Peer Review of the Watershed Assessment Model (WAM)

Final Panel Report
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Panel:

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'All models are wrong -- but some are useful' Box, 1979

Executive Summary

Panel Task

In July 2008 the Florida Department of Agriculture and Consumer Services (FDACS) contracted with the University of Florida Water Institute to convene a panel of experts to perform a review of the Watershed Assessment Model (WAM) as described in WAM Technical Model Documentation © Soil and Water Engineering Technology, Inc. 2008, Revised September 2008.

The essence of the Panel's task was to "conduct an independent and objective peer review of the functionality and documentation of the WAM as a watershed-scale modeling tool for addressing water resources issues in Florida" using the model developers' latest documentation as the primary source of information about the model. The Panel interpreted the mandate broadly, seeking to judge the adequacy of the model for its stated objectives and judging whether the written documentation articulates sufficiently the capabilities of the model for its intended use. It should be noted that the Panel could not, nor attempted to, judge the accuracy of the coding of the model nor did it perform quality control exercises to vouch that it is error free.

General Findings

The conceptual model underlying WAM includes rainfall, evapotranspiration, overland flow, groundwater flow and river flow, as well as the transport and transformation of particulate and soluble phosphorus and nitrogen, total suspended solids and biochemical oxygen demand in the system. The significant processes that affect the hydrology of Florida watersheds are included in the model. However the methodologies used to represent these processes range from quite empirical (e.g. cell to stream routing of overland and groundwater flow) to more physically-based (e.g. Boussinesq equation for shallow saturated groundwater flow in EAAMOD). Decisions regarding the level of sophistication required for modeling different hydrologic processes in different domains seem to have been made by the model developers, based on intuition and experience, to improve computational efficiency or to solve particular project-specific problems. While the Panel respects and accepts the judgment of the modelers at SWET, a more rigorous discussion and justification of the level of complexity chosen for each process and their assumptions should be included in the written documentation. Assumptions are required for the development of all models, so they should not be viewed as a shortcoming. Rather, documentation of assumptions leads to transparency in the modeling process and to improved model credibility.

The Panel believes that WAM is capable of simulating the relative effect of alternative land use and management practices on surface and subsurface hydrology and pollutant loads, on a watershed scale. It has the flexibility necessary to consider upland landscapes with deep water tables, landscapes with shallow water tables, with and without artificial drainage, and special cases, such as wetlands, urban areas and mining sites. WAM uses a GIS based grid approach to represent the watershed on a physically consistent spatial

scale, and accesses GIS data bases for soils, topography, land uses, and other inputs. While it is the Panel's opinion that the basis of the model is generally sound, like most computer models it relies on approximate methods at every stage. Furthermore the model documentation, as presented in the Technical Manual (SWET, 2008) and in the various reports of its application is insufficient. Thorough documentation of the methods is essential to support reliable calibration and application of the model by the developers and especially by other model users.

The primary strengths of WAM are its GIS foundation,, spatial detail, process-based field-scale modules, existing model database for Florida conditions, flexibility to accommodate varied hydrologic, water quality, and land and water management processes, and its facility for performing alternative scenario simulations. It provides an efficient mechanism to aggregate assumptions about system behavior and implementation of management rules at the watershed scale. It can be used to test assumptions and understanding about the watershed system and to evaluate outcomes of alternative land use and land management scenarios based on this understanding.

Weaknesses that may limit WAM's utility include its simplified approach for cell-to-stream water and solute delivery, simplified in-stream water quality processes, inability to adequately represent small-scale short-term storm event impacts, and simplified representation of impervious urban land conditions. The most significant weakness associated with the WAM model however is the pervasive lack of attention to detail in rigorously documenting assumptions, methodologies, sensitivity analyses, calibration and verification efforts, and uncertainty analyses in the WAM Technical Documentation and WAM Applications Reports.

Major Recommendations

1. The current WAM Technical Manual needs to be rewritten to provide the level of detail and clarity needed to support the model and its applications. This includes a more rigorous discussion and justification of the level of complexity and assumptions chosen for each process, an accurate description of the equations and numerical methods used to represent each process, and correction of all typographical errors in the equations. Detailed recommendations are given in the body of this report.

2. WAM components rely on a considerable number of empirical coefficients that require proper identification through standard and objective sensitivity analysis, calibration and validation practices. Since model sensitivity is likely specific for each type of application, the Panel recommends that a clearly outlined and justified sensitivity analysis for the complete WAM model be presented for a range of typical sample applications in the WAM technical documentation. This sensitivity analysis should result in recommendations regarding important model parameters that should be estimated and evaluated using standard calibration and validation exercises in model applications.

3. The Panel recommends that established and objective goodness-of-fit criteria be reported for all WAM model applications. These should consist of a combination of graphical comparison of measured vs. simulated values, and summary statistics (Nash-Sutcliff coefficient of efficiency, index of agreement, etc.) and absolute error measures (RMSE). All model applications referenced in the WAM Technical Manual and its supporting documents should contain this information. Detailed recommendations regarding good calibration and validation practices are given in the body of this report.

4. The overall tradeoffs between model strengths and weaknesses (for WAM or any model) need to be assessed in any specific application, taking into account the needed level of accuracy of model results for each application and the extent to which weaknesses may limit the utility and reliability of those predictions. With careful application, including adequate calibration and validation for each application watershed, it is the Panel's opinion that WAM can be used for the following types of watershed assessments:
    - To determine the relative impacts of alternative land use and development scenarios
    - To determine the relative impacts of BMPs on nonpoint source loads
    - TMDL allocation studies where the focus is on relative differences between scenarios.

5. For quantitative applications (e.g. to evaluate compliance with particular numerical water quality or TMDL standards), the outputs of interest should be accompanied by a margin-of-safety value derived through a formal Monte-Carlo-multivariate uncertainty analysis or other equivalent uncertainty analyses. Note that this recommendation applies equally to all hydrologic/water quality models that might be used for this purpose not just to WAM. Since this would not be a simple additional task for all model applications, the sponsoring entities of these studies need to recognize the importance of the uncertainty analyses and provide the needed budgetary resources for their execution.

6. As the model continues to evolve through applications in Florida and elsewhere, it is recommended that project budgets provide for the thorough documentation and testing of the new features as they are developed, with major or novel changes in the model submitted for peer review.

7. It is the Panel's <u>strong</u> opinion that the WAM Technical Manual and associated documentation <u>must</u> be enhanced and revised, following recommendations given herein, in order for WAM to be a widely usable and useful tool for addressing water resource issues in Florida. The Panel believes that it is well worth the time and resources required to accomplish this.

Note that more detailed recommendations can be found throughout the body of this report in italics.

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1.0 Introduction and Purpose of Review

In July 2008 the Florida Department of Agriculture and Consumer Services contracted with the University of Florida Water Institute to convene a panel of experts to perform a review of the Watershed Assessment Model (WAM) as described in WAM Technical Model Documentation © Soil and Water Engineering Technology, Inc. 2008, Revised September 2008. Relevant elements of the Statement of Work are attached in Appendix A. Members of the Panel were Professor Wendy D. Graham (UF, Chair), Mr. Anthony Donigian (AQUA TERRA Consultants), Professor Rafael Muñoz-Carpena (UF), Professor Wayne Skaggs (NCSU), and Professor Adel Shirmohammadi (U MD).

The essence of the Panel's task was to "conduct an independent and objective peer review of the functionality and documentation of the WAM as a watershed-scale modeling tool for addressing water resources issues in Florida". Specifically, the objectives of the model peer review were as follows: 1) evaluate the scientific basis underlying the model; 2) evaluate the methodology by which watershed-scale management rules and best management practices are implemented in the model; 3) evaluate methods by which the model has been calibrated and validated for at least one example application; and 4) discuss the capabilities, limitations, and recommended uses of the model. The review relied on the latest documentation of the model and model application reports as the primary source of information about the model. Supplementary information was provided during the November 19-20, 2008 workshop with the model development team. Panelists were not expected to review the code for accuracy or to run the model independently.

Section 2.0 provides background information on Non-Point Source (NPS) pollution issues, requirements of the Total Maximum Daily Load (TMDL) and Best Management Practices (BMP) programs, and the need for watershed scale models to help design and evaluate NPS, TMDL and BMP programs. Section 3.0 of this report evaluates the physical and hydrologic processes incorporated in the WAM model. Section 4.0 evaluates the methodology by which watershed-scale management rules and best management practices are implemented in the model. Section 5.0 evaluates the methods by which the model has been calibrated and validated. Section 6.0 discusses the clarity and appropriateness of the Documentation. Section 7.0 discusses the capabilities, limitations, and recommended uses of the model in comparison with other similar watershed models that have also been used in Florida. Conclusions and Recommendations are presented in Section 8.0.

2.0 Background

Nonpoint source pollution of streams, lakes, and estuaries has been a critical concern throughout the world for several decades. Nutrients (mainly nitrogen and phosphorus), one of the main types of pollutants emanating from agricultural lands, are one of the leading causes of impairments of waterbodies in the US (USEPA, 2002). Although there are many potential contributors of nonpoint source pollution including golf courses, urban development and stream bank erosion, agriculture is the leading contributor of sediment and nutrients to streams and rivers in the United States (USEPA, 1998).

Agriculture accounts for 66 percent and 65 percent of the total national phosphorus and nitrogen discharges, respectively (Gianessi et al. (1981). Agrochemicals and animal waste are extensively used in the U.S. to increase crop production, but their improper use has caused serious water quality problems in both surface and groundwater resources. For example, the application of nitrogen fertilizer to intensively cropped areas and other crop management practices, provide a considerable source of nitrate that may move to streamflow through subsurface flow or leach deeper into the soil profile and reach the groundwater system in areas with vulnerable soils and hydrogeology. This may be exacerbated by the new world-wide move towards grain-based ethanol production (Simpson et al., 2008).

Nutrient loadings from nonpoint and point sources have resulted in hypoxic conditions in many of the world's vital water bodies. Hypoxic conditions have been increasing since 1960(http://www.wau.boku.ac.at/fileadmin/_/H81/H815/Skripten/Kanwar/Chapter09.pdf). The worst hypoxic conditions are in Baltic Sea and the Black sea. The Gulf of Mexico is the third largest hypoxic area in the world (CENR, 2000). Such degradations limit the availability of good quality water for human and habitat survival.

To combat NPS, the Federal Government enacted amendments such as the Section 208 of the Clean Water Act (CWA) in 1972. Later, in 1987, congress enacted the section 319 of the Clean Water Act where it required each state to develop and implement programs to control nonpoint sources of pollution. This amendment included sources of nonpoint source pollution such as rainfall runoff from farms, urban areas, construction sites, forestry, and mining sites (Best, 2004). Several lawsuits in late 1990s led EPA to charge each state to develop a TMDL (Total maximum Daily Load) plan for each impaired waterbody (Florida Department of Environmental Protection-Division of Water Resources Management-Bureau of Watershed Management-Stormwater/Nonpoint Source Management Section, 2000).

A TMDL is defined as the maximum allowable load of a contaminant that a waterbody can receive while still meeting its water quality standard. A water quality standard consists of the designated use assigned to the water body (e.g., swimming, fishing, drinking, etc.), the water quality criteria (either numeric or narrative statement) to meet that use, and an anti-degradation policy to protect the existing use. Section 303(d) of the act says that States must identify all water quality limited segments (WQLS) (impaired waters), prioritize them, establish TMDLs for them, and submit them to the U.S.

Environmental Protection Agency (USEPA) for approval (U.S. Congress, 1972). States must determine the stressors (pollutants) and sources of impairment for WQLSs, as well as allocate TMDLs among contributing sources. To respond to the water quality problems and to meet the TMDL requirements proper NPS assessments techniques, either monitoring or modeling, need to be employed. Such techniques need to also devise and test proper best management practices (BMPs) in order to combat NPS and meet the TMDL requirements.

Numerous BMPs have been widely implemented for decades to reduce or alleviate the pollutant loadings into water bodies. However, the effectiveness of BMP in water quality improvement needs to be carefully evaluated before implementation, especially in mixed land use watersheds. Pollutant reductions resulting from the implementation of field scale or farm-level BMPs may be measured satisfactorily over time after BMPs are implemented (Gitau et al., 2004). However, the effectiveness of individual BMPs is more difficult to evaluate at the watershed level due to the complex and spatially varying physiographic nature of watersheds.

Long-term monitoring is not only expensive but also time consuming and spatially impractical at the watershed scale (Santhi et al., 2001; Chu and Shirmohammadi, 2004), particularly for mixed land use watersheds that generate both point and nonpoint source of pollution. Therefore, mathematical modeling has become a primary technology for analyzing NPS pollution and evaluating the long-term water quality impacts due to the implementation of different BMP scenarios (Shirmohammadi et. al., 1992; Chu et al., 2005). Watershed scale models that can be used to predict the effects of agricultural activity on runoff, soil erosion, and nutrient transport, are essential to analyze nonpoint source pollution and to aid in the development of Total Maximum Daily Loads (TMDLs) (Shirmohammadi et al., 2001, 2006; Borah and Bera, 2003). Since measured data are often insufficient to thoroughly depict pollution levels within a watershed, models are being used to assess the pollutant loadings into the water bodies and determine the relative impacts of implementing different practices to combat the pollution. Choosing an appropriate model for the required analysis, conducting comprehensive model calibration and validation exercises for representative conditions as defined by the American Society of Testing and Materials (ASTM, 1984), and accurately representing all assumptions, uncertainties and limitations associated with modeling results is essential for the effective and informed use of watershed scale models to design and evaluate NPS, TMDL and BMP programs.

3.0 Evaluation of WAM's physical and hydrological processes

3.1 Conceptual Model

The conceptual model underlying WAM includes rainfall, evapotranspiration, overland flow, groundwater flow and river flow, as well as the transport and transformation of particulate and soluble phosphorus, particulate and soluble nitrogen, total suspended solids and biochemical oxygen demand in the system. The methodologies used to represent these processes range from quite empirical (e.g. the cell to stream routing of overland and groundwater flow) to more physically-based (e.g. Boussinesq equation for the shallow groundwater flow equations in EAAMOD). Decisions regarding the level of sophistication required for modeling different hydrologic processes in different domains seem to have been made by the model developers, based on intuition and experience, to improve computational efficiency or to solve particular project-specific problems. While the Panel respects and accepts the judgment of the modelers at SWET, a more rigorous discussion and justification of the level of complexity chosen for each process should be included in the written documentation. Assumptions are required for the development of all models, so they should not be viewed as a shortcoming. Rather, documentation of assumptions leads to transparency in the modeling process and improved model credibility.

The Panel recommends that a clear presentation of assumptions associated with algorithms used to quantify each component of the conceptual model underlying WAM be included in the documentation in order to provide an informed presentation and discussion of the model.

WAM uses a GIS raster or grid cell representation of a watershed (the model developers recommend a grid cell size of 1 hectare for watersheds that are 26,000 km^2 or larger). Based on soils and landuse in each grid cell, one of three field-scale models is selected and run to generate overland and groundwater flow (and associated water quality constituents) produced from each grid cell on a daily basis. The model delivers the daily overland and groundwater flows and constituents to the nearest down gradient stream based on empirical flow velocities and hydrographs that are different for surface water and groundwater, but are assumed constant over the modeled domain in both space and time. There is no cell-to-cell interaction as the water and its constituents are routed to the stream. These simplifications do not allow reinfiltration of runoff once it is generated, exfiltration of groundwater to the surface, or dynamic surface or groundwater flowpaths that may vary based on hydrologic conditions.

Water quality constituents are attenuated before being delivered to the stream based on empirical attenuation coefficients that vary with flow rate, distance and land use along the assumed flow path. Thus local spatially and temporally variable interactions of constituents with soil and aquifer materials are not considered. Once in the stream, flow is routed using a modified linear reservoir routing algorithm, and constituents are attenuated based on empirical parameters that are dependent on the wetted perimeter of

the stream channel. Flow between grid cells, groundwater and streams is unidirectional, i.e. water moves from grid cells through overland flow or groundwater to streams. In other words, once water leaves a field-scale model by overland flow or groundwater flow for delivery to the nearest stream it cannot move back into the field.

Specific details on the individual components of WAM and recommendations from the Panel are summarized below.

3.2 Field-Scale Models

WAM uses a raster analysis technique to overlay GIS coverages of rainfall zones (either theissan polygons or nexrad grids), soils, land use, and wastewater treatment services areas to identify the unique combinations of these inputs over the user-specified grid cells (typically 1 hectare) that comprise the model domain. This approach allows detailed spatial consideration of inputs and variables. Soil properties and land management practices are considered constant within a grid cell.

The Basin Unique Cell Shell program (BUCShell) selects one of three separate field-scale models to simulate each unique cell combination. The currently available field models are GLEAMS (Knisel, 1993), EAAMOD (SWET, 2008), and a special case module written specifically for WAM to handle wetlands, impervious urban areas and other unique uses such as mining operations. The default field-scale model is GLEAMS. The choice of a field-scale model other than GLEAMS is triggered for use within BUCShell by either a land use or soil code being listed in special inputs files.

It is difficult to discern from the current documentation which combinations of land uses and soils codes trigger use of which models. The Panel recommends that the model developers add a table to the documentation to make this decision process clearer.

