Peer Review of the Regional Simulation Model

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Introduction

The South Florida Water Management District commissioned a panel to perform a peer review of the Regional Simulation Model and its elements, the Hydrologic Simulation Engine (HSE) and the Management Simulation Engine (MSE). The members of the Panel were Dr. Rafael L. Bras (Chair), Dr. Victor M. Ponce, and Dr. Daniel Sheer. The Panel reviewed material and prepared for a workshop that was held July 24 and 25, 2019 at the offices of the SFWMD in West Palm Beach, Fl. This report is based on the outcome of that workshop and the review of material before and after the meeting.

The Scope of Work listed the following goals for the Peer Review:

1. "Determining if object-oriented design and computational sequencing used in HSE/MSE of RSM is suitable for simulating the hydraulics, hydrology, and the operations control needs of the south Florida hydrologic system;"
2. "Evaluating if our the "multiple editions" approach to numerical solutions is appropriate for use in regional hydrologic modeling in south Florida, and if this perpetual evolution" is leveraging the proper disciplines and approaches and translating them correctly;
3. "Determining if the RSM is generally applicable for hydrologic modeling in south Florida."

In the process of seeking answers to the above questions, the Panel raised several issues that we will discuss in some detail in the body of the report. Our responses to the questions can be summarized in the following way:

1. The object-oriented modular design of RSM is valuable. The idea that elements can be added almost at will and solved within the same numerical framework is attractive. The platform can effectively integrate the expertise of many. The downside is that the framework is computationally complicated and its mastery challenging.
2. The Panel found the "multiple editions" confusing at times, although the appropriateness of solutions and techniques is not in question. As will be pointed out, the Panel advocates for a true integration of models.
3. The Panel feels that the RSM formulation is appropriate to the hydrology of South Florida.

Before going further, the Panel wishes to express its appreciation to the staff of the District for its preparation and cooperation. Furthermore, the Panel states that the District has a good product and dedicated employees who work well under resource-limited conditions.

The following sections address issues that arose during the workshop, all related to the three questions above.

What is the mission? What is the right level of complexity?

It is important that model development be guided by the problem at hand. Once the problem is identified and understood, then the question is what is the proper modeling approach to solve that problem. It is easy to be absorbed by the modeling and the tool development and lose sight of why we are doing it and what is the problem to be solved. Complexity does not necessarily "makes best."

MSE development

1) The existing MSE is quite coarse, with a limited number of rule forms available to a user.
2) Creating objects that implement new rule forms requires programming in C++, and is and will be beyond the capability of other than model developers or those rare individuals with both programming and water resource management experience.
3) A simple language that allows a non-programmer user to create new operating strategies for both individual objects, basins, and system wide would be highly desirable. A parser could translate that language to XML.
4) The use of assessors to compute target flows in the MSE is problematic. New assessor objects would need to be developed to implement any new strategy, limiting the utility of the modeling software as described above. Those objects will need to be complex, even in dendritic systems, and will require the use of some system solver in other systems. An optimization solver formulation for the MSE is recommended. It will need to be substantially more capable than the current lpsolve-based formulation. Some of those capabilities (e.g. continuous balancing of weighted deviation from targets, iteration to convergence, etc.) will require the iteration of the solver itself.
5) The SFWMD may wish to consider if model utility is the overarching goal of RSM development. If so, tradeoffs between utility, cost, time to completion, open source and other coding requirements should be carefully weighed.
6) To be truly useful to users other than those with access to the model developers, the MSE needs a fully functional GUI. There are many water management simulation software packages with GUIs that can serve as design guides.

Models integration

It is difficult to follow the different "models". The Panel was confused with and surprised by the fact that the basin model and the mesh model (above and below the "red line") were not integrated. The lack of integration limits utility and make full utilization of RSM by other than agency staff very difficult. The lack of integration should be made very clear in any presentation or discussion.

The approach of setting gate openings and running a much shorter time step holds promise for computational efficiency, temporal resolution and linkage with MSE. In particular, a Basins-structured LP-based MSE could determine flows at structures. These flows could be converted to gate openings, and the grid-based model run. Actual flows at gates set by MSE would be different coming out of the grid solve. These could be set as constraints in the MSE which would then be resolved to provide a consistent solution for both models. This approach might resolve the problem of integrating the Basins and grid solutions and should be pursued.

Another example of lack of integration is the “hydrology model” output serving as input to the mesh model. Logically, it should be integrated into the RSM. This can lead to reconciliation, compatibility problems, particularly in natural systems.

