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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

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Executive Summary

The South Florida Water Management District 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 greater flexibility for further model development. There is currently no commercially available competing 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 object-oriented programming approach used in the RSM makes it possible to simulate a wide variety of hydrologic, hydraulic, and water-resource processes and to impose the complex set of operational rules and conditions that are unique to water management in South Florida.

After reviewing the RSM model documentation and supporting references, several recommendations for further improvement of the RSM are made in this report. These recommendations point to several equations that need to be corrected in the model documentation, and possibly the model itself, some aspects of the model 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, concerns about the formulation and validity of some hydrologic process modules, and concerns about the applicability of the management simulation engine (MSE). 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 more fully, it is anticipated that efficiency of the numerical-solution algorithms will become a major issue giving development of more robust solution methods a heightened priority.

The model documentation in its current draft form needs significant improvement in organization and content. Specific recommendations are made regarding reorganization of the documentation, and suggestions are provided for additional documentation describing model assumptions, numerical solution procedures, model-calibration methods, control of numerical errors, and model-validation techniques and results.

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

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 components 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 taken into account. The ground-water component of any regional-scale hydrologic model must necessarily 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 managed flow conditions in South Florida. The RSM simulates surface-water and ground-water hydrology, interaction between surface water and ground water, 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 component of the RSM simulates the natural hydrology, water-control features, water-conveyance systems, and water-storage systems. The MSE component of the RSM 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 component of the RSM is capable of identifying optimal water-management protocols for meeting various water-allocation and hydrologic-state objectives.

Within the HSE component of the RSM, hydrologic process modules (HPMs) solve 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, and HPMs have been developed for agricultural, urban, and natural systems. The inclusion of HPMs in the RSM accounts for the impact of small-scale hydrologic processes and land-use heterogeneity in the regional model, without having to use an extremely fine mesh that would make computations impractical.

The RSM is a significant improvement over the current regional-scale water-management model (WMM) used by the SFWMD. Computational features of the RSM that make this model different from the WMM 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 hydrology unique to South Florida. Compared to the currently used WMM, the RSM is more complex but designed to be more understandable and transparent to users, have a steeper learning curve, and be 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: assess the scientific soundness of the model, assess the conceptual framework of the model, identify the appropriate use of the model, make suggestions for modifications and improvements in the model, assess the model documentation, suggest validation tests for the model, suggest validation tests for the HPMs in the model, and 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 documentation provided to the peer review panel prior to 22 June 2005, an interactive workshop with SFWMD model developers on 22-23 June 2005, a helicopter and airboat tour of the modeled area, and follow-up correspondence between the model developers and the peer review panel up to 9 September 2005. This report is intended 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 that there is a self-correcting open process in place for continued assessment of the scientific approaches.

2.1 General

It was difficult to completely assess the scientific soundness of the RSM from the 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 model documentation in its current draft state does not provide adequate coverage of the equations solved by the model and the numerical techniques used to affect their solution. Extensive descriptions of validation examples were not provided. However, a significant amount of supporting information in the form of journal articles, unpublished papers, and online documents was provided and/or identified for panel use. Based on this information, the panel attempted to assess the scientific soundness of the model.

2.2 Basic Equations and Formulation

Several equations are not stated correctly in the RSM documentation. The seriousness of these discrepancies depends on whether they are simply typographical errors or whether these errors exist in the RSM code. Specific equations of concern are as follows:

- There is a ΔL variable missing from Equation 2.30 in the Theory Manual

- The exponent in Equation 2.39 in the Theory Manual should be 2/3 instead of 5/3

The ground-water component of the RSM assumes that the subsurface geology is isotropic. The validity of this assumption throughout the model domain is questionable. Secondary solution cavities will certainly be oriented in the direction of historical flows, leading to anisotropic hydraulic conductivities and transmissivities. 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 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 level in the adjacent cell, 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. The canal-seepage formulation should be stated in terms of reach transmissivity (Chin, 1991), since leakage is not solely dependent on sediment characteristics (for example, leakage occurs even when the sediment-layer thickness is zero). Dependence of the leakage coefficient on the size of the grid cell is lost when the above equation is used e.g. larger cells should have smaller leakage coefficients. These dependencies become clear when the leakage formulation is cast in terms of a reach transmissivity.