For each unique rainfall, soils, landuse, and service area combination, the appropriate field scale model is run for one representative grid cell to generate a daily time series file of overland flow and groundwater flow with associated constituents (i.e. particulate and soluble phosphorus, particulate and soluble nitrogen, total suspended solids and biochemical oxygen demand in the system) for that unique combination.

During the November 19-20th workshop it was discovered that although the recommended grid cell size is 1 hectare, the GLEAMS and EAAMOD field-scale models both assume that that 1 hectare grid cell belongs to a "typical field" which is usually significantly larger than 1 hectare (i.e. on the order of 80-100 ha) and possesses "typical" characteristics such as overland flow lengths, field slopes and ditch/pond configurations. Thus loads are calculated off the "typical field" and then proportioned back to all 1 hectare cells in the watershed with that land use, soil, etc. on a load per unit area basis. This assumption is not discussed anywhere in the existing documentation. The Panel recommends that the model developers explain and justify this assumption in the documentation, and conduct a sensitivity analysis to look at the impact of this "typical" field assumption on important model predictions.

The field-scale models generate a daily time series file for each grid cell in the watershed. This time series file is returned to BUCShell for final post-processing for urban impervious surface contributions, wastewater generation at the source cell (sewage), and retention/detention (R/D) for edge of cell processes (See Section 3.2.4 for further discussion and recommendations regarding the post-processing methods).

3.2.1 GLEAMS

Note: The following description of GLEAMS functionality is taken largely from Shirmohammadi et al, (2001).

The Groundwater Loading Effects of Agricultural Management System (GLEAMS) model (Leonard et al., 1987 and Knisel, 1993) is a functional model used to simulate processes affecting water quality events on an agricultural field. It is the modified version of the CREAMS (Knisel, 1980) model. It is a continuous simulation model that provides more detailed prediction of water, sediment, nutrient, and pesticide movement within and through the root zone while maintaining the surface sensitivity of the CREAMS model. In order to simulate the many processes occurring on a field, the model is divided into three separate submodels. These submodels include hydrology, erosion/sediment yield, and chemical transport. The chemical transport submodel is further subdivided into nutrient and pesticide components so that one or both may be simulated as desired by the user. Knisel et al. (1989), Leonard et al. (1987), and Knisel (1993) discuss the components in detail.

The hydrology component of GLEAMS simulates runoff due to daily rainfall using a modification of the SCS curve number method. Hydrologic computations for evapotranspiration, percolation, infiltration, and runoff are determined using a daily time step (Knisel, 1993). Two options are provided in the hydrology component to estimate potential evapotranspiration. The Priestly-Taylor method (1972) using daily temperature and radiation data computed from mean monthly data is one option. The other option is the Penman-Monteith method (Jensen et al., 1990) and it requires additional data such as wind speed and dew point temperature. Water routing through the soil profile is based on the storage routing concept which allows the downward movement of water in excess of field capacity water content from one layer to the next. Comprehensive detail is provided in Knisel (1993). GLEAMS can also simulate irrigation management based maintaining a soil water content specified by the user.

The erosion component in GLEAMS is similar to the one developed for the CREAMS model (Knisel, 1980). This component considers overland, channel, impoundment, or any combination of these routes. The model uses the universal soil loss equation (USLE) and the concept of continuity of mass to predict erosion and sediment transport under different topographic and cultural conditions. Computation begins at the upper end of the overland slope. The overland flow may be selected from several possible overland flow paths. Its shape may be uniform, convex, concave, or a combination of these slopes. The

processes of detachment and deposition are both considered and each condition occurs based on the relationship between transport capacity of runoff water and sediment load.

The nutrient component of the GLEAMS model is a complex submodel and considers both nitrogen and phosphorus cycles. The nitrogen component includes: mineralization, immobilization, denitrification, ammonia volatilization, nitrogen fixation by legumes, crop N uptake, and losses of N in runoff, sediment, and percolation below the root zone. It also considers fertilizer and animal waste application. The phosphorus component includes: mineralization, immobilization, crop uptake, losses to surface runoff, sediment and leaching, and it also includes fertilizer and animal waste application. Tillage algorithms are included in the model to account for the incorporation of crop residue, fertilizer and animal waste. Soil temperature and soil moisture algorithms are also included in the model to provide proper adjustments for ammonification, nitrification, denitrification, volatilization, and mineralization rates. Rainfall nitrogen is an input for the model and may vary depending upon the study region. Initial soil total N and total P are sensitive parameters in the model. For a detailed description of the nutrient component see Knisel (1993).

GLEAMS is a well-tested model that has been applied in many locations around the world. *It is the Panel's opinion that GLEAMS is a suitable model for field-scale simulation of the effect of management practices on water, nutrients and pesticide loadings from agricultural land uses in well-drained soils in Florida.*

3.2.2 EAAMOD

EAAMOD is the field-scale model used for high-water table soils. EAAMOD was initially developed by SWET for the high water table conditions in the Everglades Agricultural Area (EAA) but has since been expanded for use in more general high water table soil conditions. EAAMOD has been used in the Everglades Agricultural Region, the Okeechobee Basin and the St. Johns River Basin in Florida. An earlier version of EAAMOD was peer reviewed in 1994-95. Two of the members of the current Panel, Drs. Graham and Skaggs participated in the 1994-95 review. A copy of the charge to the committee, their individual comments and recommendations, and a synthesis of the recommendations are attached as Appendix B to this report. Since that time, components have been added to handle nitrogen, and other changes have been made to the phosphorus algorithms and to optimize run times. The basic hydrologic components appear to be the same.

Like GLEAMS, EAAMOD contains sub-modules to simulate hydrology/hydraulics, phosphorus transport and transformation and nitrogen transport and transformation. For consistency across the watershed EAAMOD uses the potential ET calculated by the GLEAMS field-scale model. The groundwater flow model within EAAMOD uses the Dupuit-Forcheimer assumption (assumes flowlines are horizontal and the hydraulic gradient is equal to the slope of the water table and invariant with depth, (Freeze and Cherry, 1979)). It considers two separate flow regimes in the profile, namely above and below an impeding layer such as the spodic horizon in flatwood soils and the marl

caprock in Histosols. The resulting one dimensional horizontal flow equations provide the water table depth and horizontal flow for each cell across the field between drainage ditches above the impeding layer, and the piezometric head and horizontal flow below the impeding layer. The flow through the impeding layer is determined using Darcy's Law across the impeding layer with the gradient across the layer being the difference between the water table above it and the piezometric head below it. In a similar manner to DRAINMOD (Skaggs, 1978), the model keeps track of air void volume above the water table by assuming "drained to equilibrium" assumptions.

It is the Panel's opinion that the basic approach chosen to represent water movement and storage in the subsurface is appropriate. However the methods are not fully documented in the report, so it is not possible to evaluate the appropriateness of the actual algorithm and solution methods used. A few examples of issues requiring clarification and explanation are given below. While these details are not important to the model user, they are important for determining the appropriateness and correctness of the approach. Many of the needs and suggestions given below were identified in the 1994-95 peer review.

- *There is no explanation of how Q(i) is calculated in the first equation on p. 5 of the Technical Manual. It is stated that Darcy's law is used, but no explanation of how head gradients are calculated or what finite difference approximations are used. Furthermore it is not clear how the units of this equation are reconciled, i.e. although all quantities in the equation have units of inches per hour Darcy flux is measured in volumetric flow rate per <u>unit of vertical cross-sectional area</u>, rainfall and evapotranspiration are measured in volumetric flow rate per <u>unit of horizontal cross-sectional area</u> , and change in storage is the volumetric rate of change in water storage per <u>unit horizontal cross-sectional area</u>. Finally the meaning of the statement "The calculated flow is always for the left side of the cell" is unclear.*
- *It appears there may be a sign error on the right hand side of the second equation on p. 5 if S is the air void volume and DS is the change in water storage as indicated in the text. A positive value of DS indicates increased water storage according to the first equation on this page. It should therefore lead to decreased air void volume in the second equation on this page. However there is some confusion as to what DS actually represents in the first equation on p.5. The definition says change in water storage but units are (inches of air void/hr). If DS is change in air storage, second equation is correct, but the signs for R, ET, and QS in the first equation are wrong. These inconsistencies need to be resolved.*
- *It is stated that the elevation of the water table is determined by an air void volume versus water table depth relationship (different for wetting and drying conditions) that is provided by the user. Guidelines are given for how to obtain the wetting condition, but no explanation is given for how the drying condition might be obtained. The assumption that the water table will remain static unless water is added/removed beyond the wet/dry storage limits may be questionable and should be explained and justified.*

- *The equation for flow in the bottom horizon is written in terms of Darcy flux (Q) in the first equation on p. 8 then in terms of the water table elevation (H) in the upper horizon and the hydraulic head (h) in the lower horizon in the second equation on p. 8. An intermediate equation is needed that expresses Q in terms of H and h to help the reader follow this derivation. Note that the units in this equation are not clear as Q' is horizontal flow and QS is vertical flow. Are all quantities $in^3/time/in^2$ of surface area? Equation numbers would be helpful throughout the document.*
- *It is stated (top of p. 8) that the head distribution in the bottom horizon is determined by assuming that the bottom zone is "always saturated and therefore no water storage change can occur." This assumption needs more explanation and justification. Water storage changes in confined saturated aquifers can occur as a result of changes in water density and changes in porosity due to the compressibility of the fluid and aquifer material respectively. Under these mechanisms changes in water storage result in changes in hydraulic head without resulting in changes in total aquifer volume. It is possible that the model developers are assuming that there is steady-state flow in the bottom horizon, but this is not clear since no information is given about how these equations are solved through time. There is also no information given regarding how boundary conditions are applied.*

According to the EAAMOD Technical Reference Manual (SWET, 2008), overland flow to the ditches can occur when water is ponded on the land surface above the ditch water elevation, or water can flow from the ditch to the land surface when ditch water levels exceed land cell water levels. Boundary conditions can be set to the field ditches and/or neighboring secondary canals, allowing flow under field ditches to larger canals when the field ditches are not cut through the impeding layer. However no equations, flow diagrams or schematic diagrams are given in the Reference Manual to explain the mechanisms or procedures used to achieve ponding or accomplish overland flow. It is stated on p. 5 that it is assumed that infiltration capacity always exceed rainfall rates, implying only saturation excess overland flow occurs. However Figure 1 (p. 6) seems to show ponded water on the land surface above unsaturated soil, indicating an infiltration excess runoff condition. Furthermore it is not clear from the documentation whether cell to cell interaction occurs (i.e. re-infiltration of ponded water, erosion or deposition of sediments, nutrient interactions) during the overland flow process.

The Panel recommends that complete and accurate equations, flow diagrams and schematic diagrams be presented in the documentation to explain the mechanisms leading to surface ponding and overland flow in EAAMOD. This will allow users to judge the appropriateness and correctness of the approach and to better determine whether EAAMOD is a suitable field model for their application.

According to the Technical Manual, the P and N submodels handle the basic processes of soil organic matter mineralization, P adsorption process, sediment P and N detachment in both the field ditch and surface flow, N and P plant uptake, N denitrification and volatilization, and accretion. The P and N submodels are linked with the hydraulic

component to allow the movement of the P and N forms with the water.

The conceptual origin of the P and N models is not clearly established in the documentation. The P model is based on a conceptual model developed by Drs. Robert Mansel, Dean Rhue and Suresh Rao in the Soil and Water Science Department of the University of Florida, however no specific references are given. The N model seems to be an in-house development by SWET. The components contained in the N model are similar to those often found in well-established N models, however a general lack of references supporting the specific assumptions in EAAMOD did not allow the Panel to evaluate their scientific soundness. As an example, where are the temperature transformation rates in Figs. 4-7 (EAAMOD Technical Manual) taken from? Are those applicable for high water, high organic soil conditions? What is the additional enrichment coefficient used for sediment N transport? How was the assumption that "to emulate the bacterial growth dynamics, nitrification has a 2-day lag time while denitrification has a 0.5-day lag time, and all other processes are considered instantaneous" tested for the Florida conditions? In Fig. 3, how would direct volatilization (V) of organic soluble N happen? Would this not be through ammonia transformation instead of a direct process? Wouldn't the volatilization processes belong to the "Gas" column to the right of the graph?

It is the Panel's opinion that the conceptual model of the processes affecting the fate and transport of P and N in EAAMOD are reasonable based on the descriptions given in the report. However the processes and the methods used to quantify them are not fully described or properly referenced. Thus it is not possible to assess the technical correctness of the assumptions made in representing these processes.

Components of the hydrologic algorithms within EAAMOD have undergone a modest degree of testing against available analytic solutions. However, in the case of the nutrient components (P and N) the developers rely solely on comparison with previously measured data for model verification because no analytical solutions are available for comparison. One parameter at a time sensitivity analyses have been conducted for the model parameters affecting hydrologic and P transport and transformation predictions, but it is not clear that equivalent sensitivity analyses have been done for N transport and transformation predictions. Manual calibration techniques with simple visual (graphical) comparisons of observed versus predicted variables have been conducted for four applications of EAAMOD in Florida, but only one of these contain nitrogen observations. Section 6 of this report further discusses the adequacy of the calibration/validation procedures used for WAM model testing.

The basic hydrologic and nutrient modeling approaches in EAAMOD appear to be suitable for simulation of water and nutrients loadings from agricultural land uses in high water table conditions in Florida, but the current EAAMOD documentation is insufficient to support an in-depth review of the methods. The Panel recommends that the EAAMOD Technical Manual be revised to include complete descriptions of the actual equations and algorithms encoded in the model for all hydrologic, P transport and transformation and N transport and transformation processes. The Panel also

recommends that the Model developers complete the sensitivity analysis on the nitrogen submodel, and continue to build their library of calibrated and verified applications of EAAMOD using the techniques recommended in Section 6 of this report.

3.2.3 Wetlands and other special case models

For special case land uses such as wetlands, open water, and aquaculture operations, WAM uses a simplified water balance method to calculate daily water volumes contributing to surface runoff and groundwater. The water balance calculates change in water storage in the cell as the daily difference between rainfall as input and evapotranspiration (potential evapotranspiration times a user-specified evaporation adjustment factor), runoff (assumed to be ten percent of the depth of water in the cell over a user-specified depth at which runoff initiates per day), and percolation to groundwater (a user-specified constant rate) as outputs. Runoff and groundwater volumes leaving the cell are then multiplied by constant user-specified sediment, nutrient, and BOD concentrations to get constituent loads.

The assumptions underlying this simple water balance (i.e. surface runoff algorithm, constant percolation rate, constant constituent algorithms) are not discussed or justified in the documentation. In addition there is an error in the water balance equations on p. 13 of the documentation.

The Panel recommends that the model developers correct the apparent typographical error in the water balance equation, explain and justify all assumptions used to calculate the terms of the water balance and conduct a sensitivity analysis to look at the impact of these assumptions and user-specified parameter values on important model predictions.

3.2.4 Post-Processing for impervious surfaces, sewage and stormwater ponds

The GLEAMS and EAAMOD field-scale models are used to simulate water, nutrient, and sediment transport for the vegetated (pervious) portions of each grid cell according the fraction of the cell that the user-specifies as vegetated (fcrop). It is assumed that the remainder of the cell is impervious and produces runoff with constant user-specified constituent concentrations using an NRCS curve number of 99. A user-specified fraction of the runoff (with associated constituents) is assumed to re-infiltrate to groundwater through natural on-site retention. Water and constituent loads from the impervious areas are added to those from the vegetated area as the water leaves the cell. At the current time only GLEAMS can be used to simulate vegetated areas in urban, industrial or residential areas.

Additions of water and nutrients as a result of the disposal of human waste (sewage) are made for each cell based on the user-specified population density for the cell and type of sewage system (septic, failed septic, raw sewage, secondary treatment and tertiary treatment). If a retention or detention system exists in a cell, all surface runoff is routed to the system where a separate water balance is maintained.

It is the Panel's opinion that the assumptions incorporated in the post-processing algorithms are generally reasonable and appropriate given the scale and intended purpose of the WAM model. The Panel recommends that the default concentrations for constituents coming off impervious surfaces, and the constituent concentrations for the various levels of wastewater treatment be provided in a table in the documentation. References (preferably peer reviewed) for the origins of these values should be provided. In addition, justification and relevant citations for the use of constant concentrations for impervious runoff need to be included. It is unclear how wastewater treatment service areas are handled. More details regarding this implementation should be included in the documentation.

3.3 Routing Algorithms

The Basin Land Area to Stream Routing model (BLASROUTE) routes the surface runoff, groundwater and constituent loads generated by the grid cells to the closest stream reach and through the basin's stream network.

3.3.1 Overland Flow

Surface runoff generated by the field scale models is released from the grid cell over a 3 day period according to a user-specified unit hydrograph and then routed to the nearest downstream feature (which may be a stream, wetland or depression) using the following equation:

Time of travel to feature (t) = constant surface delay factor (k) + distance to feature/ surface water velocity (d/v)

The distance to the nearest feature is calculated using ESRI's least cost distance function that finds the minimal downhill distance to these features by weighting flow distance with topographic slope. The constant delay factor and surface water velocity must be specified by the user and are constant over the modeled domain.