SFWMD has long recognized the need for higher spatial and temporal resolution models for particular issues in both planning and regulation. MSRSM is an example of such a model. This integration presents a challenge. A standard protocol for obtaining and validating boundary conditions for smaller scale models from the larger scale RSM must be developed. Such a scheme might set tolerances for agreement on boundary flows where heads are used as boundary conditions (or vice versa).

The use of a variety of versions or formulations to solve different problems – each referred to as a model – is confusing. There should be ONE model – with appropriate version numbering – that is used to solve different problems.

Model management/Modeling documentation

As stated previously, the RSM is complicated to run, maintain and use. At the same time, it is a key and accepted tool (as was well articulated in the meeting by state and federal agencies and non-profits working on the Everglades and South Florida). The Panel recommends:

1. Users manuals and complete documentation are urgently needed. The Panel understands that resources are barely sufficient to keep the system going. The Panel urges the SFWMD to invest in documentation; this should be a priority.
2. Ease of use and access must be a goal. The model needs a Graphical User Interface.
3. Users should have access to documented tools for the display of model output. This includes graphical displays. A suite of such tools should be made generally available. Output formats should remain stable for long periods to facilitate user development of new display and interpretation tools.
4. The District may wish to consider hosting RSM for outside use on a server. This may greatly simplify maintenance issues. It would also facilitate agency review of model runs by outside parties. Nevertheless, the inevitable outcome of opening access will be increasing demand for help and advice.

5. Provision should be made for external access to SFWMD data bases so that external users can set up their own models
6. External model developers may create enhancements to the SFWMD. When providing the RSM to outside users the SFWMD should, to the extent possible, encourage or require that such enhancements be available to the SFWMD for internal use, or better, for general use. This includes external development of performance metrics.
7. Thought may be given to the formation of a users' group, possibly involving licensing, sharing of development and of model use experiences.
8. It is inevitable that others will challenge the results of RSM using competing models. Thought should be given and guidelines developed on methods to compare the results of differing models.
9. The District needs to develop standard procedures for the review and verification of both internal and external runs.
10. The Panel is concerned about continuity of staffing and expertise. At the moment there is a cadre of senior experts that are irreplaceable. Younger people need to be brought in and/or expertise has to be developed throughout a broader community.
11. Desktop computer CPUs with up to 64 cores/128 threads are now or will soon be available for ~$5K or less. The bottom line is that computational facilities continue to get faster and cheaper. Further, distributed computational cycles are readily available at very affordable prices from providers "in the cloud". The potential for using such options should be investigated since they could greatly reduce run times for the mesh portions of the model.

Model and input error

1) There was no comprehensive analysis of the nature of overall model errors, the difference between observed and simulated results. It is important to note that there are errors in model simulation of physical parameters, e.g. flows and stages, and there are errors in the model simulation of performance metrics. While these are related, they are NOT the same, and both need to be analyzed.
2) A close examination of time series comparisons of model errors and scatterplots is likely to reveal the existence of systemic errors, and a more thorough statistical examination of the relationship between errors and model input, output and perhaps most importantly performance metrics values may reveal the existence of systemic errors. It is desirable to have the relationships between errors and input, output, and performance metrics values be normally distributed and homoscedastic. If they are not, empirical corrections may be added to model output to correct systemic errors. There are many techniques for making such adjustments and they are likely to improve the relationship between presented values and realistic expectations of the impact of alternatives being evaluated. This should improve estimates of variance of results and otherwise greatly improving the utility of model results. Some references to techniques for model error analysis are attached.

3) The time series of model errors from calibration and verification can be useful as direct corrections to model runs. They can be added to model results as either innovations (percentages) or absolute values depending on the underlying processes, when the same historical drivers are used in simulation runs. In other cases, or where longer simulations are needed, time series of synthetic errors can be developed using the statistics of the calibration/verification errors, and these time series added to the model results. Care must be taken to preserve both serial and spatial correlation of errors in the synthetic error time series.
4) Model inputs, and particularly meteorological inputs are subject to substantive deviations from actual values and contribute to model error. It is useful to understand the nature of these errors and to identify systemic errors in order to understand and correct for remaining sources of model error. Modifications made to model physical parameters are sometimes made to reduce model errors that are largely due to errors in estimation of model drivers. There is substantial literature on methods to account for systemic errors in meteorological data. Use of these methods may considerably improve model calibration. The methods used by the NWS to correct such errors may be aimed squarely at the middle of the distribution of values, where the SFWMD's interest may concern correcting the value of the inputs at the extremes.
5) Once adjustments have been made for systemic errors and the implications of errors in model inputs (drivers) are understood, the effect of the approximations used in model formulation can also be better understood, and a priority scheme for implementing changes in model formulation can be developed.