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. This assumption is different from that used in competing models such as MODHMS and MIKE-SHE, where the head in the overland and subsurface-flow domains can be different for a single finite-difference cell, which is the analogue of a waterbody in the RSM. In these other models, 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). When a 2D model is used, coupling the overland and ground-water domains with this linking term, and computing two different head values, can produce simulations where the overland domain is recharging the ground-water domain or where ground water recharges the overland domain. Such exchange of flow between domains cannot be as readily simulated with a 2D model that assumes continuity of head between overland and ground-water domains. Furthermore, solving for two head values per waterbody would allow using different time steps to solve the overland and ground-water flow equations, which is not currently possible.

Many of the watermovers in the Hydrologic Simulation Engine (HSE) are formulated in terms of the Manning equation, which is strictly applicable only to fully developed turbulent flow. In some cases in the HSE, the Manning equation will likely 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 model developers indicated in oral presentations that hydrologic process modules (HPMs) provide source water to the HSE cells according to the following relation

$$S_i = R_{rechg} - Q_{irr} + Q_{ws} + R_{ro}$$

where S_i is the source flux into the HSE cell, R_{rechg} is the recharge, Q_{irr} is the irrigation withdrawal, Q_{ws} is the water supply withdrawal, and R_{ro} is the runoff. The sign before Q_{ws} should be changed to negative to be consistent with the definition figure (Figure 2.12) in the Theory Manual.

The governing equation for overland flow is given in Appendix B (Equation B.1) using R_{rchg} to represent the source term per unit area. This source term is not correctly represented by Equation B.2, which should be changed to

$$R_{rchg} = RF - ET - q_{int} - f$$

where *f* is the infiltration rate.

Several statements in Appendix B are not correct. Specifically, statements to the effect that the continuity and momentum equations can be combined to produce a momentum equation and that the momentum equation can be integrated along a streamline to yield the energy equation are incorrect.

2.2 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 the 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. Inertial effects in flows through structures also could be significant, dependent on the structure-discharge rate, the converging and diverging channel geometry at the structure, and the nonlinear behavior of the structure. Furthermore, the RSM strategy of recovering some of the convective inertia through the use of the flux vector, E, instead of the head vector, H, as described by Lal (1998), might be unwise. In one-dimensional flow, fully dynamic diffusivity (including all inertial terms) is closer to kinematic hydraulic diffusivity (neglecting all inertial terms) than a convective-only (partial inertia) model (Ponce, 1990).

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.

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.

2.3 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. This approach could cause the model to become 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 will likely be diminished as the number of canal segments increases and a greater number of more sophisticated water-control structures are added, potentially resulting in an increased number of iterations required 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 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 the issue, an implicit scheme is the preferred choice. 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 will usually 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 that the tradeoff is an acceptable one, that is, improved stability without unduly sacrificing convergence. It is recommended that the tradeoffs between the use of $\alpha = 1$ and that of a more convergent value such as $\alpha = 0.6$ be investigated and reported.

The use of unrealistically high values of Manning's n, such as $n = 1$, in overland-flow cells, and the use of $\alpha = 1$ for fully forward implicit solution in the South Florida application of the RSM (SFRSM) are symptomatic of attempts to overcome numerical instabilities. The Manning's n value of one is too large, and use of fully forward weighting ($\alpha = 1$) will damp wave propagation. Effects of both of these conditions on model results need to be investigated.

Waterbody mass-balance matrices should be evaluated with updated H values to accelerate convergence, which does not seem to be the case 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.

2.4 Hydrologic Process Modules

The <agimp> and the <mbrcell> modules utilize the NRCS curve number method, which is strictly applicable only to event modeling. There is no such thing as a fixed "curve number" or a constant "maximum potential retention", and a curve number obtained through calibration might not be applicable in the validation phase, unless all events happen to have a similar antecedent moisture condition (AMC). The demonstrated discrepancies between simulated and recorded flows could be partly attributed to the variability in AMC (Ponce and Hawkins, 1996).