If the nearest feature to the cell is a wetland then the distance from the wetland to the nearest stream is also calculated using the ESRI least cost distance function. The surface runoff is then routed from the wetland to the stream using the time of travel equation above. If the nearest feature to the cell is a depression then the surface runoff becomes groundwater. No cell-to-cell interaction occurs along the flow path.

Although inadequately explained in the model documentation (for example the delay factor and surface water velocity above are not discussed at all), it is the Panel's opinion that the cell-to-stream overland flow routing algorithm is a simplistic but computationally efficient means of overland flow routing that is appropriate for evaluating the hydrologic response of large watersheds where parameterizing more detailed flow routing equations is unrealistic. However the Panel recommends that the documentation be re-written to more thoroughly detail the actual algorithm used and to more thoroughly explain and justify the underlying assumptions.

Furthermore the Panel questions the statement in the documentation that "in all WAM applications to date three days has proved to be a sufficient delay for all surface water to reach the stream network". The Panel recommends that sensitivity of model predictions to the 3 day hydrograph assumption and the constant delay factor and surface water velocity be explored and documented. These factors, together with the flow attenuation that likely results from the "typical farm" assumption discussed above, all impact the timing of surface runoff delivery to the stream system and the relative importance and sensitivity of each of these contributions should be better defined.

3.3.2 Groundwater Flow

Groundwater generated by the field scale models is released from the grid cell over a 90 day period according to a user-input exponential unit hydrograph (default unit hydrograph has a 90 day duration). It is then routed to the nearest downstream feature (stream or depression) using the following equation:

Time of travel to feature (t) = constant groundwater delay factor (k) + distance to feature/ ground water velocity (d/v)

By default groundwater is routed to the nearest feature according to the Euclidean distance to that feature. If the user has specific information that the groundwater contributes to a stream at a location other than the nearest reach (for example based on prior knowledge of springshed boundaries), the user can over-ride the default option and specify the receiving stream reach during the model set-up procedure.

As for the surface water, the delay factor and groundwater velocity must be specified by the user and are constant over the modeled domain. Also, as in the surface water algorithm, no cell-to-cell interaction occurs along the groundwater flow path.

The cell-to stream ground flow routing algorithm is a simplistic but computationally efficient means of groundwater flow routing that may be appropriate for shallow flow through surficial aquifers. However in situations where regional aquifers (e.g. the Floridan aquifer) interact with the stream system it may not be appropriate. As with the overland flow routing algorithm, the Panel recommends that the documentation be re-written to more thoroughly detail the actual algorithm used to route groundwater flow and to more thoroughly document the underlying assumptions and their limitations. The Panel also recommends that sensitivity of model predictions to the 90 day hydrograph assumption (developed based on recession curves in flatwoods areas) and the constant delay factor and groundwater velocity be explored and documented.

3.3.3 Stream Flow

In WAM flow is routed through the stream network using a mass balance approach that incorporates three major assumptions:

1) the stream discharge can be estimated using Manning's equation where the energy slope is approximately equal to the water surface slope, i.e.$Q \approx \frac{AR^{2/3}S^{1/2}}{n}$, where Q is stream discharge (L^3/T), A is cross sectional area of the stream (L^2), R is the hydraulic radius (cross-sectional area divided by wetted perimeter, (L)), S is the water surface slope (-), and n is Manning's coefficient.

2) the stream reach behaves approximately like a linear reservoir so that the storage discharge relationship can be approximated by, $V = \frac{1}{K}Q$, where V is the storage (L^3) in the reach, Q is the discharge through the reach (L^3/T), and K (1/T) can be approximated from the derivative of Manning's equation i.e.$K = \frac{dQ}{dV} = \frac{dQ/dh}{dV/dh}$, where h is the height of water in the stream.

3) Streams do not interact with overland flow, ponded water, or groundwater except to receive flow according to the pre-specified input hydrographs.

In the Panel's opinion these assumptions are somewhat unconventional. Typically when calculating stream discharge using Manning's equation the energy slope is assumed to be either equal to the channel bottom slope (the kinematic wave assumption) or equal to the difference between the channel bottom slope and the water surface slope (diffusion wave assumption (Bras, 1990; Viessman et al, 1989)).

In addition the assumption that the linear reservoir constant, K, can be estimated from Manning's equation appears to be a variant on the Muskingham routing method (Bras, 1990; Viessman et a, 1989) that has not been reported in the literature to the best of the Panel's knowledge. The underlying basis for this assumption should be explored and justified. Furthermore the derivation of the routing equations is confusing and appears to be in error and/or incomplete in some places. For example

- precipitation, evapotranspiration and leakage from the stream to groundwater appear to be missing from equation 1 on p. 26. If these terms are not included in the mass balance equation these assumptions should be explicitly stated and justified;
- the use of subscript j is inconsistent in equations 1-23, particularly in reference to water slope variable s;
- it is unclear how the contribution of overland and groundwater flow to the reach ($q_{i,\ land}$ in equation 1 p. 26) factor into the derivation of K (i.e. is $dq_{i,land}/dV_i$ assumed to be zero in equation 8?);
- it is unclear how equation 11 was derived. The equation used to calculate slope should be specified and the origin of the terms Q_i and Q_j in this equation explained.
- it is unclear if the calculations of Q_{i,t_0} in equations 21-23 include $q_{i,land.}$ (we think they should)

The Panel recommends that the assumptions underlying the routing method be better described and justified in the documentation. It may be useful to contrast the conceptual underpinnings of this method to the more commonly used Muskingham method, the kinematic wave method, the diffusion wave method and the full dynamic wave equations, and to explain why this unique method is preferable to more conventional methods of stream routing.

The Panel also recommends that more detail be included in the derivations of the routing equations (equations 1-23 on p. 28) and that the errors and notational inconsistencies be corrected. It may be clearer if the derivation is re-written to proceed as follows:

- *presentation of the mass balance equation including precipitation, evaporation, and seepage (if appropriate)*
- *introduction/justification of the use of Manning's equation as the flux law (including the use of water slope as the energy slope)*
- *introduction/justification of the linear reservoir assumption to account for the storage/discharge relationship*
- *explanation/justification of the use of manning's equation to derive the reservoir constant K*
- *detailed derivation of K*
- *details for the solution for storage, discharge and stage as a function of time*
- *discussion of how boundary conditions (particularly tidal boundaries) enter into the simulation.*

The comparison of the WAM routing method with the full dynamic wave equation (solved in the DuFLow model) for the particular example presented in the documentation shows good agreement after about 5 hours when the transient effects of the initial condition appear to be smoothed out. This is an indication that the WAM routing method may give satisfactory results at longer scales (i.e. daily, weekly, monthly, or annual averages).

The panel recommends that the WAM stream routing algorithm be more rigorously classified in terms of other published flow routing methods, and that it be evaluated against published routing methods over a larger range of test problems to reveal its strengths and weaknesses. The algorithm should then be documented in the WAM technical manual and/or in the peer reviewed literature.

3.3.4 Hydraulic Structures and Point Sources/Withdrawals of Water

Weirs, top- or bottom-opening gated structures, culverts and pumps can be placed at the top or bottom of any stream reach or reservoir using standard weir equations or specified operating rules. Known point sources of domestic or industrial effluent (or direct surface water withdrawals) can be added to (or subtracted from) any stream reach. Known groundwater withdrawals from the surficial aquifer beneath a sub-basin are withdrawn from the receiving stream reach for that sub-basin. If insufficient water for surface water withdrawals exists in the stream reach water is taken from the next downstream reach. If

insufficient water for groundwater withdrawals exists in the stream reach a groundwater deficit pool is created which must be refilled with groundwater before groundwater flow to the stream reoccurs.

It is the Panel's opinion that hydraulic structures and point sources/withdrawals of surface water are well represented in the WAM model from a water balance perspective. Because WAM was developed specifically for conditions in Florida where a wide range of hydraulic structures, pumps, etc. are frequently encountered, WAM handles these conditions more easily than most of the competing watershed scale models. However the representation of groundwater withdrawals is a significant simplification.

3. 4 Constituent Transport and Transformation

No physically-based nutrient transformations occur after nutrients are generated by the field-scale models. Details of the empirical attenuation processes that are assumed to occur during overland, groundwater and stream flow are summarized below.

3.4.1 Overland Flow

Once surface runoff leaves a source cell its constituents are attenuated before being delivered to the nearest feature (stream, wetland or depression) using the following equation:

$$C = C_0 + (C_0 - C_b)e^{-ad\,q^{-b}}$$

where C is the concentration of the constituent at the end of the flow path (and on delivery to the next feature), C_0 is the constituent concentration at the beginning of the flowpath, C_b is the background constituent concentration in the source cell, q is the overland flow volume leaving the source cell during that day, and d is the flow distance calculated using the ESRI least cost function as detailed above. Parameters C_b, a and b are user-specified parameters for each constituent based on the land use of the cell of origin.

The Panel recognizes the need for developing a simplified conceptual model for nutrient and sediment attenuation in large watershed models. However the Panel recommends that the sensitivity of important model predictions to the form of the attenuation equation (particularly the nonlinearity introduced by the term q^{-b}), as well as to the values of the parameters C_b, a and b be explored and discussed. Since parameters C_b, a and b are essentially unmeasurable, a table of values used for past applications, and guidelines for determining their values for specific applications should be provided.

3.4.2 Groundwater Flow

The documentation states that source loads are attenuated in groundwater, but does not give the algorithms used for this attenuation. During the November 19-20th workshop the model developers indicated that removal of 100% of sediment, 90% of phosphorus, and

20% of nitrogen is predicted when they are carried by groundwater, regardless of flow distance, flows volume etc.

The Panel recommends that all algorithms for attenuation of constituents in groundwater be included explicitly in the documentation. All assumptions associated with these algorithms should be explained and justified, and sensitivity to these assumptions evaluated. It is the panel's opinion that although the groundwater flow and attenuation algorithms may be sufficient to deliver water and constituents to the streams, the methods are very approximate, as they do not consider the physical groundwater flow, transport and transformation processes. Therefore WAM should not be used to estimate local groundwater concentrations.

3.4.3 Stream Network

The attenuation of sediments and nutrients during a stream flow simulation time-step, τ, is calculated using the following equation:

$$C(\tau) = C_b + (C_0 - C_b)e^{-(a\tau/R)}$$

Where C (τ) is the concentration of the constituent at the end of the time step of length τ, C_b is the background concentration of the constituent in the reach, C_0 is the concentration of the constituent at the beginning of the time step, R is the hydraulic radius of the stream reach (stream area divided by wetted perimeter), and a is a user specified attenuation parameter.

The above equation is used to attenuate constituents in streams, canals, lakes and sloughs. The overland flow attenuation equation is used to attenuate constituents as they travel over uplands, and through wetlands and depressions.

The Panel recommends that the sensitivity of important model predictions to the value of the parameter, a, be explored and discussed. Since this parameter is essentially unmeasurable, guidelines for determining its values should be provided. A table of all default attenuation factors, along with pertinent references and assumptions, should be provided in the model documentation.

The concept of a "fuzzy" reach is briefly introduced in the WAM documentation (p. 15) as an intermediate between overland flow/attenuation and channel flow/ attenuation. According to discussions during the November 19-20th workshop, a reach can be designated as "fuzzy" if the user wishes to calculate overland attenuation based on the distance to this reach, but does not want to begin computation of channel flow in this reach. In this case water and constituents are delivered to the nearest reach that is designated as a "computational" channel, but constituents are attenuated based only on the distance to the closer "fuzzy" reach. Apparently, fuzzy reaches are used to limit attenuation of constituents in the overland flow algorithm while reducing the computation time required to route water and attenuate constituents in the stream network.

The Panel recommends that the "fuzzy reach" concept be further explained and justified in the documentation, and sensitivity of important model predictions to implementation of this concept should be explored. Guidelines and implications for designating a reach as fuzzy should be detailed in the documentation since this is an unconventional construct.

4.0 Evaluation of the methodology by which watershed-scale management rules and best management practices are implemented in the model

Best management practices (BMPs), both structural and non-structural, are implemented as a single practice or as a system of practices to reduce nonpoint source pollution (NPS) inputs to receiving waters (Chu, et. al., 2005). According to the Soil and Water Conservation Society (SWCS), BMPs are referred to as practices or combinations of practices that may be selected and used in a given area to control both point and nonpoint source pollution in a practical, economical, and institutionally feasible manner. SWET (2008) uses the BMP definition given by the Florida Department of Agriculture and Consumer Services, which states "*BMPs are practical, cost-effective actions that agricultural and urban landowners or managers can take to reduce the amount of pesticides, fertilizers, animal waste, and other pollutants entering our water resources*." Mostaghimi et al. (2001) provide a detailed discussion of different BMPS, both non-structural and structural.

To evaluate watershed scale effects of BMPs, WAM relies upon the strength of the advanced version of the field-scale CREAMS model known as the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Leonard, et al., 1987; Knisel, 1993) and two other field scale models, EAAMOD (SWET, 2008) and a special case model, developed specifically for WAM (SWET, 2008), that handles land uses such as wetlands, open waters, mining operations, and aquaculture operations. WAM has an advanced and sophisticated pixel-based GIS interface, which makes hydrologic and NPS simulations for diverse soils and land use scenarios convenient and input and output data manipulation robust.

Each field-scale model has its own level of complexity depending upon the algorithms used and the level of input required. Model documentation for each field-scale model must highlight its strengths, weaknesses, level of input data required and ease of use, so that users can evaluate which field-scale model best fits their application (Shirmohammadi et. al., 2001a). Models that have been exposed to extensive calibration and validation processes are a better choice compared to those that have not had such tests. The GLEAMS model (Knisel, 1993) has been calibrated and tested in many parts of the United States and around the world (Shirmohammadi et al., 2001b). Therefore, having GLEAMS as a unit management model structured inside of the WAM is a great advantage for NPS assessment and BMP evaluation for agricultural systems. The other two field scale models, EAAMOD, and the model for the special land use scenarios (SWET, 2008) have been developed by the WAM team for specific high water table conditions and other land uses such as wetlands and open bodies of water in Florida, and thus may be more appropriate for specific Florida conditions. These two models have been tested for some Florida conditions (e.g. Zhang and Gornak, 1999, SWET, 2008) and on a limited level for the conditions in New Zealand (SWET, 2008). However, their use in other physiographic regions requires further testing and evaluation.

The Panel recommends that WAM developers more rigorously document the level of testing and review that EAAMOD and the model for the special case land uses have gone through. Special features of these two models should be highlighted and their appropriateness for Florida conditions should be documented compared to the other unit management or watershed scale models that exist (e.g. HSPF and SWAT). The WAM documentation should be revised to highlight the strengths, weaknesses, and level of input data required for each field-scale model so that the user can make appropriate decisions in selecting the most appropriate field-scale models for each soil/land use configuration.

In general the field-scale models within WAM are used to simulate fertility and water management BMPs for both urban and agricultural land uses (page 35 of Assessment Report of Caloosahatchee River Basin, SWET, 2007). In the Caloosahatchee River Basin report a table is provided that lists assumed characteristics for the agricultural and urban land management practices that are selectable from the "Apply BMP" menu in the WAM interface. These BMPs can either be used as a single BMP or in combination depending upon the nutrient reduction needs and the cost of implementation. Other BMPs, e.g. street sweeping in urban areas, and installation of regional treatment facilities are not simulated using process models, but are applied with assumed efficacies.

The Panel recommends that a table (similar to the Table 2 in the report referenced above) summarizing and precisely defining all BMPs that are available within WAM be included in the model documentation. Comprehensive listings of BMPs for Florida can be found in the Florida Department of Agricultural and Consumer Services' many BMP manuals (see e.g. FDACS (2005), FDEP (2000),Florida Green Industries, (2002)) . References for the basis and assumptions associated with each BMP should be included in the table, and it should be clear from the table which BMP efficacies are simulated and which are assumed a priori. This information will be helpful for model users and stakeholders and will provide more confidence in the values that are contained in the "Apply BMP" menu in WAM's structure.

Each field scale model (e.g., GLEAMS and EAAMOD) imbedded in the WAM has its own structure and format for the representation of different soils, cropping systems, tillage, nutrient application regimes, etc. For example, the original GLEAMS model (Knisel, 1993) has its own front end set of software for compiling input parameters. It also has a User's manual with step-by-step instructions for each input parameter. The WAM developers have appropriately imbedded the features of the field scale models into the WAM model, but sufficient instructions are not provided in the WAM documentation for model users to understand how these models are implemented.

The Panel recommends including a section at the end of the Technical Model Documentation to provide some instructions as to how to compile parameters controlling different BMPs in WAM. They do not need to go into a detailed parameter-by-parameter instruction, rather they should give some direction as to how the user should go about assembling rainfall data, temperature data, parameter values for GLEAMS, parameter values for EAAMOD, etc. They should refer the user to each model's previously

published user's manual while providing a sample example in the documentation for few of the parameters.