Use of the full unsteady flow equations for flow in a horizontal channel

In the typical case, the forces acting on a 1-D formulation of unsteady open-channel flow are: (1) gravity, (2) friction, (3) pressure gradient, and (4) inertia. Significantly, in a horizontal channel the gravitational force vanishes, while the three other forces remain. This renders the Manning equation inappropriate, since the driving force in this equation is the gravitational force. Thus, for modeling unsteady flows in horizontal channels (the case of South Florida) there appears to be no other choice than to use the full Saint-Venant equations. A diffusion wave formulation may not suffice, because it neglects inertia. The latter is bound to play an increasing role in the momentum balance as the gravitational force vanishes.

The need to include lateral contributions (seepage in and out of the control volume) in the analysis of wave propagation in South Florida applications remains to be fully clarified. Great strides along these lines have already been made by SFWMD scientists. The additional terms in the mass and momentum balance equations need to be carefully identified. Their relative importance may be determined following the work of Ponce (1982). (see Appendix for references)

Dynamic hydraulic diffusivity in convection-diffusion modeling of surface runoff

An established approach to modeling flood flows used in RSM is that of Hayami (1951), who combined the governing equations of continuity and motion (the Saint Venant equations) into a second-order partial differential equation with discharge *Q* as the dependent variable. This equation, effectively a convection-diffusion model of surface runoff, has been widely used in practice. It consists of~~;~~: (1) a rate-of-rise term, (2) a convective term, of first order, and (3) a diffusive term, of second order. In Hayami's formulation, the coefficient of the convective term is the kinematic wave celerity (Seddon celerity); the coefficient of the diffusive term is the hydraulic diffusivity (Hayami diffusivity).

The hydraulic diffusivity used in RSM follows the original Hayami formulation of a diffusion wave, wherein the inertia terms (in the equation of motion) are neglected. This approximation works well for low Froude number flows. However, for high Froude number flows, the neglect of inertia proves to be increasingly unjustified. As shown in Ponce (1991), the true hydraulic diffusivity of the convection-diffusion model of flood flows is the *dynamic* hydraulic diffusivity, which is a function of the Vedernikov number (Powell, 1948). In fact, for Vedernikov $\boldsymbol{V} = 1$, all wave diffusion vanishes and the flow is poised to develop physical surface instabilities, *i.e.*, the so-called *roll waves*. This fits admirably with physical reality, confirming the theoretical basis of the Vedernikov-dependent diffusivity, *i.e.*, the *dynamic* hydraulic diffusivity.

We recommend that a dynamic hydraulic diffusivity be incorporated into all instances where surface-water convection-diffusion is being modeled in RMS. This extension provides *a lot of bang for the buck*, since the structure of the computation remains basically the same. Ponce's formulation clarifies the work of Dooge and his associates, as recounted recently by Nuccitelli and Ponce (2014).

Numerical Methods, Accuracy and Errors

Computational efficiency

1) Run times for the models are currently undesirably, but perhaps not unavoidably, long
2) There was discussion of neural net and other AI based emulators for the model, but these were not reviewed. They should be.
3) All comments on error analysis made above apply to any model emulators as well. Errors should be assessed against data as well as against RSM results.
4) If a linear programing solver is used for the MSE it may well be possible to solve both the MSE and HSE in a single pass. This would largely eliminate the need for custom iteration schemes, except when linear approximation tolerances are exceeded. This should be pursued
5) Solvers other than LPsolve (the GNU solver tested) should be tested. Commercial solvers may be substantially more computationally efficient.

The appropriateness of the TVDLF

In its newest implementation, the RSM model uses the Total Variation Diminishing Lax-Friedrichs method (TVDLF), which is shown to be accurate and stable for both kinematic and diffusion flows such as those prevalent in Southern Florida (Lal and Toth, 2013). The method uses a linearized conservative implicit formulation of the simplified St. Venant equations, thereby avoiding the iterative formulations that would normally be necessary when solving a nonlinear scheme. SFWMD scientists have extensively tested the method, with favorable results in terms of numerical accuracy and runtime.

The success of the method in simulating a wide array of problems, including dry channel bed and steep bottom slopes, must be attributed to its use of weighting factors to incorporate numerical diffusion as needed to control the instabilities that would normally appear in connection with sharp (*i.e.*, nonlinear) changes in model variables. The panel welcomes the use of the TVDLF method and supports its continued use; the downside, however, is the increased level of complexity, compared to more conventional methods.