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.

The <mbrcell> module uses the following empirical relationship to calculate the rainfall excess (Appendix C.5, Equation 42),

$$ER = \frac{(P_{tot} - 0.2S_{pa})^2}{P_{tot} + 0.8S_{pa} + uns}$$

where ER is the excess rainfall, P_{tot} is the daily rainfall, S_{pa} is the potential abstraction, and uns is the water storage in the unsaturated zone. This equation differs from the conventional NRCS curve number equation (Chin, 2000) in that the variable "uns" is included. Additional scientific justification needs to be provided for deviating from conventional engineering practice.

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, 2004).

The <ramcc> HPM calculates the daily water budget for each soil zone according to the relation

$$STO_{t,i} = STO_{t-1,i} + P_t + IRR_t - ET_{t,i} -/+ Redist_{t,i} - Perc_{t,i} - Upflux_{t,i}$$

This equation is incorrect, since the minus sign before $Upflux_{t,i}$ should be a plus sign.

The <prr> HPM uses the NRCS curve number method to estimate the maximum soil moisture capacity, L_{max}, according to the relation

$$L_{\max} = \frac{1000}{CN} - 10$$

This equation is valid only for U.S. Customary units and not for SI units. The appropriate conversion factor should be included in the model.

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 by the model based on climatic input such as maximum and minimum temperature. It is recommended that calculation of PET be incorporated into the RSM, rather than specifying it as input data, especially since fairly simple relationships currently are being used 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 consideration of climate-variability scenarios. If historical PET estimates were derived using different methodologies than incorporated in the RSM, then it would be appropriate to include the historical PETs as input to the RSM. In addition, if computation of PET within the model significantly increases the RSM run time, then calculation of the PET outside of the RSM would be justified.

The role of the Management Simulation Engine (MSE) needs to be clarified. This well documented component of the RSM is designed to utilize the results of the HPM simulation to optimize operation of hydraulic structures to achieve some desired outcome. As presently configured, the hydraulic structures are not capable of being operated in accordance with the MSE algorithms; hence, the current utility of the MSE in regional simulation is limited. However, if the effectiveness of the MSE in achieving water-management objectives can be demonstrated, operational features of the hydraulic structures could 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 in that Lake Okeechobee is treated as a reservoir. Winds effects on Florida Bay are an important forcing mechanism that produces backwater effects along the coast. The present conceptual framework of the RSM excludes treatment of wind-stress forcing in all watermovers.

Conveyance in sloughs traversing through overland-flow cells is not accounted for; sloughs are treated simply as surface depressions in the storage-volume relationship of the RSM. Therefore, representation of the ridge and slough wetland landscape needs to be factored into the mesh-generation and flow-simulation processes.

The need for long-term regional simulations of 35-40 years is essential in assessing South-Florida water demands, and 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 South Florida applications of the RSM. Therefore, the following RSM capabilities are desirable:

- The land-surface mesh configuration and definition in the HSE of RSM should be 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 that alter the landscape should be treated by dynamically varying the RSM mesh configuration and applicable parameters
- Structure, levee, and canal configurations should be 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.

4. Use of Model in South Florida

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

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 is due to improved process and hydraulic-structure representations and increased spatial resolution provided by the RSM. 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 flows is to force a depth gradient mechanically, at which time some inertia might be present. This flow is unsteady and the Manning equation is not able to provide the unsteadiness and associated convection and diffusion properties of a wave governed primarily by friction and a depth gradient. There is an urgent need to perform theoretical work to identify the convective and diffusive properties of such waves and to build the canal model on these premises. Barring this, an alternative is to implement full dynamic-wave modeling in the canals, with all the attendant nonlinearities, which will likely impose the additional data requirements and increased numerical efforts typically associated with dynamic-wave computations.

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 shown to include the tidal transition zone.

5. Modifications and Improvements

The goal of this section is to make suggestions on 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 considered in the canal water balance. This is simple to implement, and it should slightly improve model accuracy.