In summary the Panel finds that the field scale models with WAM are generally appropriate to simulate BMPs for Florida conditions. They are capable of considering almost every land feature and BMP that may be implementable in Florida. Developers of the model have made extensive efforts to represent all possible land management systems, both agriculture and urban. WAM's strength relies on both its versatile GIS interface and its use of unit management models such as GLEAMS and EAAMOD. The GIS interface permits consideration of spatial variability in land use, soils and management practices to very small unit of management with a cell size of 1 ha. Simulation of BMPs in the unit cell source areas by well tested and validated models, such as GLEAMS, is a great advantage. Nevertheless the EAAMOD model and its technical documentation must be improved as summarized above in order to provide the credibility needed for others to reliably use this field-scale model.

5.0 Evaluation of the methods by which the model has been calibrated and validated for an example application

This section first presents standard practices for calibration and testing of watershed models as a reference for the discussion of the methods used for the WAM model. This is followed by the evaluation of the methods by which the model has been calibrated/ validated as presented in the Technical Manual and the sample application (Caloosahatchee River, 2007) report.

5.1 Recommended standard practices for calibration and testing of watershed models

Calibration and validation have been defined by the American Society of Testing and Materials, as follows (ASTM, 1984):

- calibration is a test of the model with known input and output information that is used to adjust or estimate factors for which data are not available;
- validation is a comparison of model results with numerical data independently derived from experiments or observations of the environment.

Donigian (2002) suggests that good modeling practice requires three phases related to initial model parameterization (Phase I), calibration/validation (Phase II), and analysis of alternatives (Phase III). For this, experimental datasets must be first selected and then compared with simulated values. When calibrating/verifying a model, some criteria must be defined to evaluate the goodness-of-fit of the model simulation using the estimated parameters. Several authors point out that to assess the performance of the model calibration and subsequent verification, the use of a single statistic might be misleading and instead a combination of several statistics and graphical analysis should be used (Berthouex and Brown, 2002; James and Burges, 1982; Tufte, 1983; Legates and McCabe, 1999; Moriasi et al., 2007). This “weight-of-evidence” approach (Donigian, 2002) based on the combination of these techniques constitutes the required standard practice to calibrate/validate watershed models used in exposure/risk and environmental assessment studies today. The selection of the best combination of model efficiency measures should judiciously reflect the intended use of the model and the model outputs and ranges for a particular application (Janssen and Heuberger, 1995).

5.1.1 Selection of experimental calibration/validation datasets

A split-sample calibration/validation procedure is commonly used and recommended for watershed modeling studies (Donigian, 2002). The procedure consists of the separation of the experimental dataset into two independent subsets one of which will be used for parameter calibration based on an inverse modeling procedure, and the second for testing of the model using the parameters identified in the calibration process without further modification. In the split of the complete data set it is important to select two periods of data that sufficiently explore the full range of values that the model will be used for. Each

of the independent subsets can contain discontinuous periods to ensure full testing of the experimental range during the calibration and verification process.

5.1.2 Selection of important parameters and ranges used in the calibration and validation process

The selection of model parameters to be used in the model calibration/validation process must rely on an objective determination of the parameters relative importance for a specific application. This is especially critical for complex environmental models where the importance of parameters might change for each specific application, especially in a model like WAM where the structure (model components used) is dynamically modified through BUCSHELL.

The role of the sensitivity analysis is to determine the strength of the relation between a given uncertain input factor (parameter) and the model outputs. Saltelli et al. (2004) indicate that the formal application of sensitivity analysis allows the modeler to:

- examine model behavior
- simplify the model
- identify important input factors and interactions to guide the calibration of the model
- identify input data or parameters that should be measured or estimated more accurately to reduce the uncertainty of the model outputs
- identify optimal locations where additional data should be measured to reduce the uncertainty of the model

The sensitivity of a model output to a given input factor has been traditionally expressed mathematically as the derivative of the model output with respect to the input, sometimes normalized by either the central values where the derivative is calculated or by the standard deviations of the input and output values (Haan et al., 1995). These sensitivity measurements are "local" because they are fixed to a point (base value) or narrow range where the derivative is taken. Local sensitivity indexes are classified as "one−parameter−at−a−time" (OAT) methods, i.e. they quantify the effect of a single parameter by assuming all others are fixed (Saltelli et al., 2004).

Local OAT sensitivity indices are only efficient if all factors in a model produce linear output responses, or if some type of average can be used over the parametric space. When the model outputs' responses to changes in the input factors are non−linear, an alternative "global" sensitivity approach, where the entire parametric space of the model is explored simultaneously for all input factors, is needed. The advantage of the global approach over a local OAT method is that it results in the overall ranking of parameter importance and provides information not only about the direct (first order) effect of the individual factors over the output, but also about their interaction (higher order) effects. Different types of global sensitivity methods can be selected based on the objective of the analysis, the number of uncertain input factors, the degree of regularity of the model, and the computing time for single model simulation (Cukier et al., 1973, 1978; Koda et al., 1979; Morris, 1991; Saltelli et al., 2000a, 2004; Sobol, 1990; Wallach et al., 2006). Examples

of applications of global techniques to water quality models can be found in van Griensven et al. (2006) and Muñoz-Carpena et al. (2007).

5.1.3 Graphical comparison of measured vs. simulated results

Visual inspection of the model results can be made through graphical comparison of time series of measured data superimposed with simulated values, cumulative time series, and cumulative frequency distributions of observed and simulated fluxes or state variable (flow duration curves), scatter plots of measured vs. simulated values plotted with a 1:1 line (line of perfect agreement), and residual and outlier graphical analysis (James and Burges, 1982; Legates and McCabe, 1999; Donigian, 2002). Proper use of these graphical tools provides the modeler an assessment of model agreement and identification of common types of errors/deviations such as overall fitting, bias (systematic vs. random), mass balance, behavior at low/high output ranges, etc. Graphical analysis becomes cumbersome in distributed models when the same type of data (model output) is available at different locations, or when many different outputs are considered. In addition, automatic inverse calibration procedures typically rely on calculated performance measures (statistics) and do not accommodate graphical evidence well. In spite of this, good hydrological judgment of model performance must include the visual inspection of results by the user and not rely entirely on automated calculations of statistics. Balanced manual-automatic interactions avoids subjectivity of the results and ensures the overall quality of the calibration/validation effort (James and Burges, 1982).

5.1.4 Statistical comparison of measured vs. simulated results

Many statistics of goodness-of-fit have been suggested for model evaluation. However, the use of simple correlation or correlation-based measures (Pearson's r, non-linear regression coefficient, R^2) should be avoided since these measures are oversensitive to extreme values (outliers) and are insensitive to additive and proportional differences between model predictions and observations (Berthouex and Brown, 2002; Legates and McCabe, 1999; McCuen, 1975). Similarly, a simple linear regression of measured vs. predicted values must be avoided since it does not assess goodness-of-fit but a measure of the systematic relationship between the series compared. Instead, summary statistics and absolute error measures have been proposed (Legates and McCabe, 1999). Most of the proposed indexes present limitations and must be used judiciously and in combination with others. For example, the coefficient of efficiency (Nash and Sutcliffe, 1970), C_{eff}, and the index of agreement (Legates and McCabe, 1999) have been widely shown to effectively evaluate the performance of hydrologic models. However, it can present limitations in some applications (Krause et al., 2005; McCuen et al, 2006) that warrant the need to combine it with other statistics and graphical analysis. Legates and McCabe (1999) propose (Table 1) the combined use of C_{eff} with the root mean square error (also called residual variation or standard error of estimate), RMSE, as useful measures of the prediction capability of a model since they indicate the precision with which the model estimates the value of the dependent variable (Berthouex and Brown, 2002). Other similar statistics like the percent bias and the ratio of the RMSE to the standard deviation of the measured data could also be used (Moriasi et al., 2007).

Table 1. Statistics used in assessing the model performance with the optimized parameters.

Statistic	Equation	Best fit
Coefficient of efficiency	$C_{eff} = 1 - \frac{\sum_{i=1}^{N}\left(Y_{o_i} - Y_{s_i}\right)^2}{\sum_{i=1}^{N}\left(Y_{o_i} - \overline{Y}_o\right)^2}$	1.0
Root Mean Square Error	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Y_{o_i} - Y_{s_i}\right)^2}{N}}$	0.0

where Y_{oi} and Y_{si} are the observed and the predicted values at time t_i, respectively; N is the total number of data pairs; $\overline{Y}_o$ is the average of the observed values.

The Panel recommends that established goodness-of-fit criteria, consisting of a combination of graphical comparison of measured vs. simulated values, and summary statistics (coefficient of efficiency, index of agreement, etc.) and absolute error measures (RMSE) be reported for all WAM model applications. In particular all model applications referenced in the WAM Technical Manual and its supporting documents should contain this information.

5.1.5 Assessment of error in modeling predictions

WAM model applications, like with many other watershed models, are sometimes used in absolute (quantitative) mode (i.e. TMDL applications) as opposed to analysis of alternatives based on relative changes introduced by the adoption of different management practices. The issue of model uncertainty has important policy, regulatory, and management implications, thus understanding the source and magnitude of uncertainty and its impact on TMDL assessment must be studied in depth (Muñoz-Carpena et al., 2006).

Haan et al. (1995) outlined a statistical procedure for evaluating hydrology and water quality models. Their procedure included: conducting local OAT sensitivity analysis, generating probability distributions for model inputs, generating probability distributions for the model outputs, and using the probability distributions of the model outputs to assess uncertainty. Shirmohammadi et al. (2006) present an in-depth review of sources of uncertainty (e.g., input variability, model algorithms, model calibration data, and scale), and methods of uncertainty evaluation and strategies for communicating uncertainty in TMDL models to users. The uncertainty evaluation methods studied by the authors were: a) First Order Approximation; b) Mean Value First Order Reliability Method; c) Monte Carlo; d) Latin Hypercube Sampling with Constrained Monte Carlo; and e) Generalized Likelihood Uncertainty Estimation. In four case studies presented by the authors to highlight uncertainty quantification in TMDL models, results indicate that uncertainty in TMDL models is a significant issue and should be taken into consideration not only during the TMDL development phase, but also in the design of BMPs during the TMDL implementation phase. First Order Error (FOE) analysis and Monte Carlo Simulation (MCS) or any modified versions of these two basic methods may be used to assess uncertainty. This collective study concludes that the best method to account for

uncertainty would be to develop uncertainty probability distribution functions and incorporate such uncertainties into TMDL load allocation through the margin of safety, the magnitude of which is generally selected arbitrarily at the present time. It is recommended that explicit quantification of uncertainty be required as an integral part of the TMDL process. This will benefit private industry, the scientific community, regulatory agencies, and action agencies involved with TMDL development and implementation.

5.2 Review of existing calibration/validation practices of the WAM model

WAM's Technical Manual underscores that a comprehensive description of the watershed system relies on a relatively large number of modeling components and parameters. However, in the Panel's opinion the document understates the effort required to properly calibrate and test the model for specific applications (see for example pg. 12 of the sample application for the Caloosahatchee River where it is stated that "Note that the H[ydrologic]&H[ydraulic] calibration procedure for the WAM model is really a verification process of the physical layout and operational controls of the flow network because WAM is a physically based model that has limited non-physical or statistical calibration parameters to adjust"). Section 2 of this report questions the physical nature of many aspects of the model and clearly establishes the large number of physical and empirical parameters that require identification for this H&H (for example in-stream attenuation, hydrograph shapes or partitioning rules, surface and groundwater velocities, etc.) and other components (crop and soil coefficients, attenuation coefficients, etc.).

It is the Panel's opinion that the WAM model relies on a considerable number of empirical coefficients that require proper identification through standard and objective calibration and validation practices.

After review of the Technical Manual and sample Caloosahatchee River application report, the Panel found that no standard and consistent calibration/validation of the WAM model is provided. In the case of the Technical Manual, although a section listing previous applications of the model is presented, these are described as "successful" and no further details are offered to support this claim (i.e. graphical or statistical goodness-of-fit of simulated and measured values).

The Panel recommends that a table summarizing the quality of the predictions obtained by the model against measured data in previous WAM applications be included in the Technical Manual to establish the value of the tool, and that following standard model evaluation practices, this table contain comparative and error statistics as described in Section 5.1.

Similarly, in the review of the WAM Caloosahatchee sample application report, the Panel found that the calibration/validation of the model and model components presented lacks important information and is quite subjective. Specifically, the presentation of model calibration/validation exercise relies on the inclusion of a large number of plots at the end without presentation of a summary of results or further analysis.

The Panel recommends a comprehensive revision of the calibration/validation procedure in a sample application following standard practices outlined in Section 5.1 above.

Details of the existing calibration/validation procedure of the WAM model presented in the Caloosahatchee River sample application are discussed below and recommendations for improvement are provided.

5.2.2 Selection of data for calibration/validation of the WAM model

The selection of independent calibration and testing periods for hydrological model evaluation, rather separated in time (1995-1999 vs. 1991-1993), seems arbitrary and needs to be carefully explained. Did both periods capture the significant range of model outputs relevant to the application? For the case of water quality, the discussion on p. 16 indicates that some parameters were adjusted based on field data that are not shown.

The Panel recommends that the selection of the independent calibration and validation data subsets be justified with additional description in the sample application and that this practice is followed in every future application of the model.

5.2.3 Selection of parameters for calibration/validation of the WAM model

The calibration process used in the Caloosahatchee River application seems to be a manual calibration, one parameter at a time that ignores interactions and subjectively pre-selects important parameters. The subset of calibrated parameters selected in the sample application is not clearly spelled out in the descriptions provided. Since no formal sensitivity of the overall WAM model (instead of individual components) is presented, the selection of the set of parameters to calibrate seems subjective. For the subset of parameters selected, the relative sensitivity of the model predictions were based on an arbitrary increase or decrease of 20% of the base parameter values, when possibly a larger range might have provided different results.

Although the vast experience of the development team can simplify the selection of the important parameter and relevant ranges to use in specific applications, this will likely be a daunting task for external users of the model and could easily lead to inappropriate model applications without further guidance. In this context, inappropriate parameter identification is a major risk for future WAM applications.

The Panel recommends that clearly outlined and justified sensitivity analysis be presented in the Technical Manual with due attention to the identification of the important model parameters used for calibration, ranges used in the sensitivity evaluation, and discussion of potential interactions among the important parameters selected. A table listing the most sensitive parameters should be included and clear and exhaustive guidance should be provided for the selection of each of the model parameters.

5.2.4 Calibration/validation practices used on the WAM model

In the Caloosahatchee application report the developers rely on simple visual comparison of predictions vs. measured time series that is subjective in many cases and results in weak claims that the model fits measured data well. Examples of this are: a) page 14, 1st paragraph, although Figure A-37 does not show a good agreement between WAM and DHI in simulating flow in Roberts Canal near C-43, the document states that "The DHI and WAM are similar …"; b) page 16 of the report indicates that nutrient predictions of the model matched "well" with measured data, however Figures A-37 through A-39 do not support this claim; c) page 31, 2nd Paragraph, Figures C6 and C17 data do not support the statement that WAM and Mike-SHE "agree reasonably well".

To avoid subjective claims, the Panel recommends that standard model calibration/validation practices as presented in Section 5.1 be added to the Technical Manual for an example application and adopted for all future model applications. The calibration/validation should include an interpretative summary supported by both the statistical and visual comparisons.

5.2.5 Analysis of Model Prediction Uncertainty

The estimated uncertainty error of the model predictions is not discussed in the Technical Manual or the Caloosahatchee Application report, even though the WAM model predictions could be used in absolute (quantitative) mode by the clients (i.e. to evaluated numerical compliance with TMDL applications), in addition to analysis of alternatives based on relative changes introduced by the adoption of different management practices (Shirmohammadi et al., 2006).

The Panel recommends that for quantitative WAM applications (e.g. to evaluate compliance with particular numerical water quality or TMDL standards)*, the outputs of interest be accompanied by a margin-of-safety value derived through a formal Monte-Carlo-multivariate uncertainty analysis or other equivalent uncertainty analysis methodology. It should be noted that this recommendation applies equally to all hydrologic models that might be used for this purpose not just to WAM. The Panel is aware that, in practice, uncertainty analysis is rarely performed at the present time. However, the research literature indicates a great interest in this direction (e.g. Sohrabi, et. al., 2003, Shirmohammadi et. al., 2006). It is important that the sponsoring entities of these studies recognize the importance of uncertainty analyses and provide the needed budgetary resources for their execution.*

6.0 Clarity and Appropriateness of the Documentation

The model documentation, as presented in the Technical Manual (SWET, 2008) and in the various reports of its application, is not sufficient to support the potential applications of WAM in Florida and other locations. The model is capable of simulating the relative effect of alternative land use and management practices on surface and subsurface hydrology and pollutant loads, on a watershed scale. It has the flexibility necessary to consider upland landscapes with deep water tables, landscapes with shallow water tables, with and without artificial drainage, and special cases, such as wetlands, urban areas and mining sites. WAM uses a GIS based grid approach to represent the watershed on a physically consistent spatial scale, and accesses GIS data bases for soils, topography, land uses, and other inputs. It has been applied to address a wide range of important issues, such as the effectiveness of Best Management Practices (BMPS), on both large and relatively small watersheds. The need for, and acceptance of WAM by local, state and federal agencies in Florida is obvious from its record of application in the state. Data sets have already been developed for about 33% of the state, and there is clearly potential for a much wider application in Florida and other states. While the basis of the model is sound, as discussed in the above sections, it relies on approximate methods throughout. Thorough documentation of the methods is essential to support reliable calibration and application of the model. The current WAM Technical Manual needs to be rewritten to provide the level of detail and clarity needed to support the model and its applications.

