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Peer Review of the Regional Simulation Model (RSM)

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Intersection of Urban Area and the Everglades
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 is called the Regional Simulation Model (RSM). The RSM is a significant improvement over the currently-used South Florida Water Management Model (SFWMM), with key improvements being more efficient computational algorithms, better spatial resolution using triangular instead of square grid cells, more transparent to client users, and greater flexibility for further development. There is currently no available competing model that has all the features planned for the RSM, and this model should be ideally suited for South-Florida conditions. The object-oriented programming approach used in RSM makes it possible to simulate a wide variety of hydrologic processes and to impose the complex set of water-management rules and conditions that are unique to South Florida.

After reviewing the RSM model and supporting documentation, 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 the coastal areas), 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). A particularly urgent need is in the validation of the RSM in South Florida, and the inclusion of the results of pending validation studies in the model documentation. As application of the model in South Florida becomes more extensive, it is anticipated that the efficiency of the numerical-solution algorithms will become a major issue, and further development of efficient solution procedures will have a high priority.

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

The District is well on its way to developing 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, and the District is to be commended for including this formative peer-review in the RSM development cycle.

1. Introduction

Both ground water and surface water have significant influences on the regional hydrology of South Florida, and any applicable regional-scale hydrologic model must be capable of conjunctively simulating both hydrologic components. The surface-water component a regional-scale hydrologic model must necessarily account for the stormwater-management systems in urban areas, crop-management and irrigation practices in agricultural areas, overland flow in natural areas, and open-channel flow in the extensive canal network in South Florida. The performance curves and operational rules of the canal hydraulic structures must all be taken into account. The ground-water component of any applicable regional-scale hydrologic model must necessarily simulate the shallow water table that frequently rises above ground level, the highly permeable aquifers, the significant withdrawals for water supply, and the seepage into and out of surface waters, primarily canals.

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 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; and the MSE component of 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 those planned for the future. 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 extremely fine meshes that would make computations impractical.

The RSM is a significant improvement of the current regional-scale water-management model (WMM) used by the District. 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; 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 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.

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 District modelers on 22-23 June 2005, and follow-up correspondence between the District and the peer-review panel up to 9 September 2005. This report is intended provide formative input to assist the District in development of the RSM, and the comments contained in this report do not necessarily apply to later versions of the model, documentation, and applications of the model.

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 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 conclusively assess the scientific soundness of the model from the information provided by the District, since the available model documentation did not provide a complete description of the model. The model documentation in its current state does not provide adequate coverage of the equations solved by the model and the numerical techniques used, and extensive descriptions of validation examples were not provided. However, a large amount of documentation and information was provided to the panel and, based on the information provided, the panel has made an attempt to assess the scientific soundness of the model.

2.2 Basic Equations and Formulation

There are several equations that are not stated correctly in the RSM documentation. The seriousness of this situation depends on whether these are simply typographical errors in the documentation, or whether these errors actually 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
- Use of the storage coefficient in all equations is incorrect, since this variable is applicable to confined and semi-confined aquifers. In all instances, the storage coefficient should be replaced by the specific yield.

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, since secondary solution cavities will certainly be oriented in the direction of the historical flows, leading to anisotropic hydraulic conductivities and transmissivities. If anisotropy cannot be incorporated in the model, then the validity and limitations of assuming isotropy should stated clearly in the theory manual.

The canal seepage watermover is based on the following linear relationship between the water-surface elevation in a canal, H_i, and the water level in the adjacent cell, H_m:

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

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 the 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) and the dependence of the leakage coefficient on the size of the grid cell is lost when the above equation is used. Larger cells should have smaller leakage coefficients. These dependencies become clear when the leakage formulation is cast in terms of a reach transmissivity.

