed. Consolidation of error analyses stemming from the RSM conceptual formulation and development—presented in various papers by Lal (1998, 1998a, 2000)—into a single document on "Guidelines for Managing Numerical Error" as proposed by the SFWMD will be a highly beneficial contribution to the RSM Documentation Set. Error is common to all numerical models, model implementations, and simulation designs, to some extent. Presentation of guidelines for controlling model behavior and illustration of erroneous numerical artifacts should help alleviate mistakes in judgment by RSM users. A well crafted set of sensitivity analyses demonstrating the effects of parameter ranges on model results also can be beneficial in helping client users to minimize the potential for erroneous simulations. A single document or chapter specifically discussing model uncertainty and numerical error will represent a vast improvement to the RSM documentation.

All of the assumptions used to develop the RSM to simulate regional flow in South Florida should be clearly stated and justified. Model limitations that arise from neglect of the inertia terms, and the consequences of these limitations in operational water management and restoration planning, must be clearly identified and discussed. Since one motivation for developing the RSM is the absence of other models with similar capabilities, clearly stated model assumptions and limitations will facilitate comparative evaluations with other physically based, spatially distributed models. For example, MODHMS or MIKE-SHE can simulate variably saturated flow using Richard's equation, which is not currently planned for RSM.

Additional documentation is needed to describe the validation of the RSM. Currently available validation examples in South Florida should be described in sufficient detail to allow users of the RSM to reproduce the same results. Reproducing all documented examples builds model confidence and identifies any irregularities that might result from using different computer platforms. The documentation of validation examples also should be sufficient to allow users of other physically based, spatially distributed models to simulate these scenarios for comparative purposes and to build confidence in the RSM.

The numerical techniques used in the RSM need to be documented in significantly more detail. Specifically, it should be clearly stated how the different matrices are assembled for the waterbody mass-balance equation.

Since the RSM is generic and potentially useful in regions that are similar to South Florida, a description of the main hydrological features of South Florida would be helpful in the Theory Manual. Such a description should be supported by figures showing the main areas in South Florida (Lake Okeechobee, Everglades agricultural area, water conservation areas, Everglades National Park, and urban areas), the main canals and control structures, and a short description of the geology. References should be made to other documents that present more details about the system, to allow the interested reader to get more information without lengthening the Theory Manual. Unique characteristics of the South Florida area that are particularly relevant to the RSM and that could be described in the Theory Manual are: (1) the competing objectives for water use (flood control, water supply, water quality, and environmental protection); (2) the extremely mild-gradient topography; (3) the proximity of extensive wetlands and urban areas, which correspond to very different hydrologic regimes; (4) the presence of the low-permeability layer, muck, overlying the bedrock in the water conservation areas and Everglades National Park; (5) the nature of the aquifer which is extremely permeable near the coast, and (6) the potential for salt-water intrusion which cannot be simulated at regional scale.

In defining the applicability of the RSM, there must be identification of what is considered "generic" model code. If the RSM code without South Florida regional modeling features constitutes the generic RSM, then those features should not be documented in the RSM Theory Manual but should be documented in the SFRSM and NSRSM implementation reports instead, as suggested in the SFWMD's response summary to the Panel. However, as the SFWMD response further indicates, it would remain beneficial to identify the important hydrologic characteristics of South Florida in the RSM Theory Manual to demonstrate the potential suitability of the RSM to simulate other water bodies. In the same section of the Theory Manual, there should be a discussion of the object-oriented feature and its advantages in tailoring the generic RSM to simulate dissimilar water bodies.

Detailed editorial comments on the RSM documentation submitted by the Panel to the SFWMD prior to 22 June 2005 are presented in Appendix II. It is recommended that the manual be reviewed by a competent technical editor to resolve problems with language, grammar, and consistency of scientific terminology.

7. Validation of Regional Simulation Model

The goal of this section is to suggest additional tests to validate the RSM.

There are three types of error in modeling: (1) numerical error caused by round off and/or truncation, (2) physical error attributed to inaccurate parameter estimation, and (3) error that is traceable to limited or poor-quality data. RSM calibration and validation examples should identify these three sources of error. Numerical error can be minimized by a judicious choice of grid resolution and time step and physical error can be minimized by the proper choice of parameter values, while data-quality error usually can be assessed only qualitatively. However, the importance of data-quality error cannot be overemphasized. Full model validation requires explicit separation of error; otherwise, one could be calibrating numerical errors against physical and/or data-quality errors. The validation procedure should take into account the following considerations: (1) to the extent possible, eliminate numerical error; (2) calibrate physical parameters to acceptable values; and (3) if necessary, assess the quality of measured input data.

The Panel is reassured that the SFWMD will make every effort to distinguish between the three types of error which arise in mathematical modeling. First, numerical errors should be minimized; second, physical errors should be investigated, identified, and corrected; and third, data-quality errors should be acknowledged and, to the extent possible, resolved. As the SFWMD has adroitly recognized, disregarding this triad results in bad modeling practice.