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 give better resolution of the spatial distribution of water on the land surface. The water-surface elevation calculated for each cell using the RSM model could be combined with a more detailed subcell GIS land-surface elevation coverage to yield more refined estimates of the spatial extent of flooding.

The RSM solves all equations for regional flow simultaneously. Formulation of the surface-water, ground-water, and canal-flow equations for coupled-matrix solution forces the simulation to be conducted at a unique time step for all waterbodies within the system. Flow conditions in the most dynamic waterbody of the system should govern the chosen time step. Thus, unnecessary flow computations will be carried out in the other waterbodies, e.g., 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. Furthermore, consideration should be given to making the time step in the RSM dynamically variable during the simulation. It is more computationally efficient and accurate to adjust the simulation time step dynamically to closely match the flow conditions. For example, 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 should be considered.

Other numerical enhancements that can be considered in future developments 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 another technique that becomes attractive for large-scale simulations of coupled surface and subsurface flows that potentially require very large simulation times. It consists of splitting the total flow domain into several pieces or subdomains, for example using the boundaries of sub-watersheds, solving for flow for each subdomain individually, and then linking all subdomains using an iterative approach.

Preliminary applications of the RSM in South Florida have primarily focused on two-dimensional ground-water flow, with the intention of building more three-dimensional models in the future, 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;l) is currently used to construct the triangular meshes for the ground-water component of the RSM and, 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 “Horizons” feature of GMS, which makes it possible to utilize boreholes, hand-sketched cross-sections between boreholes, and user-defined or 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.

The very nature of South Florida and the complexity of the RSM make it a classic example of a highly parameterized system. A new parameter-estimation algorithm called "SVD-Assist" (= "Single Value Decomposition – Assist") is available and is designed to work with highly parameterized systems. Applications of this new algorithm have shown remarkable success. SVD-Assist is able to calibrate systems with thousands of parameters in a stable fashion and relatively quickly. 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, breaking the hydraulic conductivity (K) array into multiple polygons results in abrupt discontinuities in the K values along the polygon boundaries. This seems to be an arbitrary way to break up the K array into subsections. The main problem is that the original interpolation was performed across the entire model domain. If the model 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 the current zone. At that point, the multipliers could be applied to zones without violating the integrity of the original interpolation. Another approach the modelers might want to consider is the "pilot point" method. With this method, the modeler defines a series of points in the model where the K values are allowed to vary up or down during the parameter estimation process. An interpolation algorithm is then used at each step to interpolate the K values to 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 represent specific geologic features, the pilot point method would seem more appropriate. The pilot point 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 since the developers would simply need to download the XMDF library and implement 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 on the usefulness of the model documentation, including whether the level of detail is sufficient or more is needed, 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: Regional Simulation Model Philosophy, Governing Equations Using the Traditional Approach, and 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.

- Descriptions of the HSE and HPM should be in separate chapters.

- Appendix A (Regional Simulation Model Philosophy), particularly A.2 (Scope of the RSM), should be part of Chapter 1 (Introduction).

- Appendix B (Governing Equations Using the Traditional Approach) should be part of Chapter 2 (Hydrologic Simulation Engine Theory and Concepts).

- Reference papers should be listed as references and copies of these papers should not be part of the Appendix. The Theory Manual suffers significantly by having technical papers describing critical aspects and concepts related to the RSM development attached as 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 continuity and clarity.

  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 HPM white paper (Appendix C.5) should be assimilated into the main body of the Theory Manual as a separate chapter.

- The MSE white paper (Appendix C.6) should be assimilated into the main body of the Theory Manual as a separate chapter.

In the MSE white paper, the fact that the models used for comparative analyses with the RSM were not developed with the same purpose and scope as the RSM should be noted. 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, since the purpose and scope driving their developments were quite different from those of the RSM. 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.

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

- Consistent terminology should be used throughout the Theory Manual and supporting documentation. A glossary would make the Theory Manual easier to understand and unambiguous.

- Use one set of units in 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.