The overland/ground-water flow interaction in RSM is simulated with the assumption of continuity of head for the overland and groundwater components of the model, since there is only one head value computed for a single waterbody. This assumption is different from that used in some other competing models, for example MODHMS or MIKE-SHE, where the head in the overland and subsurface flow domains can be different. Different heads in overland and subsurface domains can lead to fluid flow between the two domains, and can produce simulations where either the overland domain is recharging the groundwater flow domain, or the opposite. Such exchange flow between domains cannot be as readily simulated with the assumption of continuity of head in cells where overland flow is occurring.

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, the Manning equation has been used to describe mixed turbulent-laminar and even laminar flow. 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 overland-flow applications in the model are not fully turbulent, it is recommended that *N* be used instead of *n*.

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. The figure showing the positive direction of Q_{ws} needs to have an arrow pointing in one direction.

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 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 of the convective acceleration term limits the ability of RSM to accurately simulate spatial variability in flow conveyance. The diffusion-wave approach is primarily suited for overland flow on 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 significantly 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 E instead of H, as described by Lal (1998), may be unwise. In one-dimensional flow, the fully-dynamic diffusivity (including all inertia terms) is closer to the kinematic hydraulic diffusivity (neglecting all inertia terms) than the 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 remains an open question in the scientific literature.

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 are reconciled with the diffusion-wave assumption, which has built-in physical diffusion through the hysteresis in the rating.

In summary, adopting the diffusion-wave approach for RSM development imposes 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 a practical one when simulating regional overland flows, and inclusion of the inertia terms is likely to make the model difficult to control.

2.3 Numerical Methods

The solution of all watermover and waterbody equations in the HSE is integrated into in one global matrix as opposed to sub-matrix solutions coupled by boundary fluxes. This approach could cause the model to become excessively 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, sounds excessive and is likely a symptom of increasing system complexity and/or linear assumptions made in the RSM. Typically, the factors that increase computational run times are the non-linear terms, which are not included in the diffusion-wave approximation of the RSM. The computational advantage of the diffusion-wave approach might be outweighed by the numerical intensity of the global-matrix solution of the RSM.

The use of an implicit versus explicit numerical solution scheme is a tradeoff that needs to be assessed judiciously. Implicit schemes are usually unconditionally stable, while explicit schemes 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. Once the focus shifts from stability to convergence, an explicit scheme can compete effectively with an implicit scheme. The explicit scheme will usually achieve convergence at the same time as stability, while the implicit scheme may be stable throughout a wide range of grid resolutions, while remaining nonconvergent for some subrange. Therefore, it should not be a priori assumed 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 or the other by itself. This balance should be obtained through the simultaneous minimization of round off and truncation errors, in the sense of 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 SFRSM are symptomatic of attempts to overcome numerical instabilities and/or increase the rate of convergence. 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.

To accelerate convergence in the RSM, the waterbody mass-balance matrices should be evaluated with updated H values, which does not seem to be the case in the current version of RSM. As described in 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 may not be applicable in the validation phase, unless all events happen to have similar antecedent moisture conditions (AMC). The demonstrated discrepancies between simulated and recorded flows may be partly attributed to the variability in AMCs (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 may not be practical.

The <mbrcell> module uses the following relationship to calculate the rainfall excess,

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

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 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 that 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 the PET be incorporated into the RSM, rather than specifying it as input data, especially since fairly simple relationships are currently being used to estimate PET. The PET may vary temporally in a long-term model application, particularly as land-use changes and ecosystem-restoration practices are implemented. Furthermore, the inclusion of PET calculation in the model would allow the consideration of climate-variability scenarios.

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 the hydraulic structures in achieving some desired outcome. There is a significant concern that the hydraulic structures, in reality, not capable of being operated in accordance with the MSE algorithms, hence the utility of the MSE in regional simulation is limited.

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 given that Lake Okeechobee is included 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 are not accounted for, since sloughs are treated simply as surface depressions in the storage-volume relationship. Representation of the ridge and slough wetland landscape needs to be included in 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 the appropriate use of the RSM in South Florida conditions.