The issue of calibrating physical parameters to acceptable values is controversial. One group of individuals with expertise in this area would argue that the constraints on the physical parameters should be limited to realistic values. This allows modelers to determine the parameter values that best fit the observed data. These optimal parameters can be compared to realistic parameter ranges in order to assess the conceptual validity of the model. Another group of experts would argue that physical parameter ranges should not be constrained in order to enforce the conceptual basis of the model. In this case, extreme and often unrealistic values of the optimal parameters would serve as an indication that conceptual problems might exist in the model. To accommodate both of these views, a model could have the option of either specifying acceptable ranges of physical parameters or not constraining these parameters at all. The modeler would then interpret the estimated physical parameters accordingly. The Panel recognizes that the inclusion of tools and techniques to constrain model parameters to acceptable ranges is currently part of the long-term RSM development strategy, and the current version of the RSM provides features that are similar to this recommendation.

The diffusion-wave approach of the RSM is a single-equation solution for one unknown in which a simplified flow velocity term is incorporated into the continuity equation. Flows are computed in terms of change in head; flow velocities or discharges are not computed directly. In this approach, the Manning equation for overland or canal flow becomes a calibration term for computed water levels. Derived flow velocities are a result of this water-level calibration, rather than being calibrated directly as in the case of unsteady-flow models. This could cast doubt on the validity of using RSM flow results to define transport rates for future work, when it is planned to extend the model with water-quality process modules (WQPMs) to address water-quality restoration issues.

Although model calibration using stage (water level) data alone is common engineering practice, it does not guarantee fully accurate model calibration. Stage data typically are used for model calibration simply because of their ready availability. However, different mass transports can result from the same water level, and if velocity or discharge data are available—either as discrete values or explicit ranges—they should be factored into the model calibration process. Such a two-variable approach is required to achieve credible mass transport results for use in addressing water quality problems. Both stage and flow velocity (or discharge) are dependent variables in the governing equations (mass and momentum conservation). Therefore, in a dynamic flow model that simultaneously solves these governing equations, stage and velocity can be concurrently assessed and employed in the calibration process. This is not the case with a diffusion-wave model, in which the lone dependent variable is water level. Given this model-calibration limitation, caution must be exercised in using mass transport results from a diffusion-wave model to compute constituent concentrations for water quality analyses.

The behavior of surface flow is nonlinear or quasi-linear, implying that flow parameters might vary throughout the range of possible flow conditions. A clear example of this is demonstrated in diffusion-wave routing in a natural channel, where the Muskingum-Cunge parameters vary not only with stage, but also with rate-of-change in stage. Conventional parameter estimation approaches will miss the peaks and valleys of the flow variability. A three-stage parameter calibration (low, average, and high) might be more appropriate in the RSM to account for the inherent nonlinearity of surface-flow behavior. The Panel is reassured that the SFWMD will implement a three-stage parameter calibration to better simulate the nonlinearities inherent in the physical process.

Systematic benchmarking should be used to ensure that modifications to the RSM code do not introduce errors in the solution. Verification examples are needed to show that the RSM can reproduce results from analytical solutions or other numerical models. Consideration should be given to incorporating nine HSE verification examples in the Theory Manual: three examples for surface flow, three examples for subsurface flow and three examples for coupled surface and subsurface flow. Documenting more verification examples as the model evolves should be a priority.

Tests should be done to demonstrate the significance of errors introduced by using the HSE solution from the previous time step to compute water balances in model cells. These demonstrations should resolve accuracy issues and answer questions such as whether the time lag constrains the HSE time step. In addition, sensitivity tests should be conducted to determine the effect of this time lag in RSM applications.

Validation of the RSM requires applying the model to a particular area, calibrating the model, and then comparing predicted and simulated hydrologic variables. As of the time of this panel review, validation of the RSM has not been accomplished and documented. A RSM implementation to current conditions in South Florida (SFRSM) and a RSM application to historic conditions (natural system) in South Florida (NSRSM) will be documented and submitted for peer review in the near future. The outcomes of these forthcoming peer reviews will be a key basis for assessing the validity of the RSM.

8. Validation of Hydrologic Process Modules

The goal of this section is to suggest tests for the HPM approach to simulating local hydrology, and to make recommendations for improvement or expansion of the approach.

Very limited evidence is presented to validate the documented HPMs. For example, there is no evidence that the hydrology of agricultural areas in south Miami-Dade County can be described accurately by any of the HPMs identified in the RSM documentation. Addition of validation results, either directly or by reference, into the model documentation would justify application of the HPMs.

The validity of the HPMs should be assessed by conducting more studies like that of Chin and Patterson (2005) at various locations within the RSM application area in South Florida. Such studies address the quantitative relationships between hydrologic variables and these relationships can be included either as new HPMs or adapted to existing HPMs.