The name "Theory Manual" might not be the best way to describe the model-supporting document. Consideration should be given to having two sets of manuals: One manual titled "User's Manual" containing a description of how to run the model and a second manual titled "Technical Reference Manual" or simply "Reference Manual". The Technical Reference Manual would contain all the information that is necessary to understand the model, but not necessarily to run it. Portions of the theory that are deemed necessary for understanding the model should be included in the Technical Reference Manual.

6.2 Hydrologic Simulation Engine Theory and Concepts

The vectors **E** and **V** both represent the volumetric flux, but they are not used consistently in theoretical equations derived from the Reynolds transport theorem. Although the equations are correct, a consistent notation should be used to avoid confusion on the part of the reader. It is recommended that **E** be replaced by **V** in all instances.

6.3 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 addition, many of the parameter values suggested for use in the HPMs are presented without references that describe the context in which the cited parameters were derived. All tabular presentations of suggested parameter values should have a "References" column.

Validation experiments are specific to individual HPMs. There is only one set of HPM validation experiments in the documentation. Since these validation experiments apply only to the <prr> module, it is recommended that the <prr> validation be documented in the section where the <prr> module is described. In general, HPM validation experiments should be reported in the section where the basis of the HPM is described. The duration of the rainfall and the head boundary conditions in the <prr> validation experiments need to be specified in the documentation.

6.3.1 <unsat>

This HPM uses different equations dependent on the elevation of the water table relative to ground surface. Whereas the equations appear to be reasonably heuristic 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.

6.3.2 <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.

6.3.3 <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 (2004) 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 the 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.

The <prr> module quantifies the soil-water upflux from the water table into the root zone as a wedge of water placed into the root zone due to the placement of the water table at the beginning of each time step. However, there is no description of how the wedge is used, how the wedge is parameterized, and what methodology should be used for estimating the wedge parameters.

6.3.4 <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 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.

Several definitions seem incorrect, specifically:

- for "fcPumpoff" change "water supply pump turn-on" to "collector ditch turn-off"
- for "fcPumpOn" change "water supply pump turn-on" to "collector ditch turn-on"
- for "fcPumpoff" change "Trigger elevation for water supply pump turn-on" to "Trigger elevation for water supply pump turn-off"
- for "maxLevel" change "Trigger elevation for water supply pump turn-on" to "Trigger elevation for pump turn-on"
- for "minLevel" change "Trigger elevation for water supply pump turn-on" to "Trigger elevation for pump turn-off".

6.3.5 <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 typically taken to be a function of the depth to the water table, not a function of the soil series.

The weir equations given in the documentation are not dimensionally homogeneous; hence, the units of the variables in these equations must be given.

A typical value of 5.2 m for a 25-year 3-day storm, as stated in Table 7 of the Theory Manual, is not correct.

6.3.6 <mbrcell>

The guidance provided in the documentation gives a range of values and a typical value for the time of concentration (3600 seconds, typical) and the water content at field capacity (20 cm, typical). 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.

6.3.7 <cu>

A suggested range and a typical value for the variable “septic” are needed.

6.4 Needs for Additional Material

The Theory Manual asserts that a challenge in modeling complex hydrologic systems is to maintain an acceptable level of numerical errors. However, no guidance is given on what is an acceptable level of numerical errors and what numerical errors to expect in applying the RSM. In addition, there is no clear statement on the sources of numerical errors in the RSM. Identification of suspicious numerical behavior and manifestations of numerical errors 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 in the main body of the Theory Manual.

All the assumptions behind the application of RSM to simulate regional flow in South Florida should be clearly stated and justified. It is not a weakness to simplify the description of a given flow process if it is justified, but it can be a weakness if the conditions under which the assumptions are valid are not stated clearly. 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. Clearly stated model assumptions and limitations will facilitate comparative evaluations with other models that do not require the same assumptions. For example, MODHMS or MIKE-SHE can simulate more complex subsurface flow processes, such as variably saturated flow, and MODFLOW has some options that are not in 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 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 models (for example MIKE-SHE) to simulate these scenarios for comparative purposes.

The numerical techniques used in the model 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. 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 on 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 shallow-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 (WCA) and Everglades National Park (ENP); (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 but that is addressable at local scale.

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 any additional tests to validate the RSM.