Stability and Convergence

The laws of mass and momentum conservation, which underpin all physical-process modeling of unsteady flows, may be combined, through appropriate linearization, into a single second-order, convection-diffusion equation (Hayami, 1951). In one extreme, when the diffusion term vanishes, the equation becomes hyperbolic; in the other extreme, when the convection term vanishes, the equation becomes parabolic.

Numerical models of hyperbolic systems are subject to the Courant law, which expresses the ratio of physical celerity (c) to numerical celerity ($\Delta x/\Delta t$), also referred to as the *grid ratio.* On the other hand, numerical models of parabolic systems are subject to what has sometimes been referred to (for lack of a better name) as the cell Reynolds number law, which expresses the ratio of physical diffusivity (ν) to numerical, or grid, diffusivity $[(\Delta x)^2/\Delta t]$. Both Courant and cell Reynolds numbers control the properties of numerical models of unsteady flow; their values should be calculated *a priori* (Ponce *et al.*, 2001).

The properties of numerical schemes may be analyzed using various tools of advanced mathematics. A time-tested approach uses Fourier analysis to develop amplitude and phase portraits following the pioneering work of Leendeertse (1967). Significant strides along these lines have already been accomplished by SFWMD scientists. Further clarification of various concepts appears to be in order at this juncture.

In hyperbolic systems, an assessment of numerical accuracy (*i.e.*, convergence) focuses on the spatial resolution $L/\Delta x$, where L is the predominant wavelength of the perturbation and Δx is the chosen space step. Generally, numerical models of hyperbolic systems are shown to be more accurate when the grid size follows the characteristic lines, *i.e.*, for a Courant number $C = 1$, wherein the physical celerity c matches the grid ratio $\Delta x/\Delta t$. In theory, selecting a sufficiently high spatial resolution, say, $L/\Delta x \geq 100$ and a Courant number $C = 1$ should suffice. In practice, however, a certain scheme may lack enough numerical diffusion to confront the high-frequency perturbations that are likely to appear in well-balanced schemes; thus, additional filtering (numerical diffusion) is normally required to render the system workable.

For instance, there is a wealth of accumulated experience on the numerical properties of the well-known Preissmann scheme, wherein stability and convergence are determined by the spatial resolution $L/\Delta x$, the Courant number C, and the weighting factor ϑ (Ponce *et. al.*, 1978). The latter is required to control nonlinear instabilities which tend to plague the computation as the scheme approaches second order. Values of the weighting factor in the range $0.55 \leq \vartheta \leq 1$ are recommended, with values near the lower limit approaching convergence (to second order) at the expense of stability, and values near the upper limit approaching stability at the expense of convergence.

Choice of spatial resolution for good modeling practice

The determination of the proper spatial resolution lies at the crux of good modeling practice, as the experience with RSM clearly shows. No amount of time spent on this effort is wasted. Our recommendation is to start with a target spatial resolution $\Delta x/L \geq 100$. [The number 10 is definitely too low, and 1000 may be impractical]. Calculating spatial resolution entails an estimation of: (a) the mean flow velocity, (b) the wave celerity corresponding to the prevailing type of friction and cross-sectional shape, and (c) the wavelength of the predominant perturbation. Values of wave celerity for a comprehensive set of frictional formulations and cross-sectional shapes have been presented by Ponce (2014).

We recommend that the selected wave sizes remain within the diffusion wave range, since the dynamic wave range is very likely to be too diffusive to be of any practical interest (Lighthill and Whitham, 1955). The dimensionless wave propagation chart of Ponce and Simons (1977) may be used as a suitable indicator of the appropriate wave scale required to nail down the proper spatial resolution (see appendix).

S*olution Methods*

While implicit schemes are unconditionally stable, a similar statement may not follow for explicit schemes. This is certainly the case for both surface and groundwater flows. On this basis, implicit schemes are generally preferred over explicit schemes.

It may be true that implicit schemes are not subject to *an upper limit* on the time step in order to remain stable. However, the use of time steps greatly exceeding this limit renders the model inaccurate (nonconvergent). Thus, the use of implicit schemes with Courant numbers greatly exceeding 1 (C >> 1) must be viewed with extreme caution, begging for a Fourier analysis for proof of convergence. Furthermore, certain explicit schemes are not subject to a stability condition, as demonstrated by Ponce *et al.* (1979) in connection with convection modeling.

The tradeoffs between explicit and implicit schemes are, therefore, clear: While implicit schemes are more stable, they require matrix inversion and the actual time step is effectively limited in size by accuracy considerations. Explicit schemes, on the other hand, are simpler to develop and execute, requiring no matrix inversion and no downstream boundary (Ponce *et al.*, 1979; Ponce *et al.*, 2001). Viewed in this light, explicit schemes are poised to remain along implicit schemes in the tool bag of the numerical modeler of unsteady flows.