The rather glowing introduction of the WAM Technical Manual may lead to expectations that exceed model capabilities or that are misleading. An example is the statement in the second paragraph of the introduction, "These spatial datasets are linked to detailed attribute information ……that creates a *complete spatial understanding of the processes within a watershed*". This statement combined with the information in the next paragraph that the model is based on a grid cell representation caused the Panel to initially assume that it is based on a finite difference solution of physically-based governing differential equations with full consideration of saturated and unsaturated subsurface flow, cell-to-cell transport of water and solutes, etc. After more review however it becomes clear that this level of detail is not considered in WAM.

The model developers are justifiably proud of the capabilities of the model. The fact that it can be used to simulate the primary processes and their interactions on complex, large watersheds is indeed impressive. However the purpose of this manual should be to document the model, not to advertise or promote it. It is the Panel's opinion that a better approach is to be very direct about the level of approximation with statements about simplifying assumptions and, in some cases, what the model does not do. There is need to be very clear about the fact that, while the model is based on strict balances for water and constituents (i.e., principle of conservation of mass), it uses approximate algorithms to move both surface and subsurface water from each cell to the outlet, and to attenuate the constituent load in route.

Some of the model assumptions and simplifications are listed in the Technical Manual under the section, Model Limitations, but, as stated in the text, the list is not comprehensive, and in some cases oversimplifies the assumptions made. For example #7 states, "The transport of water and constituents is dependent on flow distances, gradients, and the type of conveyance system". Implicit in this statement is the assumption that the transport, whether surface or subsurface, can be quantified in terms of the stated variables, without regard to flow and interaction with processes in adjoining cells, or cells along the route. Neglecting the cell-to-cell interaction is a critical assumption and should be stated explicitly. Further, the flow processes are treated as one-dimensional, without regard for the effects of convergence (either vertical or lateral in the case of groundwater), which will be relevant for many situations. Given the many different processes simulated in this model, it would probably be better to document the assumptions and simplifications when the algorithms are discussed, rather than to summarize them in a comprehensive list. The general list of model limitations currently in the manual is useful and should be included in the manual, but all assumptions and approximations should be documented as the methods are presented.

WAM was developed over a 25 year period with several different versions, modifications, names, and many different applications. Some of the versions and algorithms were documented, to varying degrees, and others not. This results in some confusion with regard to the names of variables, algorithms and inputs. The Technical Manual needs to be carefully edited to insure consistency in names of processes, algorithms, variables and inputs.

Review of the various WAM manuals and reports, and discussion with the developers during the November 19-20 workshop, indicated that developments of new model features or capabilities were usually precipitated by needs encountered in specific applications. Algorithms were modified or new ones added to address needs or situations not formerly considered in the model. Changes or additions to the model may have been described in project reports, but not thoroughly documented, nor subjected to peer review. In most cases the client was/is primarily interested in the solution to the problem, not the testing or documentation of new or modified algorithms necessary to obtain the solution. However, thorough documentation of the model algorithms and inputs is essential if the model is to be reliably used by others, as emphasized previously herein.

As the model continues to evolve through applications in Florida and elsewhere, it is recommended that project budgets provide for the thorough documentation and testing of the new features as they are developed, with major or novel changes in the model submitted for peer review.

Specific needs for additional and/or improved documentation of the model and its applications have been identified in the Sections 3, 4, and 5 of this report. It is the Panel's strong opinion that WAM and its Technical Manual must be enhanced and revised, closely following these recommendations, in order for WAM to be a widely usable and useful tool for addressing water resource issues in Florida. The panel believes that it is well worth the time and resources required to accomplish this.

7.0 Discussion of the capabilities, limitations, and recommended uses of the model

The focus of this section is to investigate the capabilities, limitations and recommended uses of WAM. One method to accomplish this is to demonstrate how WAM compares with other well-known and widely-used watershed-scale models, and especially those that have been used in Florida. Much of the model information in this section was derived from a number of prior published model reviews and was adapted and/or refined by the Panel Members. These model reviews included:

1. North Palm Beach County Pollution Loading and Abatement Analysis: Model Selection Report. (Tetra Tech, Inc., 2003).
2. Watershed-Scale Hydrologic and Nonpoint-Source Pollution Models: Review of Mathematical Bases. (Borah and Bera, 2003).
3. Watershed-Scale Hydrologic and Nonpoint-Source Pollution Models: Review of Applications. (Borah and Bera, 2004).
4. Hydrologic Components of Watershed-Scale Models. (Migliaccio and Srivastava, 2007).
5. Evaluation of Integrated Surface Water and Groundwater Modeling Tools. (Camp Dresser & McKee, 2001).
6. A review of erosion and sediment transport models. (Merritt et al, 2003).
7. Water Quality Models: A Survey and Assessment. (Fitzpatrick et al, 2001) Prepared for the Water Environment Research Foundation.

Since the emergence of WAM as a modeling tool has been relatively recent, and its applications have been Florida focused, many of these reviews did not include WAM. Nevertheless they provide a broad spectrum of assessments of capabilities and processes on a number of comparable watershed scale models.

7.1 Comparison of WAM Capabilities and Limitations with Other Watershed Models

Tables 2 and 3 were developed from the above model reviews, knowledge of specific models by Panel members, and review of the WAM documentation provided for this effort. Table 2 provides brief descriptions of selected capabilities of WAM compared to three other major watershed models: BASINS/HSPF, SWAT, and MIKE-SHE. These three models were selected because they include capabilities comparable to WAM, they are widely used for watershed modeling and TMDLs, they are supported by governmental agencies (SWAT, BASINS/HSPF) or private firms (MIKE-SHE), and they may be considered the most likely alternatives to WAM. Section 7.1.1 provides short paragraph summaries of these three models for those readers who are not familiar with them. Table 2 is a slight adaptation and modification of information provided in the review by Borah and Bera (2003); the WAM column has been added (and descriptions of other models have been removed), and selected table inserts for the other three models have been revised based on direct knowledge of individual Panel members.

Table 3 is an assessment of how WAM compares with the other three models for a wide range of general characteristics, flow processes, agricultural and urban BMP simulation, and water quality processes. We have used a relative ranking scale from 1 to 3, with a dash ('-') indicating that a specific process/property is not included or available in a specific model. The relative rankings are defined as follows:

1. Low: Basic, relatively simple (often empirical) representation/capability
2. Medium: Moderate complexity and usually process based
3. High: Current State-of-the-art, or close to it

Note that these relative rankings reflect the ability of the model to simulate individual processes and assume that the model has been applied and parameterized correctly. These rankings should not be summed.

Most comprehensive watershed models, including all of those discussed herein, are not adequately characterized by the simple designations of 'empirical, "statistical', 'conceptual', or 'process-based' that are often used in model reviews of this type; consequently we have not taken that approach in this review. Most comprehensive watershed-scale models are hybrids, or combinations of both physically-based process equations and empirical approximations – this is true for all the models discussed here.

Empiricism does not imply a negative characteristic, or a second-rate model, only that the user needs to understand how this empiricism might limit use and interpretation of the model results. To aid the user, these limitations should also be explicitly pointed out by the developers in the model's technical documentation, as noted above in Section 6.0.

7.1.1 Overviews of BASINS/HSPF, SWAT, MIKE-SHE

Brief summaries of these three models, and modeling systems, are provided below as general background for those readers not familiar with them. These summaries are taken essentially verbatim from the review by Borah and Bera (2003) to provide descriptions from relatively unbiased, non-developers of these models. Note that minor revisions and additions to the original descriptions are shown <u>underlined.</u>

HSPF, the Hydrological Simulation Program – Fortran (Donigian et al., 1995), first publicly released in 1980, was put together by <u>Hydrocomp, Inc.</u> (Johanson et al., 1980) under contract with the U.S. Environmental Protection Agency (USEPA). It is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF is an extension of several previously developed models: the Stanford Watershed Model (SWM) (Crawford and Linsley, 1966), the Hydrologic Simulation Program (HSP) including HSP Quality (Hydrocomp, 1977), the Agricultural Runoff Management (ARM) model (Donigian and Davis, 1978), and the Nonpoint Source Runoff (NPS) model (Donigian and Crawford, 1979). HSPF uses many of the software tools developed by the U.S. Geological Survey (USGS) for providing interactive capabilities on model input, data storage, input-output analyses, and

calibration. … HSPF has been incorporated as a nonpoint-source model (NPSM) into the USEPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which was developed by Tetra Tech, Inc. (Lahlou et al., 1998), under contract with the USEPA. The main purpose of BASINS is to analyze … and develop TMDL standards and guidelines nationwide. The most recent version is BASINS4 (US EPA, 2007; Duda et al., 2003) which is based on an open-source code concept and includes a number of models as plug-in components, including HSPF and SWAT.

SWAT, the Soil and Water Assessment Tool (Arnold et al., 1998; Neitsch et al., 2002), was developed at the USDA-ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. It emerged mainly from SWRRB (Arnold et al., 1990) and features from CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and ROTO (Arnold et al., 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yield in large ungauged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational model that operates on a daily time step. The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Although most of the applications of SWAT have been on a daily time step, recent additions to the model are the Green and Ampt (1911) infiltration equation using rainfall input at any time increment, and channel routing at an hourly time step (Arnold, 2002). Similar to HSPF, SWAT is also incorporated into the USEPA's BASINS for nonpoint-course simulations on agricultural lands, and has been enhanced to accommodate urban land categories.

MIKE SHE (Refsgaard and Storm, 1995), based on SHE, the European Hydrological System (Abbott et al., 1986a, 1986b), is a comprehensive, distributed, and physically based numerical model simulating water, sediment, and water quality parameters in two-dimensional overland grids, one-dimensional channels, and one-dimensional unsaturated and three-dimensional saturated flow layers. It also has both continuous long-term and single-event simulation capabilities. The model was developed by a European consortium of three organizations: the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute.

Table 2. Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Model components/ capabilities	Runoff and water quality constituents for pervious and impervious areas modeled by choice of 3 alternative methods, with GLEAMS (default choice), EAAMOD, and special case module; routing from each grid cell for both overland and groundwater with delay factors; extensive GIS interface and uses 1 ha cells; channel routing with a modified linear reservoir approach	Runoff and water quality constituents on pervious and impervious land areas, simple and complex (process-based) WQ options, and water and constituents in stream channels and mixed reservoirs. Currently, part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation, and user interface with pre- and post-processing, GIS, and UNIRAS for graphical presentation.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcView GIS platform.
Temporal scale	Long term; daily for field models, and sub-daily steps for channel routing.	Long term; variable constant steps (typically hourly, but can range from 5-min to daily).	Long term and storm event; variable steps depending numerical stability.	Long term; daily steps.
Watershed representation	GIS raster or grid-based representation of watershed, with rain zones, soils, land use, etc. overlain; 1-D channel and reservoirs; considers wetlands, depressions, etc.	Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.	2-D rectangular/square overland grids, 1-D channels, 1-D unsaturated and 3-D saturated flow layers.	Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
Rainfall excess on overland/ water balance	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.	Water budget considering interception, ET, and infiltration with empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Runoff on overland	Runoff curve number generating daily runoff volume, routed over 3 days with user-defined fractions	Empirical outflow depth to detention storage relation and flow using Chezy-Manning equation.	2-D diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.

Table 2. Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003) (con't)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Subsurface flow	Subsurface flow from field-scale models routed based on user-defined fractions (90 day default)	Interflow outflow, percolation, and groundwater outflow using empirical storage and recession relations.	3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model (Sloan et al., 1983), and groundwater flow using empirical relations.
Runoff in channel	Derivative of a linear-reservoir routing approach, 1-D simulation	Routing based on 'storage' or 'kinematic-wave' methods; All inflows assumed to enter upstream end, and outflow is a depth-discharge function of reac volume or user-supplied demanc Flexible options to handle time and volume varying demands, and multiple outflow points.	Uses MIKE-11 model with optional full (St. Venant) or 1-D diffusive wave equations solved by an implicit finite-difference scheme. Both complex and simple hydrologic methods available.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.
Flow in reservoir	Same as channel, with flexible placement of weirs, gated structures, culverts and pumps	Same as channel, with flexibility to handle user-defined reservoir operations and structures.	Same as channel, with wide range of capabilities to handle hydraulic structures and operations.	Water balance and user-provided outflow (measured or targeted).
Overland sediment	Uses CREAMS/GLEAMS approach, based on USLE with channel, impoundment, and alternative overland flow paths and configurations.	Rainfall splash detachment and wash off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	2D overland flow model drives MIKE SHE SE (soil erosion) model.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) expressed in terms of runoff volume, peak flow, and USLE factors.
Channel sediment	Empirical attenuation factors used to account for losses during channel travel time	Non-cohesive (sand) sediment transport using user-defined relation with flow velocity or Toffaleti or Colby method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	Hydraulic in MIKE-11 simulation drives both cohesive and non-cohesive sediment transport, including suspension, resuspension, settling.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with bed erodibility and channel cover factors (for vegetation), and deposition based on particle fall velocity.

Table 2. Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003) (con't)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Reservoir sediment	Same as channel.	Same as channel.	Same as channel.	Outflow using simple continuity based on volumes and concentrations of inflow, outflow, and storage.
Chemical simulation	Field-scale GLEAMS module can handle nutrients and pesticides, including runoff and movement through the soil to groundwater. All components of N and p cycles including crop uptake are considered.	Soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic N, phosphate, organic P, pesticides in dissolved, adsorbed, and crystallized forms, and tracer chemicals chloride or bromide to calibrate solute movement through soil profiles.	Dissolved conservative solutes in surface, soil, and ground waters by solving numerically the advection-dispersion equation for the respective regimes. MIKE-11 water quality capabilities used for surface water quality.	Nitrate-N based on water volume and average concentration, runoff P based on partitioning factor, daily organic N and sediment adsorbed P losses using loading functions, crop N and P use from supply and demand, and pesticides based on plant leaf-area-index, application efficiency, wash off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives.
BMP evaluation	Extensive BMP capabilities in GLEAMS and other field scale modules. , EAAMOD provides capabilities for shallow water table /drained soils.	Nutrient, pesticide, and irrigation management by parameter changes, or simple BMP module with removal efficiencies.	Extensive BMP capabilities expected for the process-based land modules.	Agricultural management: tillage, irrigation, fertilization, pesticide applications, and grazing.

Table 3. Comparative Capabilities/Properties of WAM and Selected Other Watershed Models

Property/Process	Comparative Levels of Property/Process Simulation			
	WAM	**BASINS-HSPF**	**MIKE-SHE**	**SWAT**
General				
Spatial Scale	3	3	2	3
Spatial Discretization	3	2	3	2
Temporal Scale	2	3	3	2
Temporal Discretization	2	3	3	2
GIS Interaction	3	2	3	2
Experience/Applications in FL	3	2	2	1
Availability	Public Domain	Public Domain	Private	Public Domain
Cost	Free	Free	Major Cost	Free
Readily Available Input Parameters	3	3	1	3
Number of Parameters	2	2	3	2
Quality of Documentation	1	2	2	2
Flow Processes				
Rainfall	3	2	3	2
Surface Irrigation	2	2	2	2
Drainage/Controlled /Subirrigation	3	1	3	1
Interception	2	2	3	2
Evaporation	2	2	2	2
Transpiration	2	2	2	2
Overland flow	1	2	3	1
Vadose zone flow	2	2	3	2
Groundwater flow	1	1	3	1
Channel Flow	2	2	3	2
Groundwater-River exchange	–	–	2	–
Vadose Zone/ Groundwater interactions	1 (GLEAMS) 2 (EAAMOD) 1 (BLASROUTE)	2	3	1
Groundwater/Stream water extraction	1	1	3	1
Surface water structures	3	1	3	1
Ag BMP simulation				

Property/Process	Comparative Levels of Property/Process Simulation			
	WAM	**BASINS-HSPF**	**MIKE-SHE**	**SWAT**
Land uses simulated	3	3	3	3
Crop growth	3	1	3	3
Nutrient uptake	2	3	3	2
Irrigation management	2	2	2	2
Nutrient management	2	2	2	2
Other practices	2	2	2	2
Urban BMP simulation				
Practices simulated	1	2	3	1
Nutrient transport and transformation				
Within cell/land phase	2	2	3	2
Within overland flow	1	1	3	1
Within wetlands	1	–	3	–
Within groundwater	1	2	3	?
Within River	1	3	3	2
Sediment transport				
Within cell/land phase	2	2	3	2
Within overland flow	1	2	3	1
Within wetlands	1	–	3	–
Within River	1	2	2	2
BOD simulation				
Within cell/land phase	1	2	2	2
Within overland flow	1	1	?	1
Within wetlands	1	–	?	–
Within groundwater	1	1	?	1
Within River	1	2	2	2

Legend:

- – Process/capability not included
- ? Unknown to panel members
1. Low - Basic, relatively simple (often empirical) representation/capability
2. Moderate - Moderate complexity and usually process based
3. High - Current State-of-The-Art, or close to it

7.2 WAM Strengths and Weaknesses

Analysis of the relative rankings in Table 3 can provide a basis for defining the relative strengths and weaknesses of WAM compared to the other major models, and thus help to establish expected limitations on its use. Based on this analysis, and supported by review of the WAM documentation and November 2008 Peer Review Workshop, the Panel has determined that the strengths of WAM are as follows:

- The high level of spatial definition provided by the GIS cell-based representation of the watershed.
- The process-based representation of the submodels, GLEAMS and EAAMOD, for the land phase simulations.
- The available model setup for Florida conditions, essentially state-wide, based on extensive GIS data coverages.
- The ability to represent flow structures and facilities common to Florida waterways.
- The ability to represent springsheds, and groundwater basins with different areas than surface water basins.
- The apparent efficiency of the WAM modeling system for executing watershed and BMP scenarios.
- The apparent ability to represent, or approximate, reversing flow situations for estuarine conditions.
- The ability to simulate field based BMP's using contiguous cells that form physically understandable hydrologic unit management systems. This allows simulation of different landscape topographic features (e.g., uniform slope, convex, concave, and combination thereof) when this information is available.
- The ability to represent high water table conditions including drainage, controlled drainage, and subsurface irrigation.