The calibrated and validated version of the model is appropriate for simulating the current water-management system in South Florida, as well as the historic (pre-drainage) natural system. The calibrated and validated model will be particularly useful for simulating various alternatives in Everglades restoration, and assessing water-supply, and flood-control alternatives in South Florida.

For canals of nearly-zero bed slope, such as those in South Florida, the only way to induce flows is to mechanically force a depth gradient, at which time some inertia may 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 eventually 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, instabilities, and extensive data requirements that characterize 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 times, both rainfall and ET should be considered in the canal water balance. This is simple to implement, and it should slightly improve the 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 elevation calculated for each cell using the RSM model could be combined with more detailed sub-cell GIS elevation coverage to yield more accurate 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 dynamically adjust the simulation time step 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.

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. GMS software 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 model make it a classic example of a highly-parameterized system. A new parameter-estimation algorithm called “SVD-Assist” is available and is designed work with highly-parameterized systems. Applications of this new algorithm have shown remarkable success. It is able to calibrate systems with thousands of parameters in a stable fashion and in a relatively small period of time. The algorithm can be accessed in the most recent version of PEST which can be downloaded from the PEST website (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 sub-sections. The main problem is that the original interpolation was performed across the entire model domain. If the 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 may wish 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 seems 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 XMDF model format could be used to replace the NetCDF portion of the RSM input/output file format. Based current experience with XMDF, it is likely that this would result in much smaller file sizes than NetCDF. It would be simple 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, where limitations and restrictions on the use of the model, imposed by assumptions in the model formulation, should be 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 contained 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).

  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

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

  where f is the infiltration rate. There are several statements in Appendix B that are not correct. Specifically, statements indicating 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 not correct.

- 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 which 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.

  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 development was quite different than that 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 model. A glossary would make the documentation 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 Florida.

The name "Theory Manual" may 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" containing all the information that is necessary to understand the model, but not necessarily to run it. The portions of the theory that are deemed absolutely 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** 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. Also, many of the parameter values suggested for use in the models 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 reported in the documentation and, since these validation experiments apply only to the <prr> module, it is recommended that the <prr> validation documentation be included 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 needs to be given.

6.3.1 <unsat>

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

6.3.2 <layer5>

Both Θ_{cap} and Ew are 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, and guidance should be provided for selecting these variables. Specifically, Lmax depends on the depth to the water table and soil type, and 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 on how the wedge is used, how the wedge is parameterized, and the methodology 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 give 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 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” is 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 are typical numerical errors are to be expected in applying the RSM. Also 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 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 clearly stated. Model limitations arising from neglect of 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 also 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 may result from using different computer platforms. The documentation of validation examples should also 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, EAA, WCA, ENP, 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 model and that could be described in the Theory Manual are: (1) the competing objectives for water use (flooding control, water supply and environmental protection); (2) the extremely flat topography; (3) the proximity of extensive wetlands and urban areas, which corresponds to very different hydrologic regimes; (4) the presence of the low-permeability layer, muck, overlying the bedrock in the WCA and 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 the regional scale but that is addressed at local scale.

Many detailed editorial comments on the RSM documentation existing prior to 22 June 2005 were submitted by the panel to the District and are contained 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 usage.

7. Validation of Regional Simulation Model

The goal of this section is to suggest any additional tests that to further validate RSM.

There are three types of errors in modeling: (1) numerical errors, which are caused by roundoff and/or truncation, (2) physical errors, attributed to inaccurate parameter estimation, and (3) errors that are traceable to poor data quality. Calibration and validation examples using RSM should identify these three sources of errors. Numerical errors can be minimized by a judicious choice of grid resolution, physical errors can be minimized by the proper choice of parameter ranges, and data-quality errors can usually only be assessed in a qualitative way, however, their importance cannot be overemphasized. Full-model validation demands the 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 the numerical errors; (2) calibrate to the expected values of the physical parameters; and (3) If necessary, assess the quality of the measured data.