Summary

South Florida is one of the most intensely managed environments in the world. The control of its water resources dates back hundreds of years and is essential to the social, economic and ecological well-being of the region. During our visit several constituents including federal and state agencies, as well as not for profit institutions stated the need of a reliable, stable and credible representation of the region; a model that allows them to explore management alternatives, do planning, or study the impact of future climatic conditions. The Panel concludes that RSM serves that purpose and is a suitable for simulating the hydraulics, hydrology, and the operations control needs of the South Florida hydrologic system. It builds on a legacy of models customized to represent the unique physical and water management demands of South Florida. The Panel does have several observations and recommendations discussed in the body of this report. Some of the key conclusions are:

1. There is concern about continuity of expertise. This is a complicated model, very much dependent on a few very knowledgeable individuals.
2. There is a need of investment on appropriate user interfaces (like GUIs), manuals and ways to facilitate access by outside users.
3. Model integration is important and encouraged, that includes basin, mesh, MSE and hydrologic models.
4. Model and input errors must be quantified and used to improve model results.
5. A diffusion wave formulation may not suffice, because it neglects inertia. This should be studied.
6. A dynamic hydraulic diffusivity should be incorporated into all instances where surface-water convection-diffusion is being modeled in RMS.
7. Criteria for determining time and space discretization must be ~~explicit and~~ founded on solid theoretical foundations.
8. Model complexity should be in tune with the problem at hand.

Appendix

By Victor M. Ponce

This Draft Report contains Panelist Victor M. Ponce's contributions and recommendations after attending the South Florida Water Management District (SFWMD) Peer Review of the Regional Simulation Model's (RSM), held in West Palm Beach, Florida, on July 24-25, 2019. The specific focus of the peer review is on identifying strengths, weaknesses, and possible applications of the RSM model, with regards to its suitability for simulating the hydraulics, hydrology, and operations control needs of the South Florida hydrologic system. This report is a contribution to the Draft Report to be prepared by the Panel based on input of its three members and discussion thereof.

This review has concluded that the methodologies included in RSM are adequate for its use in South Florida. To improve and complement current efforts, the author recommends that District scientists spend additional time on the issues of numerical accuracy, particularly on the determination of the applicable Courant and cell Reynolds numbers for specific model runs. The author's experience in this area is offered to serve as a suitable framework for the analysis.

1. On strategies for model control to manage instabilities

All numerical models, and RSM is no exception, have a way of becoming unstable under a certain set of circumstances. Thus, it seems appropriate, at the start, to provide a general discussion on strategies for model control to manage instabilities. A good physically based mathematical model is based on generally accepted partial differential equations describing the relevant physical processes. RSM uses 1-D and 2-D formulations of watershed, channel, reservoir, and groundwater flow, coupling them as appropriate to better represent the physical reality at the chosen level of abstraction.

All numerical models suffer from problems of stability and convergence. Stability is related to roundoff errors; convergence to discretization errors (O'Brien *et al.*, 1950). A model run on a computer of infinite word length would theoretically be free from roundoff errors; therefore, stable. However, such a computer does not exist. The computers in use today typically have a 32-bit word length, that is, each rational number is represented by a collection of 32 zeros (0) and ones (1), with an accuracy of approximately seven (7) significant digits. In practice, however, this accuracy is not enough; in the longer runs, roundoff errors propagate beyond the stated accuracy, eventually rendering the solution unstable.

Convergence, which is akin to accuracy (in the sense of *convergence to* the analytical solution), is determined by the size of the discretization, *i.e.*, the values of the discrete space and time steps, which are chosen by the person performing the modeling. In theory, the steps should be small enough to reduce the (n+1)th-order errors of an n-th order scheme to insignificant amounts. This is normally obtained by a careful choice of the discrete steps in order to achieve good spatial and temporal resolutions. The temptation may be to choose very small discrete steps; however, generally this is not the answer. Decreasing the discrete steps *increases* the number of computations required to reach a solution, thereby *increasing* the chance for round-off errors to propagate, not to mention the increased computer time required to get a solution.

In practice, the control of numerical instability is seen to be a careful balancing act: How to build a scheme that has enough numerical diffusion to handle the high-frequency perturbations that are responsible for the instability, while at the same time making sure that the solution itself is not being substantially affected by the artificially introduced numerical diffusion. This dilemma is at the crux of all numerical modeling.