The Panel has determined that the weaknesses of WAM are as follows:

- The lack of physical process representation of in-stream processes other than flow routing, i.e. the simple, empirical attenuation of water quality constituents during cell to stream and in-stream transport.
- The inability to represent storm event impacts due to the daily time-step of the land-phase modules, the unit hydrograph routing with fixed delay times (i.e. 3-days for surface and 90-days for subsurface), and the simple attenuation factor approach for water quality constituents.
- The simple representation of impervious urban land uses with constant water quality concentrations
- Insufficient documentation of the unique in-stream flow routing procedures
- Insufficient model documentation, especially the User's manual. In light of this the potential for misuse appears to be high for non-highly trained model users – i.e. SWET appears to be highly skilled in WAM applications but the empiricism of many model parameters can lead to inappropriate applications by other users not as highly skilled
- Lack of adequate level of statistically-based calibration and validation results of model for the cases studies. Developers use simple statistics such as Coefficient of Determination (r^2) instead of using parameters such as Nash-Sutcliff Coefficient of Efficiency (C_{eff}) and Root Mean Square Error (RMSE).

8.0 Conclusions and Recommendations

Choices between more physically-based process-oriented models and more empirical models depend on modeling purpose. Detailed, high-resolution, physically- based models (such as MIKE SHE) are more useful as research tools for process studies at the small-scale where physical parameters are relatively homogeneous and feasible to measure. The large (and largely unmeasurable) spatial variability at the basin scale justifies a more approximate empirical approach (e.g. WAM, HSPF or SWAT) at the basin-scale. However it must be recognized that the parameters of an approximate empirical model represent an average over a large area and often integrate several processes and their variability. Thus the physical interpretation of parameters is rather vague and should be regarded with skepticism, and the model predictions should be considered more as indices rather than as true values (Bergstrom, 1991).

It is also important to bear in mind that models can never be completely verified. Rather modeling should be viewed as a process of repeated tests of hypotheses that result in growing understanding of the physical system and growing confidence in the decisions made based on model results (Bergstrom, 1991). Given the complexity of all watershed models, it is the model developers' responsibility to accurately judge a model's applicability, weaknesses and uncertainties in particular situations. Responsible model application requires that all assumptions, results and limitations be clearly represented and interpreted to decision makers in an understandable way.

8.1 Conclusions

The conceptual model underlying WAM includes rainfall, evapotranspiration, overland flow, groundwater flow and river flow, as well as the transport and transformation of particulate and soluble phosphorus, particulate and soluble nitrogen, total suspended solids and biochemical oxygen demand in the system. The significant processes that affect the hydrology of Florida watersheds are included in the model, however the methodologies used to represent these processes range from quite empirical (e.g. cell to stream routing of overland and groundwater flow) to more physically-based (e.g. Boussinesq equation for shallow saturated groundwater flow in EAAMOD). Decisions regarding the level of sophistication required for modeling different hydrologic processes in different domains seem to have been made by the model developers, based on intuition and experience, to improve computational efficiency, or to solve particular project-specific problems. While the Panel respects and accepts the judgment of the modelers at SWET, a more rigorous discussion and justification of the level of complexity chosen for each process should be included in the written documentation. Assumptions are required for the development of all models, so they should not be viewed as a shortcoming. Rather, documentation of assumptions leads to transparency in the modeling process and improved credibility of the model.

The Panel believes that WAM is capable of simulating the relative effect of alternative land use and management practices on surface and subsurface hydrology and pollutant loads, on a watershed scale. It has the flexibility necessary to consider upland landscapes with deep water tables, landscapes with shallow water tables, with and without artificial drainage, and special cases, such as wetlands, urban areas and mining sites. WAM uses a GIS based grid approach to represent the watershed on a physically consistent spatial scale, and accesses GIS data bases for

soils, topography, land uses, and other inputs. While the Panel believes that the basis of the model is generally sound, like most computer models it relies on approximate methods at every stage. Furthermore the model documentation, as presented in the Technical Manual (SWET, 2008) and in the various reports of its application is insufficient. Thorough documentation of the methods is essential to support reliable calibration and application of the model by the developers and especially by other model users.

The primary strengths of WAM are its GIS foundation, spatial detail, process-based land field-scale modules, model database for Florida conditions, flexibility to accommodate varied hydrologic, water quality, land and water management processes, and its facility for performing alternative scenario simulations. It provides an efficient mechanism to aggregate assumptions about system behavior and implementation of management rules to the watershed scale. It can be used to test assumptions and understanding about the watershed system and to evaluate outcomes of alternative land use and land management scenarios based on this understanding

Weaknesses that may limit WAM's utility include its simplified approach for cell-to-stream water and solute delivery, simplified in-stream water quality processes, inability to adequately represent small-scale short-term storm event impacts, and simplified representation of impervious urban land conditions. The most significant weakness associated with the WAM model however is the pervasive lack of attention to detail in rigorously documenting assumptions, methodologies, sensitivity analyses, calibration and verification efforts, and uncertainty analyses in the WAM Technical Documentation and WAM Applications Reports.

8.2 Major Recommendations

1. The current WAM Technical Manual needs to be rewritten to provide the level of detail and clarity needed to support the model and its applications. This includes a more rigorous discussion and justification of the level of complexity chosen for each process, an accurate description of the equations and numerical methods used to represent each process, and correction of all typographical errors in the equations. Detailed recommendations are given in the body of this report.

2. WAM components rely on a considerable number of empirical coefficients that require proper identification through standard and objective sensitivity analysis, calibration and validation practices. Since model sensitivity is likely specific for each type of application, the Panel recommends that a clearly outlined and justified sensitivity analysis for the complete WAM model be presented for a range of typical sample applications in the WAM technical documentation. This sensitivity analysis should result in recommendations regarding important model parameters that should be estimated and evaluated using standard calibration and validation exercises specific to each type of model applications. Detailed recommendations and references for standard sensitivity, calibration and validation procedures are given in the body of this report

3. The Panel recommends that established goodness-of-fit criteria be reported for all WAM model applications. These should consist of a combination of graphical comparison of measured vs. simulated values, and summary statistics (Nash-Sutcliff coefficient of efficiency, index of agreement, etc.) and absolute error measures (RMSE). All model

applications referenced in the WAM Technical Manual and its supporting documents should contain this information. Detailed recommendations regarding good calibration and validation practices are given in the body of this report.

4. The overall tradeoffs between model strengths and weaknesses (for WAM or any model) need to be assessed in any specific application, taking into account the needed level of accuracy of model results for each application and the extent to which weaknesses may limit the utility and reliability of those predictions. With careful application, including adequate calibration and validation for each application watershed, it is the panel's opinion that WAM can be used for the following types of watershed assessments:
    - To determine the relative impacts of alternative land use and development scenarios
    - To determine the relative impacts of BMPs on nonpoint source loads
    - TMDL allocation studies where the focus is on relative differences between scenarios.

5. For quantitative applications (e.g. to evaluate compliance with particular numerical water quality or TMDL standards), the outputs of interest should be accompanied by a margin-of-safety value derived through a formal Monte-Carlo-multivariate uncertainty analysis or other equivalent uncertainty analyses. Note that this recommendation applies equally to all hydrologic/water quality models that might be used for this purpose not just to WAM. Since this would not be a simple additional task for all model applications, the sponsoring entities of these studies need to recognize the importance of the uncertainty analyses and provide the needed budgetary resources for their execution.

6. As the model continues to evolve through applications in Florida and elsewhere, it is recommended that project budgets provide for the thorough documentation and testing of the new features as they are developed, with major or novel changes in the model submitted for peer review.

7. It is the panel's <u>strong</u> opinion that the WAM Technical Manual and associated documentation <u>must</u> be enhanced and revised, following recommendations given herein, in order for WAM to be a widely usable and useful tool for addressing water resource issues in Florida. The panel believes that it is well worth the time and resources required to accomplish this.

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Appendix A: Scope of Work

PEER REVIEW OF THE
WATERSHED ASSESSMENT MODEL (WAM)

Introduction/Background

The Watershed Assessment Model (WAM) is a computer model capable of simulating water quality and surface water and groundwater responses to rainfall based on detailed GIS spatial data across a watershed. The model predicts the detailed hydrologic, nutrient, TSS, and BOD responses as modified by hydraulic infrastructure, changes in land use and alterations to operating rules for water control structures.

WAM is used by Florida agencies (SJRWMD, SFWMD, FDEP, and FDACS) and EPA for water resource management and planning purposes, including TMDL development and the BMAP process. Many important regional water management decisions have been aided by simulations of the water quality and quantity hydrodynamics simulations provided by WAM. Due to this widespread use, it is prudent to conduct a peer review of the model to evaluate the model algorithms and procedures, as well as, its usage and applicability.

Objective

To conduct an independent and objective peer review of the functionality and documentation of the WAM as a watershed-scale modeling tool for addressing water resources issues in Florida. Specifically, the objectives of the model peer review are as follows: 1) evaluate the scientific basis underlying the model; 2) evaluate the methodology by which watershed-scale management rules and best management practices are implemented in the model; 3) evaluate methods by which the model has been calibrated and validated for at least one example application; and 4) discuss the capabilities, limitations, and recommended uses of the model. The review shall rely on the latest documentation of the model and model application reports as the primary source of information about the model. Supplementary information may be provided during phone meetings and workshops with the model development team. Panelists will not be expected to review the code for accuracy or to run the model independently.

Tasks

Task 1: The first task is to form the peer review panel:

- Position 1: Chair, UF Water Institute Director, Wendy Graham
- Position 2: Expert familiar with Florida conditions
- Position 3: Expert familiar with HSPF, SWAT and/or BASINS :
- Position 4: External Academic Hydrologic Modeling Expert
- Position 5: Expert in Modeling Uncertainty Analysis

Task 2: Model Development Group (SWET) provides Model Documentation Report and Model Application/Calibration Report(s) to Peer Review Panel

Task 3: Panel conducts preliminary review of documentation and application reports and submits questions/requests to model development group prior to the first workshop.

Task 4: Hold first workshop. Model Development group presents key aspects of the model and provides answers to questions submitted by the Panel.

Task 5: Draft Report. Panel submits draft report prior to Model Development Group and Funding Agencies prior to the second workshop.

Task 6: Hold Second workshop (either by web meeting or in person if necessary). Model development team provides responses or clarifications to Draft Report.

Task 7: Panel submits Final Report to Funding Agencies.

Schedule

Task Number	Description	Time for Delivery
1	Water Institute Forms Panel	3 weeks after Date of Execution of Contract
2	Model Development Group Delivers Documentation to Panel Members	5 weeks after Date of Execution of Contract
3	Panelists submit list of questions to Model Development Group	4 weeks after Delivery of Documentation
4	First Workshop in Gainesville	6 weeks after Delivery of Documentation
5	Panel submits draft final report to Funders and Model Development Group	4 weeks after workshop
6	Second Workshop (by web meeting or in person if necessary)	2 weeks after submission of draft report
7	Panel Submits Final Report to Funders	4 weeks after second workshop

Appendix B: EAAMOD 1994-1995 Peer Review

UNIVERSITY OF FLORIDA

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MEMORANDUM

To: Dr. R. Wayne Skaggs
Dr. Ken Campbell
Dr. Ramesh Reddy
Dr. Wendy Graham

Date: August 29, 1994

From: Forrest T. Izuno

Subject: EAAMOD Review Team Charge

By now you should have all received a copy of Dr. Bottcher's EAAMOD. You have all spoken informally with either Ms. Laurene Capone and/or myself about the purpose of the review. This memorandum outlines specifically what we as a committee should be looking for as we evaluate the model. I am also enclosing a copy of a memorandum from the granting agency outlining their Technical Oversight Committee's desires and concerns.

The charges of the committee are as follows:

1. To evaluate the technical "correctness" and appropriateness of the processes used in the model; Has
2. To determine whether Dr. Bottcher's approach to the sensitivity analysis accurately represents the model capabilities;
3. To determine whether Dr. Bottcher's approach to the model development is such that absolute model prediction errors are in fact within the bounds of the errors expected in field data used to calibrate the model;
4. To assess whether the model could be used as a tool for comparing the effects of implementing different BMPs on a farm without having inherent model errors obscure the phosphorus reduction predictions; field scale
5. To determine whether the model is practical enough such that farmers can eventually use it to select and evaluate BMPs for their farms after collecting and inputting a reasonable data set;

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6. To ascertain whether the model can be a useful tool for researchers to use to compare BMP related P load reductions from year to year for a farm by mitigating the hydrologic effects on annual P load differences;

7. To make suggestions as to how the model could be improved in order for it to be of practical use if it isn't already; and

8. To satisfy ourselves that the model is a piece of work that the University of Florida/IFAS can endorse.

As a reminder, we are tentatively set to meet in Gainesville for a presentation by Dr. Bottcher on September 12th at 9:00 am. At that time, Dr. Bottcher will answer your questions. Following that presentation, we will meet to determine the committee's consensus.

Thanks again for your assistance.

c: Mr. Ed Barber

ED BARBER & ASSOCIATES
Environmental Consulting
Environmental Management Services
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MEMORANDUM

To: Forrest Izuno

From: Ed Barber

Date: August 10, 1994

Subject: IFAS Model for Best Management Practices

It is my understanding that you have organized a meeting with a committee from IFAS that may be used to provide peer review of the Model EAAMOD.

As we discussed I have some thoughts and concerns regarding this issue. Please regard these items as suggestions. We intend for you and the committee to develop your own review criteria.

I feel that the model basically should provide support for the overall BMP effort as directed by you. I do not anticipate that it would or should serve any regulatory function because of the obvious potential for error built into the calculations.

I therefore view the model as being more a tool for you, the researcher, and for the grower to determine general effectiveness of a BMP or series of BMPs for a farm that has not been intensely studied. The model, therefore, must be practical in its application. The predictive capabilities of the model must also be precise enough to be of value within a useful range of load reductions for phosphorus. We really do no want the model to increase significantly the error more than is presently inherent in the sampling and analysis.

Procedurally, I would like to see the primary interaction between the modeler and committee in writing. As a governmental body we need to build a good record for expenditure of funds. The model also should "stand on its own legs" without the need of verbal explanation. Keep in mind that reviewers, such as agency personnel, will not have the benefit of such explanation and will be reviewing this model strictly on it own performance merit.

If I can be of further assistance please let me know, I will call you in a few weeks to check on your progress.

Review of EAAMOD
by
R. Wayne Skaggs

INTRODUCTION

The purpose of this document is to report the results of my review of the simulation model, EAAMOD. EAAMOD was developed by Dr. Del Bottcher and colleagues to describe field scale hydrology and phosphorus transport in the Everglades Agricultural Area (EAA). The review team (Dr. Ken Campbell, Dr. Ramesh Reddy, Dr. Wendy Graham and myself) were charged with the following tasks:

1. To evaluate the technical "correctness" and appropriateness of the processes used in the model;

2. To determine whether Dr. Bottcher's approach to the sensitivity analysis accurately represents the model capabilities;

3. To determine whether Dr. Bottcher's approach to the model development is such that absolute model prediction errors are in fact within the bounds of the errors expected in field data used to calibrate the model;

4. To assess whether the model could be used as a tool for comparing the effects of implementing different BMPs on a farm without having inherent model errors obscure the phosphorus reduction predictions;

5. To determine whether the model is practical enough such that farmers can eventually use it to select and evaluate BMPs for their farms after collecting and inputting a reasonable data set;

6. To ascertain whether the model can be a useful tool for researchers to use to compare BMP related P load reductions from year to year for a farm by mitigating the hydrologic effects on annual P load differences;

7. To make suggestions as to how the model could be improved in order for it to be of practical use if it isn't already; and

8. To satisfy ourselves that the model is a piece of work that the University of Florida/IFAS can endorse.

I have reviewed the report on EAAMOD. I also had two of my graduate students who are working on development of similar simulation models review the model documentation and run simulations with the model. I attended a review session on September 12, 1994 in Gainesville where Dr. Bottcher made an oral presentation on the model and answered questions by the review panel. At that meeting Dr. Bottcher submitted additional documentation on sensitivity analyses and results of field testing of the model. This documentation has also been reviewed; it is referred to as the 9-12-94 supplement and is covered in this report.