9. Suitability for Meeting Client Goals

The goal of this section is to evaluate whether the model is suitable for meeting client goals.

The three groups of RSM clients are: (1) internal (SFWMD) modelers; (2) SFWMD users of the model (e.g. water-supply permitting, operations, interagency teams); and (3) non-SFWMD users, including consultants, public utilities, environmental groups, and the agricultural industry. In order for the model to be used correctly, all clients expect clear statements on the model assumptions and unambiguous statements regarding what the model does and does not simulate. It should be made clear in the documentation that the intended use of the RSM is evaluation of long-term effects of management decisions that impact conflicting water-control issues such as flood protection, water supply, water quality, irrigation, and ecosystem conservation and restoration. Clients expect that all equations solved or used in the model be included in the documentation and written in such a way that a user/client knows exactly how each input parameter is incorporated into the model. More work needs to be done on addressing client needs in the documentation.

In order to make the model more user-friendly, a graphical user interface (GUI) is essential, and systematic tutorials covering simple and potentially complex model applications would be useful for most clients. The SFWMD is currently developing a GUI to support application of the RSM.

The infrastructure and atmosphere of cooperation at the SFWMD appears to be such that the goals of SFWMD modelers and users of the model will be met. The solicitation of input from SFWMD users by modelers, and a concerted attempt to address these issues appears to be in place.

The goals of non-SFWMD users of the model are diverse, and are likely to depend on their particular applications of the model. Most non-SFWMD users likely will desire a well documented, scientifically sound, validated, and user-friendly model. More work needs to be done in these areas for the RSM to meet these anticipated non-SFWMD client goals.

10. Conclusions and Recommendations

The SFWMD is to be commended for its effort to develop a state-of-the-art regional-scale water-management model for South Florida. The Regional Simulation Model (RSM) is a significant improvement over the currently used South Florida Water Management Model (SFWMM). The object-oriented approach in the RSM makes it easier to maintain and improve, capable of simulating a wider variety of processes, and capable of incorporating a more complex set of water-management rules. The unstructured grid capability of the RSM provides increased spatial resolution that should lead to more accurate simulation results. The extensible property of the RSM over the SFWMM should increase the model's longevity by readily facilitating the addition of new features over the lifetime of its use.

Some key panel recommendations for improving the RSM and its documentation are as follows:

- The validity of the RSM assumption that subsurface geology is isotropic throughout the model domain should be clearly stated.

- The canal-seepage watermover should include the reach transmissivity in addition to the sediment-layer conductivity. The fact that bottom-sediment layers have minimal effect on canal leakage and sediment layers rarely exist on the sides of canals should be recognized.

- The diffusion-wave approach used by the RSM is not applicable over the entire South Florida domain. Specifically, flows in coastal areas influenced by tides cannot be simulated using the diffusion-wave approximation and simulation of certain flow conditions in low-gradient highly regulated canals could be inaccurate using a diffusion-wave model.

- The numerically intensive computational performance of the RSM applications appears to be excessive. The computational advantage of the diffusion-wave approach might be outweighed by the numerical intensity of the global-matrix solution of the RSM. Alternative sub-matrix solutions should be considered in the future if computation time becomes more of an issue.

- Use of an explicit numerical scheme should be considered in addition to a fully implicit scheme.

- Computation of potential evapotranspiration should be considered for inclusion in the RSM.

- The effects of wind-stress forcing on large open-water bodies should be considered within the generic RSM even though their treatment might not be required in a regional-scale application such as the SFRSM.

- Conveyance in sloughs should be treated explicitly to avoid losing it in the storage-volume relationship.

- Consideration should be given to incorporating rainfall and ET in the canal water balance.

- To improve model run times and efficiency, consideration should be given to partially decoupling the surface-water and ground-water solutions to allow different time steps to be used in these components. In addition, consideration should be given to re-implementing dynamic time stepping in the RSM.

- Recent developments in GMS, PEST, and XMDF software could be used to improve RSM efficiency.

- The model documentation needs significant improvement in organization and content. Several specific recommendations are provided in the Documentation section of this report.

- Model assumptions, numerical methods, model calibration, numerical errors, and model validation should be more fully explained in the RSM documentation and presented in a cohesive fashion in the Theory Manual.

- Local studies need to be performed and documented to validate the hydrologic process modules.

- The current model and documentation need further improvement to more adequately address and fulfill client goals and expectations.

The SFWMD has made a commendable effort to develop and document the RSM. Inclusion of a peer-review component in the RSM development process provides important quality-control and continuous-improvement assurances that can be expected to generate unbiased technical advice on model development. The RSM is on track to become a state-of-the-art, essential, and scientifically defensible tool for water management in South Florida. The peer-review panel anticipates that the recommendations contained in this report will be given serious consideration by the SFWMD to achieve this goal.

APPENDIX I: References

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