The laws of mass and momentum conservation, which underpin all physical-process modeling of unsteady flows, may be combined, through appropriate linearization, into a single second-order, convection-diffusion equation (Hayami, 1951). In one extreme, when the diffusion term vanishes, the equation becomes hyperbolic; in the other extreme, when the convection term vanishes, the equation becomes parabolic.

Numerical models of hyperbolic systems are subject to the Courant law, which expresses the ratio of physical celerity (c) to numerical celerity ($\Delta x/\Delta t$), also referred to as the *grid ratio.* On the other hand, numerical models of parabolic systems are subject to what has sometimes been referred to (for lack of a better name) as the cell Reynolds number law, which expresses the ratio of physical diffusivity (ν) to numerical, or grid, diffusivity [$(\Delta x)^2/\Delta t$]. Both Courant and cell Reynolds numbers control the properties of numerical models of unsteady flow; their values should be calculated *a priori* (Ponce *et al.*, 2001).

The properties of numerical schemes may be analyzed using various tools of advanced mathematics. A time-tested approach uses Fourier analysis to develop amplitude and phase portraits following the pioneering work of Leendeertse (1967). Significant strides along these lines have already been accomplished by SFWMD scientists. Further clarification of various concepts appears to be in order at this juncture.

In hyperbolic systems, an assessment of numerical accuracy (*i.e.*, convergence) focuses on the spatial resolution $L/\Delta x$, where L is the predominant wavelength of the perturbation and Δx is the chosen space step. Generally, numerical models of hyperbolic systems are shown to be more accurate when the grid size follows the characteristic lines, *i.e.*, for a Courant number $C = 1$, wherein the physical celerity c matches the grid ratio $\Delta x/\Delta t$. In theory, selecting a sufficiently high spatial resolution, say, $L/\Delta x \geq 100$ and a Courant number $C = 1$ should suffice. In practice, however, a certain scheme may lack enough numerical diffusion to confront the high-frequency perturbations that are likely to appear in well-balanced schemes; thus, additional filtering (numerical diffusion) is normally required to render the system workable.

For instance, there is a wealth of accumulated experience on the numerical properties of the well-known Preissmann scheme, wherein stability and convergence are determined by the spatial resolution $L / \Delta x$, the Courant number C, and the weighting factor ϑ (Ponce *et. al.*, 1978). The latter is required to control nonlinear instabilities which tend to plague the computation as the scheme approaches second order. Values of the weighting factor in the range $0.55 \leq \vartheta \leq 1$ are recommended, with values near the lower limit approaching convergence (to second order) at the expense of stability, and values near the upper limit approaching stability at the expense of convergence.

An excellent example of the use of Fourier analysis in numerical modeling of flood flows is that of the Muskingum-Cunge model, a diffusion wave model that is based on the matching of physical and numerical diffusivities (Cunge, 1969). A review of the amplitude and phase portraits of the Muskingum-Cunge model, including an online calculator, has recently been accomplished by Vuppalapati and Ponce (2016).

2. On the appropriateness of the TVDLF model implemented in RMS

In its newest implementation, the RSM model uses the Total Variation Diminishing Lax-Friedrichs method (TVDLF), which is shown to be accurate and stable for both kinematic and diffusion flows such as those prevalent in Southern Florida (Lal and Toth, 2013). The method uses a linearized conservative implicit formulation of the simplified St. Venant equations, thereby avoiding the iterative formulations that would normally be necessary when solving a nonlinear scheme. SFWMD scientists have extensively tested the method, with favorable results in terms of numerical accuracy and runtime.

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3. On the use of a dynamic hydraulic diffusivity in convection-diffusion modeling of surface runoff

An established approach to modeling flood flows used in RSM is that of Hayami (1951), who combined the governing equations of continuity and motion (the Saint Venant equations) into a second-order partial differential equation with discharge *Q* as the dependent variable. This equation, effectively a convection-diffusion model of surface runoff, has been widely used in practice. It consists of; (1) a rate-of-rise term, (2) a convective term, of first order, and (3) a diffusive term, of second order. In Hayami's formulation, the coefficient of the convective term is the kinematic wave celerity (Seddon celerity); the coefficient of the diffusive term is the hydraulic diffusivity (Hayami diffusivity).

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We recommend that a dynamic hydraulic diffusivity be incorporated into all instances where surface-water convection-diffusion is being modeled in RMS. This extension provides *a lot of bang for the buck*, since the structure of the computation remains basically the same. Ponce's formulation clarifies the work of Dooge and his associates, as recounted recently by Nuccitelli and Ponce (2014).