NEED FOR A SIMULATION MODEL

I will attempt to address each of the numbered charges to the committee as listed above. First, I will express my opinion about the need for developing a simulation model. With all of the field data that have been collected and plans to continue collecting data, why are simulation models necessary?

There are a multitude of factors that affect losses of P from agricultural lands in the EAA. The effect of management practices on these losses depend on weather conditions, soil properties, and site conditions. This general statement is true for water management practices used to reduce phosphorus loadings by simply reducing the volume of drainage water. It is also true for the BMPs, such as soil testing to reduce unnecessary fertilizer applications, aimed at reducing P concentrations. For example the impact of controlled drainage on P outflows will be different in drought years than in years when rainfall is greater than normal. Rainfall that occurs immediately after fertilizer is applied will have a different effect on P loss (and on the impact of reducing fertilizer applications on that loss) than if it occurs a week or more after fertilization. The long-range average impact of BMPs include the effects of such extremes (i.e, droughts, large rainfall events, rainfall directly after fertilization, etc.). A reliable simulation model can be used

to evaluate these long-term average impacts. Detailed and expensive monitoring on many sites over many years would be necessary to determine such impacts experimentally.

RESULTS OF THE REVIEW

Task 1. To evaluate the technical correctness and appropriateness of the processes used in the model.

Water movement and storage processes.

The model is based on numerical solutions of the continuity equation. The cross-section of the field is broken down into cells of width Δx and an equation based on conservation of mass is written for each cell. In the limit as $\Delta x \rightarrow 0$ this reduces to the continuity equation. The methods assume that flow is primarily horizontal, but does consider vertical flow through a restrictive layer (the caprock) and in the unsaturated zone near the surface. Flow in the saturated zone is calculated using the Dupuit-Forchheimeir (D-F) assumptions. This means that the continuity equation for the upper layer reduces to the well-known Boussinesq equation, although it isn't written that way or recognized in the model documentation. Since the D-F assumptions are used, and vertical flow, storage in the unsaturated zone, and related flow processes are approximated, the model may be classified as a quasi-two-dimensional, approximate model.

Experiments and observations on these and similar soils in many areas indicate that the dominate drainage processes are horizontal, so the basic approach chosen to model the water movement and storage seems appropriate. The capability of the model to describe lateral flow in both the surface layer and in the subsurface layer below a restrictive horizon (the caprock) is necessary for the soils in the EAA. It allows description in quantitative terms of flow above and below the restrictive layer to drainage ditches. It also considers flow underneath the ditch to deeper canals located beyond ditches that do not penetrate the restrictive layer. The strength of the approach is that use of the D-F assumptions and the other simplifications employed should

provide a relatively robust, easy to use model, compared to more exact approaches that consider two-dimensional flow in both the saturated and unsaturated zones. Lateral variations in hydraulic conductivity of the upper layer can be considered, and it is possible to simulate the effects of time varying boundary conditions at the ditches. Weaknesses of the approach include the fact that unsaturated processes are approximated and may cause errors for certain conditions; furthermore the numerical solutions may not converge for certain choices of inputs (according to our experience in running the model). While the approach is much less computationally demanding than more exact treatments based on solutions to the Richard's equation, it still requires considerable computer time to run multi-year simulations, even on today's fast computers.

In the final analysis the technical validity and appropriateness of the processes used in the model are best judged on the basis of comparisons with more exact models and against field data. Testing of the model will be discussed in a subsequent section. Based on my experience with similar models and drainage situations, the basic approach used to model the flow processes seems to be appropriate. The methods are not fully documented in the report, so it is not possible to evaluate the details of the solution methods, etc., but the approach is similar to other models that have been successfully used (e.g. Parsons et al., 1991a&b) and should be on track. There are a number of questions and suggestions as will be discussed below. Many of these questions arise because the report does not clearly describe methods and algorithms used in the model. Suggestions for clarification of descriptions in the report follow.

1. Equation at the bottom of page 9. I think it should read Q(i+1) - Q(i) rather than Q(i) - Q(i+1) to be consistent with Figure 1.

2. There is no explanation of how Q(i) is calculated. I assume $Q = -K\ h\ \frac{dh}{dx}$ which may be written in several ways in finite difference form.

i.e.

$$Q(i) = -K(i)\ h(i)\ \frac{h(i+1) - h(i-1)}{2\ \Delta x}$$

Or

$$Q(i) = -K(i)\ h(i)\ \frac{h(i+1) - h(i)}{\Delta x}$$

The equation used should be given after the equation at the bottom of page 9. It would be helpful to number the equations for reference.

3. I think the sign is wrong on the right hand side of the equation on page 11. The fact that the model WP keeps track of the air void volume rather than the water volume is the method that is used in DRAINMOD, though it isn't referenced. At the bottom of page 11 it is stated that the wet condition is "similar to field capacity." I don't think field capacity is a very well defined term (it is often taken as water content at 1/3 bar of suction) and probably shouldn't be used. I think what is meant is that the relationship between air volume (or drained pore space) and water table depth is defined by a "drained to equilibrium" condition above the water table. No explanation is given for how the "dry" curve is obtained. It is needed. As I understand it the model uses two curves ("wet" and "dry") for the relationship between air volume and water table depth. It would be helpful to show an example of those curves in addition to the diagram in Figure 2 which depicts the situation for a given water table depth. The assumption that the water table will

remain static as water is removed from the profile such that the soil water distribution changes from the wet condition to the dry conditions is questionable, in my opinion. It may hold approximately for the organic soils in the EAA, but it does not hold for either the mineral or organic soils that I have worked with. My experience indicates that the water table continues to fall due to upward water movement to supply part of the ET demand as the top part of the profile "dries out".

4. The second equation on page 13 is a finite difference form of the continuity equation written in terms of the water table elevations and hydraulic heads rather than Q. This should be proceeded by an explanation of how Q and Q' are expressed in terms of those heads. Similar equations with appropriate explanations are needed for the upper zone. There is just not enough information given for the reader to follow or understand the development of the equations, or how they are solved. These equations are written for a point in time. How are the solutions affected by the h and H values in the previous time step? Is an explicit or an implicit formulation used?

5. The brief (one sentence) explanation at top of page 14 concerning the solution technique for solving simultaneous equations is meaningless without more information. The simultaneous equations referred to are the ones at the bottom of page 13 and the parallel equation for the upper zone. The latter equation should be presented in terms of h, not Q. Are the equations written for all nodes or just the interior nodes? How are the

boundary conditions applied? To say that the LU Decomposition technique is used without more detail is not very helpful.

These details discussed in the above points are not particularly important to the user, assuming the model is valid and working properly. They are important for determining the appropriateness or correctness of the approaches.

6. The explanation on page 14 of how surface water runoff and flooding are handled is not at all clear. It is stated elsewhere that infiltration is assumed to be equal to rainfall rate for the soils in the EAA. That seems reasonable for these highly permeable soils. But what happens when the water table rises to the surface? In actuality surface water accumulates concerning runoff and/or storage on the surface. It isn't clear how the model handles this. Discussion of flooding on page 14 apparently refers to flooding from the ditch onto the field. More explanation with diagrams or sketches would help the reader understand this. This aspect would seem to be especially important in quantifying losses of sediment and P due to surface runoff.

   Question: When surface is flooded, there would be no gradient in h. Is subsurface flow zero for that condition?

<u>Phosphorus Sub-Model</u> (PMOVE)

The phosphorus submodel uses flows predicted by the hydrology submodel (WP) to calculate the movement of soluble P within the soil profile and to the drainage ditches. The model assumes transport of soluble P is by advection; dispersion is neglected to simplify the calculations and inputs required. Water table positions and soil water movement by infiltration, upward flux etc. are used in PMOVE to determine the depths of aerobic and anaerobic zones, mineralization of organic P, and the available P within those zones. A partitioning coefficient is used to determine soluble P from the available P.

The processes affecting movement and fate of P within the profile, and methods used in the model to approximate them seem reasonable based on the descriptions given in the report. However, all of the processes and the methods used to quantify them are not described. For example, it is stated that the model considers addition of P to the available pool by net mineralization of organic P, but there is no description of the equations, etc. used to quantify the process. There is reference to the mineralization coefficients in the material distributed 9-12-94 on sensitivity testing, but the process is not described on pages 14-20 of the report where the P submodel is discussed. The use of a simple partitioning coefficient for separating soluble and adsorbed P is justified based on experimental data in Appendix D, which was not included in my version of the report. It isn't clear what happens (or what error results) if the P concentration exceeds those that are described by linear isotherms (0-2 mg L^{-1}). Initial P concentrations above the marl layer were > 10 mg L^{-1} in the example input file--far above the linear range.

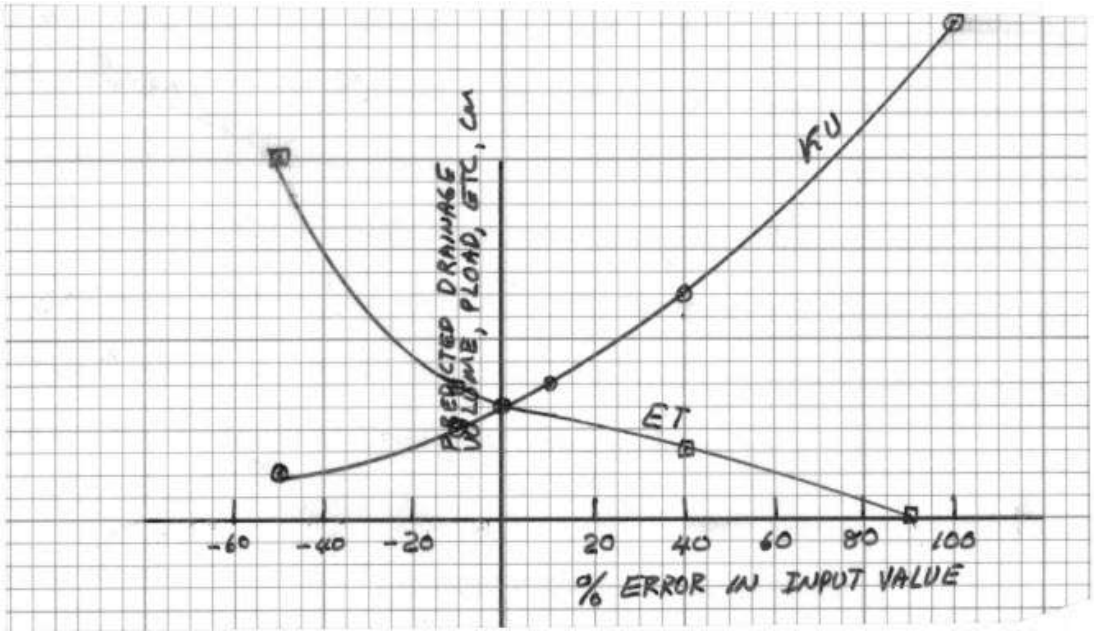
Methods used to predict the sediment P and losses via sediment P are not clear to me. Empirical equations given on page 20 adjust a "base sediment P" in terms of crop or cover, recent rainfall and ditch depth. It isn't clear how (or if) sediment P depends on surface runoff (and erosion rates), or if the equation P concentration in the drainage water leaving the farm ditch. In any case, the report states that sediment P can represent between 20 and 80 percent of the total P lost from a farm ditch. More effort is needed to explain clearly the processes that are used in the model for estimating sediment P losses. Consideration should be given to replacing the empirical equation on page 20 with a mechanistic approach. Because sediment P losses are potentially a large percentage of the total, independent tests are needed of the validity of this component of the model.

Task 2. To determine whether the sensitivity analysis accurately represents the model capabilities.

Results of a sensitivity analysis was distributed by Dr. Bottcher at the meeting on Sept. 12. The analysis was conducted by changing an input variable by +10% and -10% and simulating the performance of the system over a 2.5 year period. Analyses were conducted for two farms. Results were reported as a sensitivity ratio, which is the predicted percentage change in the dependent variable divided by the percentage change in the input variable. For example, if changing the hydraulic conductivity (K) by +10% increased the drainage volume by + 8%, and decreasing K by 10% decreased the drainage volume by 6% the sensitivity ratio would be (8+6)/(10+10) = 0.7.

The basic strategy of determining the sensitivity of the model by changing a single input, while holding the others constant, and determining the effect on the model predictions, is appropriate and needed. Reporting the results in terms of a sensitivity ratio is efficient, in that only a few numbers have to be tabulated or plotted. However, this presents the results in an abstract form that is hard to interpret. For one thing the dependent variable is not identified; e.g. for the hydraulic sensitivity analysis given in Figures 1 and 2, what is the dependent variable? Total subsurface drainage outflow for the 2.5 years? Annual surface + subsurface outflow? There are results given for inflow and outflow. What is inflow? Subirrigation into the profile? The physical situation that was modeled (i.e. a field with an adjacent ditch connected to a farm ditch via a culvert) for the sensitivity analysis is not adequately described. A sketch would help here. The input parameters that were tested for hydraulic sensitivity are not clearly defined. For example, what is **K-imp**? I assume this is K in the lower layer (below the restrictive or marl layer), but it isn't defined that way in the text. **Soil def** must be soil moisture deficit, but its

meaning is not clear, as it hasn't been defined. These issues are easy to clear up and should be



addressed.

The way results of the sensitivity analysis are presented implies that sensitivity of predictions to changes in the inputs (or errors in the inputs) is linear. It often isn't. Furthermore, assuming errors in the inputs of only ± 10% is very optimistic. I suggest that the sensitivity to errors of ± 50%, or better still + 100% and - 50% should be determined. These results, along with those already obtained could be plotted as shown below.

This would convey much more information about the nature of the sensitivity of the predictions to errors in the inputs, in a way that is easier to understand. The same could be done with the P predictions with the dependent variable being either cumulative P loss over 2.5 years or average yearly P loss.

In summary, I think the sensitivity analyses are on the right track, but more should be conducted for greater changes in the inputs, and the results should be presented in a way that will show the

nature of the sensitivity (linear or nonlinear) as well as its magnitude. All inputs and dependent variables (outputs or objective functions) should be clearly defined and labeled.

Task 3. To determine whether Dr. Bottcher's approach to the model development is such that absolute model prediction errors are in fact within the bounds of errors expected in field data used to calibrate the model.

The reliability of simulation models such as EAAMOD should be determined at several levels. The most basic component is the hydrology. It is unlikely that the model will be reliable over the long run if it is not capable of simulating the hydrologic processes, especially subsurface drainage and surface runoff volumes. The ability to accurately simulate these drainage processes in shallow water table systems is strongly dependent on predictions of the water table depth and soil water distributions above the water table. An equally important section of the model is that which predicts movement, transformations and fate of P. The reliability of these predictions depends on accurate simulations of the water movement processes, but it is also very strongly dependent on the validity and execution of algorithms for predicting the concentrations of soluble P, partitioning of sorbed and soluble P, sediment P lost in surface runoff, etc.

The *bottom line* test of the model is to compare measured and predicted P loads over a period of time for a range of crops and best management practices. However, at this stage in the development of the model, it is desirable, in my opinion, to also independently test the model's ability to predict the hydrology and P concentrations in the profile. At the most basic level the model could be tested against analytical solutions for water table drawdown and drainage rates. The next level would be to compare predicted and measured water table depths and drainage rates for a long record (1 to 3 years), on several sites if possible. It is my impression that both types of these tests have been done, but, except for one water table plot (Figure 8) in the 9-12-94 supplement, they have not been included in the model documentation. The one test that was

presented indicates that the model does a good job in predicting water table fluctuations in close agreement with observed values. Results of other tests and of comparisons with analytical and numerical solutions for short term events should be presented if they are available.

Tests of the reliability of the model predictions for drainage and subirrigation volumes are especially important. Reliable predictions are heavily dependent on accurate approximation of actual ET and can be tricky for drained soils. The possibility of compensating errors in ET and drainage may allow reasonably accurate water table predictions while the drainage amounts are in substantial error. Results presented in the 9-12-94 supplement for nine storm events indicated that predicted and measured outflow volumes were not in good agreement. This calls for additional testing of the models for predicting outflows for both storm events, and over the long term.

Predicted and measured concentrations of total P in the field ditch over about a 2-year period were in reasonable agreement for seven of nine sites (Figures 14-22). Predictions of soluble P were also in reasonable agreement with measured results for the same sites (Figures 23-31) although the model did not predict some of the higher observed concentrations. The observations in these comparisons were not continuous but were made for specific flow events. Comparison of measured and predicted P loading for the nine treatments of Izumo and Bottcher (1991) indicated fair agreement. Although there were exceptions, predicted losses were mostly higher than observed. Dr. Bottcher correctly states that the discrepancies could be due to errors in both predicted and measured volumes. The accuracy of the measured results was estimated to be within ± 30 percent. It is stated (in the supplement of 9-12-94) that such errors in the measured data would result in an R^2 of 0.76, even if the model were perfect. Dr. Bottcher further states that, if the model error is of equal magnitude to the error in the observed data, the (R^2) would be 0.50. I don't understand how either of these numbers were obtained.