There are three types of errors in modeling: (1) numerical errors caused by round off and/or truncation, (2) physical errors attributed to inaccurate parameter estimation, and (3) errors that are traceable to limited amounts of data or to poor data quality. RSM calibration and validation examples should identify these three sources of errors. Numerical errors can be minimized by a judicious choice of grid resolution and time step, physical errors can be minimized by the proper choice of parameter values, and data-quality errors usually can be assessed only in a qualitative way, however, the importance of data-quality errors cannot be overemphasized. Full model validation requires explicit separation of errors; 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 any numerical errors; (2) calibrate to acceptable values of physical parameters; and (3) if necessary, assess the quality of measured input data.

The issue of calibrating to acceptable values of physical parameters 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. Then 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 values should be constrained to enforce the conceptual basis of the model. In this case, extreme, but still realistic, values of the optimal parameters would serve as an indication that conceptual problems might exist in the model. To accommodate both of these views, consideration should be given to including the option in the RSM 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 diffusion-wave approach of the RSM is a single-equation solution for one unknown in which a simplified term for flow velocity is incorporated in the continuity equation. Flows are computed in terms of change in head and flow velocities or discharges are not computed directly. In this approach, the Manning equation for overland or canal flow, for instance, becomes primarily a calibration term for computed water levels. Derived flow velocities are a result of this water-level calibration and are not calibrated directly as in the case of unsteady-flow models. This fact could cast doubt on the validity of RSM flow results to define transport rates for future planned extensions of the model with water-quality process modules (WQPMs) to address water-quality restoration issues.

The behavior of surface flow is nonlinear or quasi-linear, implying that parameters defining the flow properties might not remain constant throughout the range of possible flow conditions. A clear example of this variability 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.

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, (i.e., previous day for a daily time step) to compute water balance in model cells. These demonstrations should resolve accuracy issues as well as 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 and essential 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 Chin and Patterson (2004) at various locations within the RSM application to 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 (District) modelers; (2) District users of the model (e.g. water-supply permitting, operations, interagency teams); and (3) non-District 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 also 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 written somewhere in the documentation and 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 is essential, and systematic tutorials covering simple and potentially complex model applications would be useful for most clients.

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

The goals of non-District users of the model are diverse, and their goals are likely to depend on their particular application of the model. Most non-District users will likely 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-District 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 Water Management Model (WMM). The object-oriented approach in 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 WMM 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:

- Several equations are not stated correctly in the RSM documentation. The seriousness of this situation depends on whether these errors are simply typographical or whether these errors exist in the RSM code.

- The validity of the RSM assumption that subsurface geology is isotropic throughout the model domain is questionable.

- The canal-seepage watermover should be based on reach transmissivity and not on sediment-layer conductivity.

- 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 to date 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.

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

- The soundness of basic formulations of the <agimp>, <mbrcell>, <unsat>, <ramcc>, and <prr> hydrologic process modules are questionable.

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

- The role of the management simulation engine needs to be clarified. There is a significant concern that the hydraulic structures in the canal network are not capable of being operated in accordance with the MSE algorithms, hence the utility of the MSE in regional simulation is limited.

- The effects of wind-stress forcing on the large open water bodies should be included in the RSM.

- Conveyance in sloughs should be treated explicitly rather that being lost in the storage-volume relationship.

- Land-use changes during the period of simulation should be accommodated by the RSM.

- 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 making the RSM time step dynamically variable.

- 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 suggestions are provided in this report.

- Model assumptions, numerical methods, model calibration, numerical errors, and model validation should be more fully explained in the RSM documentation.

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

- The current model and documentation needs further improvement to meet client goals.

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 District to achieve this goal.

APPENDIX I: References

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APPENDIX II: Preliminary and Editorial Comments on RSM Documentation

The attached documentation includes all comments on the RSM documentation reviewed by the panel in advance of the Panel Workshop on 22-23 June 2005. These comments include most of the editorial comments on the RSM documentation, and some of the substantive comments that are the focus of this report.

[Insert Pre-Workshop Comments Here]

APPENDIX III: District Response

[Insert District Response to Panel Report Here]