4. On the choice of spatial resolution for good modeling practice

The determination of the proper spatial resolution lies at the crux of good modeling practice, as the experience with RSM clearly shows. No amount of time spent on this effort is wasted. Our recommendation is to start with a target spatial resolution $\Delta x / L \geq 100$. [The number 10 is definitely too low, and 1000 may be impractical]. Calculating spatial resolution entails an estimation of: (a) the mean flow velocity, (b) the wave celerity corresponding to the prevailing type of friction and cross-sectional shape, and (c) the wavelength of the predominant perturbation. Values of wave celerity for a comprehensive set of frictional formulations and cross-sectional shapes have been presented by Ponce (2014).

We recommend that the selected wave sizes remain within the diffusion wave range, since the dynamic wave range is very likely to be too diffusive to be of any practical interest (Lighthill and Whitham, 1955). The dimensionless wave propagation chart of Ponce and Simons (1977) (Fig. 1) may be used as a suitable indicator of the appropriate wave scale required to nail down the proper spatial resolution. Figure 1 is global and based on theory; therefore, it is preferable to alternative approaches containing empirical components.

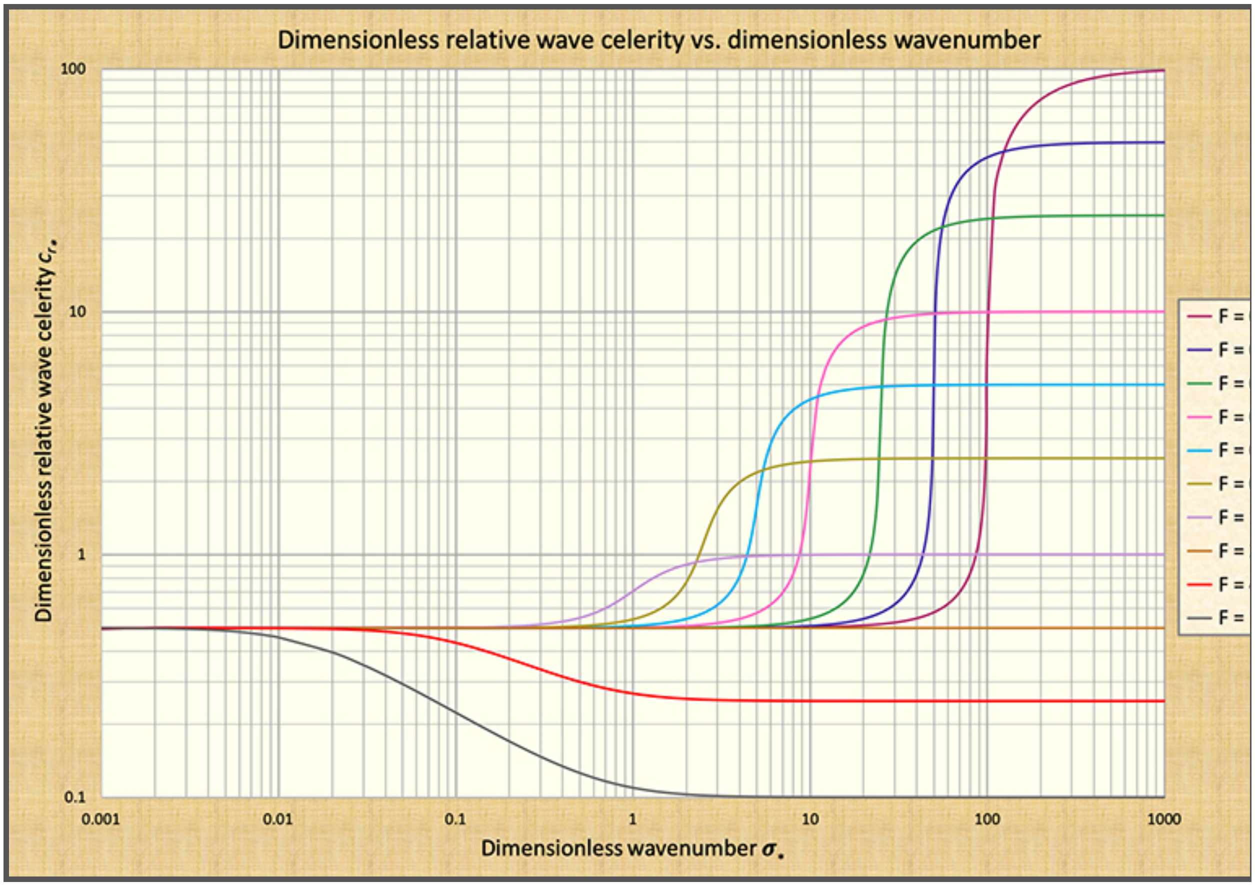

Fig. 1 Dimensionless relative wave celerity vs dimensionless wavenumber in open-channel flow.