The conclusion is that R^2 values greater than 0.50 would indicate that the model error is of equal or less magnitude than the measurement error. I don't think that such a conclusion is statistically valid. This doesn't mean that model errors are greater than errors in field measurements. It simply means that I don't believe you can prove the point in this way. Other means of presenting the results and determining modeling error should be used. I suggest that the points plotted in Figure 5 of the 9-12-94 supplement could show the field error (± 30%) as bars or brackets, on each point. It is difficult to test the reliability of a model when there is large error in the experimental data. Alternatives are to (1) improve the accuracy of field measurements and/or (2) to increase the number of field measurements and range of practices monitored (which is occurring as monitoring continues over time). Both alternatives would allow a stronger evaluation of the model.

Task 4. To assess whether the model could be used as a tool for comparing effects of implementing different BMPs on a farm without having model errors obscure the phosphorus reduction predictions.

Whether the model can reliably predict the change in P loading that results from the use of a management practice, or a change in a management practice, is of equal or greater importance than predicting the absolute magnitude of the P loading. Predictions of the inputs of five BMPS on one farm were within the limits of the impacts estimated from field measurements (Figure 7 of 9-12-94 supplement). Discussion of those results indicated that similar comparisons would be made for another farm when the phosphorus data became available. Because of the variability and error inherent in field measurements of P loading, such additional testing is strongly recommended. The results of monitoring and field experiments conducted so far, as presented in the report, do not appear to provide a sufficient data base for precisely evaluating the reliability of the model. Results are encouraging as the model predicts the impacts of BMPS that are in the

same direction and within the range of error as determined from field measurements. However, it is not possible at this time to say that the use of a given management practice will reduce P losses in drainage waters by, for example, 15% $\pm$ 5%. Further improvements in the model, and additional testing should improve the predictions and increase confidence in its application. It is my conclusion that the modeling approach is appropriate and that it will be possible to assess the long-term and short term impacts of BMPs on P losses at the field edge. More work is needed to determine the accuracy of such assessments.

Task 5. To determine whether the model is practical enough such that farmers can eventually use it to select and evaluate BMPs.

The current version of the model is not user friendly. I had two graduate students, who have experience in models of this type, independently run the model using the example data sets. They changed some parameters and made several simulations. Their experiences (as indicated in the attached unedited reports) and my review indicate that many of the required inputs are difficult to interpret. It was necessary to go to the source code to determine the meaning of some of the variables. Likewise it was difficult to understand some of the outputs of the model. These problems are understandable as the model is a "work in progress" and the user friendly interface apparently has not been developed yet. Most if not all of such problems can be solved by the development of such an interface.

A more difficult problem as revealed in some of the test runs that my students conducted. In some cases error messages were given when the convergence error criterion was set too low. Such problems are not severe for researchers or modelers, but will cause great difficulty for most farmers who do not, nor should need to, understand the numerical processes involved. Routines should be installed in the model to automatically adjust the criterion, with appropriate warning

messages, so that this problem does not occur. That is, the models needs to be very **robust** for application by farmers and their technical advisors in the EAA.

Task 6. To ascertain whether the model can be a useful tool for researchers to use to compare BMPs related P load reductions from year-to-year for a farmer by mitigating the hydrologic effects on annual P load differences.

My review indicates that the model will be a useful tool for researchers to evaluate impacts of BMPs on P losses. The current version of the model considers the most important processes affecting P losses at the field edge. Better documentation of the methods used and the inputs required is needed for researchers other than the developers, to effectively use the model. Additional work is needed to improve some of the methods, such as the algorithms used for predicting losses of sediment P. Additional testing is needed to determine its reliability and sensitivity to errors in the model inputs. With these improvements the model could be used in more or less its present form to evaluate impacts of various BMPs on field scale losses.

Management practices for reducing P loading in drainage waters are mostly implemented at the field scale. The primary objective, however, is to use the BMPs to reduce P loading downstream where drainage waters leave the farm and, ultimately, the EAA.

The report and 9-12-94 supplement include plans to extend EAAMOD to the farm scale by incorporating models and associated methods to describe the hydraulics and P transport processes in the canal network. Chemical, biological and biochemical processes affecting transport and fate of P in the canals would be considered. The 9-12-94 supplement and discussions with Dr. Bottcher indicate that the Dutch model, DUFLOW, which already considers the hydraulic, reaction and transport processes, will be linked to EAAMOD. This is a promising approach for predicting impacts of field scale BMPs on P loading at the farm and drainage basin scales. Linking a relatively computationally demanding field scale model (EAAMOD) with a numerical-based in-stream model (DUFLOW) will be a challenge. Successful completion and testing of this linked model will provide a very useful tool for researchers to evaluate basin scale impacts of BMPs. Whether it can be simplified in the short-run such that engineers, technicians and farmers can apply it to specific cases is not clear. Simplification of both the field scale model (EAAMOD) and the in-stream model will likely be necessary if such applications are to be routine.

Task 7. To make suggestions as to how the model could be improved in order for it to be of practical use if it isn't already

I have already made suggestions in this report. Important steps in developing a "practical" model are to test it so that its limits of reliability are known, and to clearly document it so that the users and other researchers can understand the basis of the model,

assumptions that are made, sensitivity to errors in the model parameters and how to interpret the outputs. My suggestions cover these points. As indicated under point 6, the linked model may be so computationally intensive that simplifications will be necessary for practical application at the farm scale. Numerical solutions in EAAMOD are necessary in part, to handle lateral variations in soil properties (hydraulic K). It may be that most applications will assume a constant or average K for the whole field. If this is true, it may be possible to use an approach that doesn't require numerical solutions for the field scale processes, thereby dramatically reducing the computation requirements while making the model more robust. Such a simplification may not be possible for several reasons, but the possibility should be thoroughly evaluated.

Task 8. To satisfy ourselves that the model is a piece of work that the University of Florida/IFAS can endorse.

As stated previously, I think the basic approach is reasonable. What is needed at this point is better description an documentation of the model, improvement of some of the algorithms as discussed, clearer presentation of the testing that has been conducted, and additional testing where data are available. Completion of these steps should result in a product that could be endorsed by IFAS and published in the scientific literature.

REFERENCES

Parsons, J.E., R.W. Skaggs and C.W. Doty. 1991a. Development and testing of a water management model (WATRCOM): Development. Transactions of the ASAE, Vol. 34(1):120-128.

Parsons, J.E., C.W. Doty and R.W. Skaggs. 1991b. Development and testing of a water management model (WATRCOM): Field testing. Transactions of the ASAE, Vol.

MEMORANDUM

DATE: October 19, 1994

TO: Dr. Forrest Izuno, Associate Professor
Everglades Research and Education Center
P.O. Box 8003
Belle Glade, FL 33430-8003

FROM: Wendy Graham, Associate Professor
Agricultural Engineering Dept., University of Florida

RE: Report on Peer Review of EAAMOD

The following summarizes my evaluation of the computer program EAAMOD. My comments are based on 1) an evaluation of the EAAMOD documentation, "EAAMOD - Everglades Agricultural Area Field-Scale Hydrologic and Phosphorus Transport Model" by Bottcher and Stuck, and 2) the one day Peer Review Committee meeting held on September 12, 1994, during which Dr. Bottcher gave a brief presentation of the model and answered committee members questions. I have not attempted to run the program myself. The format of this memo follows the format of your August 29, 1994 memo which outlined the following charges to the committee:

1. Evaluate the technical correctness and appropriateness of the processes used in the model.

The model apparently incorporates simplified, often empirical, representations of a large number of appropriate flow, transport, and transformation processes. However, details of the physical processes modeled, and assumptions required to implement them in the numerical code are not adequately discussed in the documentation. Thus it is not possible to assess the technical correctness of the assumptions made in representing these processes. The model is not verified against existing analytical solutions to simplified problems, or against other existing computer codes with similar capabilities. Furthermore, the data the model predictions are checked against appear to be inadequate either to test the accuracy of empirical or numerical approximations, or to distinguish between alternative approximations of model processes. For example, since only total phosphorus concentrations in ditches and at main discharge pumps are measured, in field process representations cannot be verified. Furthermore, simplified in-field or in-ditch representations of processes that partition phosphorus between soluble P and particulate P cannot be tested using only total P

concentrations. Individual components of all phosphorus fate and transport mechanisms in the model should be verified, even if ultimately the user is only interested in total P concentrations.

2. Determine whether the sensitivity analysis accurately represents the models capabilities.

No sensitivity analyses were included in the program documentation. I am under the impression that some model sensitivity analyses have been conducted, but I do not have any written information on the results.

3. Evaluate whether the absolute model prediction errors are within the bounds of the errors expected in the field data used to calibrate the model?

It is impossible to make this evaluation given the current available information on model performance. Model prediction errors include errors in physical process representation, errors in model parameter estimation, and numerical errors associatedwith model discretization, stability and convergence. The program documentation does not quantify any of these potential errors. Errors due to model calibration with inaccurate field data may be minor compared to the other sources of possible error in model predictions.

4. Is the model accurate enough to be useful as a tool for comparing the effects of implementing different BMPs ?

It is possible that the model simulates the important processes accurately enough to compare the effects of implementing different BMPs. However, without formal documentation of the accuracy of empirical process representations, the accuracy of numerical solution schemes, and the sensitivity of model predictions to errors in the input parameters it is impossible to tell. It should be noted that even to get reliable predictions of relative phosphorus loadings for different BMPs, the processes contributing to phosphorus loading for each BMP must be described accurately. As stated earlier, individual components of all phosphorus fate and transport mechanisms in the model must be verified, even if ultimately the user is only interested in relative total P loadings between alternate BMPs.

5. Is the model practical enough for farmers to use to evaluate alternative BMPs?

At this stage of development the model is probably too complicated for individual farmers to use.

6. Is the model a useful tool for researchers to use to evaluate alternative BMPs?

If the model were fully documented, and quantitative assessments of adequacy of simplified process descriptions, numerical solution techniques, and model sensitivity to parameter estimation errors were made available, the model would likely be a useful research tool. As it currently exists, however, the documentation is probably not rigorous enough to satisfy the research community.

UNIVERSITY OF FLORIDA **Cooperative Extension Service**

Institute of Food and Agricultural Sciences

MEMORANDUM

DATE: January 13, 1995

TO: Dr. Del Bottcher

FROM: Laurene T. Capone

RE: EAAMOD review

The following is a detailed outline of the reviewer's comments. I have tried to summarize the important details of these comments.

Please address the issues that I have summarized from the peer review. I would like to receive a response by mid February for inclusion in the Phase IV Final Report. I realize that some of the comments will take time to accomplish, please indicate where possible, when I should expect that the model and or model documentation will have the proper adjustments made. I also realize that you have already addressed many of the comments. Please indicate what you have done to deal with them and where you are in the process of completing the others. If you feel comments are not germane to the modeling effort please explain why you have chosen to refute them.

In most cases the comments made by the review team were similar (as to be expected) therefore if I listed something twice or three times, simply state that you previously addressed the question.

The real test will be when I can run this thing! Thanks again. I think this exercise will go a long ways towards ending the confusion in many minds.

c: Dr. Izuno
Ed Barber
Dr. Skaggs
Dr. Campbell
Dr. Graham
Dr. Reddy

The Institute of Food and Agricultural Sciences is an Equal Employment Opportunity - Affirmative Action Employer authorized to provide research, educational, information and other services only to individuals and institutions that function without regard to race, color, sex, age, handicap or national origin.
[illegible]

Campbell

1. Sediment transport algorithm is somewhat unsubstantiated due to a lack of measured field data to support its development and evaluation.

2. Documentation is lacking.

3. Numerical technique testing and comparison with analytical methods needs to be included.

4. Need additional model testing results comparing simulated and observed water-table elevations, outflows, and phosphorus loads for a variety of BMP treatments need to be presented to build confidence in the performance of the model.

5. Input variable and input data files are not adequately documented. Please define and describe properly.

6. Units of measure are missing in many places throughout the document.

7. Need <u>additional sensitivity analysis</u>.

Graham

1. Need details of physical processes modeled and assumptions required to implement them.

2. The model is not verified against existing analytical solutions to simplified problems, or against other existing computer codes with similar capabilities. The data the model predictions are checked against appear to be inadequate either to test the accuracy of empirical or numerical approximations, or to distinguish between alternative approximations of model processes. Regardless of the fact that we do not have TDP data is there anything else that can be done to address this concern?

3. Need formal documentation of the accuracy of empirical process representations, the accuracy of numerical solution schemes, and the sensitivity of model predictions to errors in the input parameters.

4. Describe the processes contributing to P loading accurately.

5. Individual components of all P fate and transport mechanisms in the model must be verified.

6. Address the following suggestions:
   1. Model fully documented and quantitative assessments of adequacy of simplified process descriptions
   2. Numerical solution techniques documented
   3. Model sensitivity to parameter estimation errors need to be completed.

Skaggs

1. Clarify the following: "continuity equation for the upper layer reduces to the well known Boussinesq equation, although it isn't written that way or recognized in the model documentation.

2. Please address the statement on page 4 of Skaggs' comments "weaknesses of the approach include the fact that unsaturated processes are approximated and may cause errors for certain conditions;.....".

   Can you plan to accommodate this suggestion?

3. The basic approach used to model the flow processes seem to be appropriate...**THE METHODS ARE NOT FULLY DOCUMENTED** in the report.

4. Report does not clearly describe methods & algorithms used in the model. DOCUMENTATION LACKING.

5. See page 5 of Skaggs' comments. Incorporate Dr. Skaggs' suggestions or explain why you cannot.

   Also please properly reference DRAINMOD where appropriate.

6. There is no definition of how "dry curve" is obtained. It is needed.

7. The model uses "wet and dry curves" please show an example of those curves in addition to the diagram in Fig. 2.

8. Please explain the statement on page 6 of Dr. Skaggs' review, "Water table remaining static as water is removed from the profile....? Is there a process in the model that accommodates this? If not, is it necessary to incorporate one?

9. Address #4 on page 6 of Skaggs' report. Again, here it sounds like you need to expound on documentation.

10. Provide more information about the solution technique for solving simultaneous equations. "The simultaneous equations referred to are the at the bottom of page 13 of the model and the parallel equation for the upper zone. The latter equation should be presented in terms of h, not Q. Are the equations written for all nodes or just the interior nodes? How are the boundary conditions applied. Indicating LU decomposition technique is used without documentation of detail is not very helpful." Please address this comment.

Skaggs
(continued)

11. Provide further detail as to how surface water runoff and flooding are handled within the model.

12. "When surface is flooded, there would be no gradient in h. Is subsurface flow zero for that condition? See page 7 (Skaggs). Please address this question.

13. Provide more documentation regarding the processes affecting movement and fate of P within the profile and methods used in the model to quantify them. See page 8 for details. Address what happens if the P concentration exceeds those that are described by linear isotherms (0-2 mgL^{-1}). Does the model produce an error message?

14. Methods used to predict the sediment P and losses via sediment P are not clear. I assume the work Stuck is doing will address this. When do you expect this will show up in the model/documentation?

15. The current documentation is too vague to indicate that reporting the results in terms of a sensitivity ratio is efficient yet makes it hard to interpret. Dependent variable is not identified. See page 9 (Skaggs). Please explain.

16. See page 10 (Skaggs) referencing the sensitivity analysis. What is Inflow? Subirrigation into the profile? Provide more detail as to the physical situation that was modeled for the sensitivity analysis...perhaps a sketch?

17. Input parameters that were tested for hydraulic sensitivity are **not clearly defined.**

18. What is K-imp? Define soil def?

19. Dr. Skaggs suggests that the manner in which the sensitivity analysis are presented implies that sensitivity of predictions to changes in the inputs (or errors in inputs) is linear. He states that this often <u>not the case</u>. Suggest that the sensitivity to errors of +/-50% or better still +100% and -50% should be determined. See page 10. Define limitations.

20. Finish sensitivity analysis. Dr. Skaggs suggests a different method of reporting sensitivity analysis. Incorporate suggestion or defend why not.

21. Address the following:

    The model's ability to predict the hydrology and P concentrations in the profile should be tested. Has it been? If not will it be?

22. Has the model been tested against other analytical solutions for water table drawdown and drainage rates? If not, will it? Why or why not?

23. Has the model been tested to predict the hydrology and P concentrations in the profile? See page 12.

24. Compare predicted and measured water table depths and drainage rates for a long record (1 to 3) years on several sites. Document this within the model.

25. Please explain how you arrived at your R^2 values page 13 (Skaggs).

26. Many of the required inputs are difficult to interpret. Reviewer had to go to the source code to determine the meaning of some of the variables. Please define all variables properly.

    Do the same for the outputs of the model. The interface should include this.

27. "In some cases error messages were given when the convergence criterion were set too low. Routines should be installed in the model to automatically adjust the criterion, with appropriate warning messages. Will the model have these whistles? If no, explain why not necessary.

28. "Additional work is needed to improve some of the methods, such as the algorithms used for predicting losses of sediment P. Again, I believe that the work that Stuck is doing will address this? Am I correct in this assumption?

29. Additional testing is needed to determine the model's reliability and sensitivity errors in the model inputs.

30. Dr. Skagg's suggests (not his words) "the black box approach may be necessary to reduce the computation requirements. Please list the processes which could be "black boxed".