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 accuracy of the RSM flow results needed to define transport rates for future planned extensions of the model with water-quality process modules (WQPMs) to conduct water-quality simulations to address CERP issues.

Surface-flow properties are nonlinear or quasilinear, implying that the parameters may not remain constant throughout the range of possible flows. A clear example is that of diffusion-wave routing in a natural channel, where the Muskingum-Cunge parameters vary not only with stage, but also with the rate-of-change in stage. Thus, conventional parameter estimation will miss the peaks and valleys of the flow variability. A three-stage parameter calibration (low, average, and high) may be appropriate to account for the inherent nonlinearity of surface flow.

Systematic benchmarking should be used ensure that modifications made to the RSM code do not introduce errors in the solution. Verification examples are needed to show that 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 the error 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 the model cells. This would resolve 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.

To validate the RSM requires applying the model to a particular area, calibrating the model, and then comparing predicted and simulated hydrologic variables. As of the present time, this has not been done 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 2006. 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 the improvement or expansion of the approach.

Very limited evidence is presented to validate the HPMs, and the addition of validation results, either directly or by reference, into the model documentation would support the application of HPMs. For example, there is no evidence that hydrology of the agricultural areas in south Miami-Dade county can be accurately described by any of the included HPMs.

The validity of HPMs should be assessed by conducting more studies like Chin and Patterson (2004) at various locations within the RSM coverage area. Such studies address the quantitative relationships between hydrologic variables, and these relationships can either be included as new HPMs of fitted 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 user's 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. All clients expect clear documentation on what the model does and does not do, so that the model can be used correctly. It should be made clear in the documentation that the RSM is intended for use in evaluating long-term effects of management decisions impacting conflicting uses such as flood control, water supply, water quality, and ecosystem conservation. Clients expect that all equations solved or used in the model are written somewhere in the documentation, and in such a way that a user/client knows exactly how each input parameter is incorporated in 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 step-by-step tutorials covering simple and potentially-complex model applications would be useful for most clients.

The infrastructure and atmosphere of cooperation at the District 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 serious 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 easy-to-use model. More work needs to be done in these areas for RSM to meet these anticipated non-District client goals.

10. Conclusions and Recommendations

The South Florida Water Management District is to be commended on 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, capable in incorporating a more complex set of water-management rules, and having an increased spatial resolution that should lead to more accurate results. The open nature of the model facilitates addition of new features over the lifetime of the model.

The goals of this RSM 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. Key recommendations are as follows:

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

- The ground-water component of RSM assumes that the subsurface geology is isotropic. The validity of this assumption throughout the model domain is questionable.

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

- In RSM cells where the water table rises above ground level, separate heads should be retained in the surface-water and ground-water components of the model.

- 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. Accurate simulation of low-gradient canal flows may be inaccurate using the diffusive-wave approximation.

- 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 explicit numerical schemes should be considered in addition to the 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 included 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-forcing on the large open water bodies in the RSM should be included in the model.
- 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. Also, consideration should be given to making the RSM time step dynamically variable.
- Recent software developments in GMS, PEST, and XMDF model format could be added to RSM to improve model efficiency.
- The model documentation needs significant improvement in organization and content. Several specific suggestions are provided in this report.
- Additional documentation should be added to cover model assumptions, numerical methods, model calibration, numerical errors, and model validation.
- Very little evidence is provided on the validity of the hydrologic process modules. Local studies will need to be done and documented.
- The current model and documentation needs further improvement to meet client goals.

Inclusion of a peer review component in the RSM development cycle provides an important quality-control and continuous-improvement process that can be expected to generate unbiased technical advice on the development of a state-of-the-art and defensible model.

The District modelers have made a commendable effort is developing the RSM, and associated documentation. The RSM is on track to becoming a state-of-the-art, essential, and scientifically-defensible tool for water-management in South Florida. To achieve this goal, the peer-review panel anticipates that the recommendations contained in this report be given serious consideration by the District.

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]