5. On the comparative advantages of implicit vs explicit schemes

The choice between explicit and implicit schemes continues to haunt numerical modelers. While implicit schemes are unconditionally stable, a similar statement may not follow for explicit schemes. This is certainly the case for both surface and groundwater flows. On this basis, implicit schemes are generally preferred over explicit schemes, but the complete story remains to be told.

It may be true that implicit schemes are not subject to *an upper limit* on the time step in order to remain stable. However, the use of time steps greatly exceeding this limit renders the model inaccurate (nonconvergent). Thus, the use of implicit schemes with Courant numbers greatly exceeding 1 (C >> 1) must be viewed with extreme caution, begging for a Fourier analysis for proof of convergence. Furthermore, certain explicit schemes are not subject to a stability condition, as demonstrated by Ponce *et al.* (1979) in connection with convection modeling.

The tradeoffs between explicit and implicit schemes are, therefore, clear: While implicit schemes are more stable, they require matrix inversion and the actual time step is effectively limited in size by accuracy considerations. Explicit schemes, on the other hand, are simpler to develop and execute, requiring no matrix inversion and no downstream boundary (Ponce *et al.*, 1979; Ponce *et al.*, 2001). Viewed in this light, explicit schemes are poised to remain along implicit schemes in the tool bag of the numerical modeler of unsteady flows.

6. On the need to use the full unsteady flow equations for flow in a horizontal channel

In the typical case, the forces acting on a 1-D formulation of unsteady open-channel flow are: (1) gravity, (2) friction, (3) pressure gradient, and (4) inertia. Significantly, in a horizontal channel the gravitational force vanishes, while the three other forces remain. This renders the Manning equation inapproriate, since the driving force in this equation is the gravitational force. Thus, for modeling unsteady flows in horizontal channels (the case of South Florida) there appears to be no other choice than to use the full Saint-Venant equations. A diffusion wave formulation will not suffice, because it neglects inertia. The latter is bound to play an increasing role in the momentum balance as the gravitational force vanishes.

The need to include lateral contributions (seepage in and out of the control volume) in the analysis of wave propagation in South Florida applications remains to be fully clarified. Great strides along these lines have already been made by SFWMD scientists. The additional terms in the mass and momentum balance equations need to be carefully identified. Their relative importance may be determined following the work of Ponce (1982).

7. On the need for RSM model version numbers

The term "RSM model" is being currently used to describe any and all activities under the RSM modeling framework. This explains the District's (SFWMD) reluctance to engage in explicit model version numbers to describe what amounts to activities of varied scope and in many areas. The review failed to shed additional light on this important issue. We do not have a clear answer to solve this problem, namely, the inability of RSM to connect the various modeling activities and individual projects in time and space. We encourage SFWMD scientists to continue to focus on resolving this issue.

8. On the need for consistency in model documentation

We recommend that SFWMD consider a thorough and full documentation of the RSM model via a technically edited User Manual, accompanied by a Reference Manual, as a way to ensure that potential users of the model will be able to use it in the future. Background material would consist of relevant published papers listed in the bibliography and included therein with hot links to online pdf files.

As an alternative, one certainly requiring fewer resources, the District could sponsor a publications series to be entitled, for example, *RSM Tecnical Monographs.* For consistency, each monograph would follow the same (or similar) format and describe in detail a specific portion of the model, using graphics and color as appropriate. This approach has the advantage that progress is not defined in terms of project completion.

9. Other miscellaneous recommendations

We offer the following miscellaneous recommendations:

a. The 2-D momentum equations originate in the 3-D Navier-Stokes equations, and, as such, are technically *not closed* (Flokstra, 1976; 1977). Some sort of surrogate for the missing effective stresses appears in order (Kuipers and Vreugdenhil, 1973). This is an obscure subject, perhaps deserving of more attention than that given so far.
b. Caution is recommended when using a 2-D formulation of a diffusion wave, wherein the inertia terms are neglected. Neglecting inertia is bound to eliminate physical circulation (Ponce and Yabusaki, 1981). However, it may be a reasonable assumption in the largely convective 2-D flows that prevail in South Florida.
c. The Muskingum-Cunge model of 1-D flood flows, effectively a diffusion wave model, has been analytically verified by Ponce *et al.* (1996). We suggest that the District consider including this verification test in their set of cases for model verification.

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