PEER REVIEW OF THE WATERSHED ANALYSIS RISK MANAGEMENT FRAMEWORK (WARMF)

An evaluation of WARMF for TMDL applications by independent experts using USEPA guidelines

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Final Report

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Peer Review of the WARMF Model

EXECUTIVE SUMMARY

This report documents the results of a critical evaluation of the Watershed Analysis Risk Management Framework (WARMF) by a selected group of experts from academic institutions, regulatory agencies and stakeholder organizations, including electric utilities. WARMF has been developed by Systech Engineering, Inc., under contract to EPRI. WARMF is designed to study fate and transport processes at a watershed scale, so it is a logical tool for developing Total Maximum Daily Loads (TMDLs), in support of regulator and stakeholder decision-making for watershed and water resource management.. The key objective of the review was to determine the suitability of WARMF to perform TMDL development. The majority of reviewers felt that WARMF is indeed suitable for developing TMDLs; although, potential users of WARMF need to be aware of key assumptions (see Section 4 D), issues with data needs and data quality (Sections 4 E, F), and the evaluation of model performance (Section 4 G). One of the key strengths of WARMF is its very friendly Graphical User Interface, which combined with its TMDL and Consensus modules, makes WARMF a powerful tool for supporting decision-making. The main concerns expressed with the framework are common to watershed-scale models; e.g., large-scale averaging of processes and necessary simplification of mathematical formulations to reduce data needs. Other important issues include gaps in model documentation and some difficulties with interpretation of model results and lack of built-in statistical analysis.

The peer review process followed USEPA guidelines, based on the "Guidance for Conducting External Peer Review of Environmental Regulatory Models" (EPA 100-B-94-001). To our knowledge, this is the first time that a watershed-scale model has been evaluated so thoroughly using these guidelines. The model was evaluated by the experts according to the following categories:

1. Model Purpose and Objectives: Does it fit within the regulatory context?
2. Major Defining and Limiting Considerations
3. Theoretical Basis for the Model
4. Key Assumptions
5. Parameter Value Estimation
6. Data Quality and Quantity Needs
7. Model Performance Measures
8. TMDL and Consensus Process
9. Model Documentation and User's Guide
10. General Aspects

Reviewers provided a critical assessment of WARMF in their areas of expertise, and raised valid concerns or comments in other areas as warranted. The report documents the reviewers' comments in their entirety, to avoid misrepresentation of any opinion. The objective was not to obtain a consensus document, since as in any review process, there are differences of opinion.

The reader is thus given a complete perspective on the issues, and can then proceed to make a better decision as to whether WARMF is an appropriate tool for his/her particular problem. There are a number of areas for improvement that were identified in the peer review process. Systech Engineering, Inc., was informed of all comments made by reviewers, and has provided a response in Appendix A. Systech has also proceeded to make modifications to WARMF, incorporating the recommendations of the peer review panel.

1. Objective of the Peer Review

The objective of the peer review of the Watershed Analysis Risk Management Framework (WARMF) model, developed by Systech Engineering for the Electric Power Research Institute (EPRI), is to determine its applicability for developing Total Maximum Daily Loads (TMDLs) for a range of pollutants, in accordance with Section 303(d) of the Clean Water Act (40 CFR Part 130). The model's application niche is surface water quality, which depends on inputs from point and non-point sources, atmospheric deposition, watershed processes and groundwater-borne pollutants into the receiving water bodies. In addition to the technical aspects of developing TMDLs, WARMF was also developed to assist the stakeholders in a particular watershed reach consensus on the actions needed to achieve desired water quality criteria, by providing a framework for reaching consensus during the decision-making process.

The peer review panel was tasked with evaluating the conceptual model used to develop WARMF, the mathematical formulation of the conceptual model, the numerical solution, the methods used to estimate parameter values, the process for calibrating the model, and the performance of the model with respect to observed data. The reviewers were also asked to evaluate the major assumptions, the model strength's and weaknesses, the limitations of the model, the robustness of the model predictions, the basis for calculating TMDLs, the confidence level for calculating TMDLs, and any specific areas where additional research or model development would result in significant improvements. The peer review panel also evaluated the framework provided by WARMF to reach consensus during the decision-making process.

An Acid Mine Drainage (AMD) module is being developed for the Cheat River (WV), which will extend the applicability of WARMF to watersheds with AMD. Since it is not fully completed, the AMD module has been omitted from the peer review process. The fact that AMD is not mentioned in this report does not imply that peer reviewers have reviewed and approved of the AMD module.

2. Peer Review Process

The Peer Review Panel was convened to a meeting on Dec. 6, 1999 at EPRI, for a presentation of the Peer Review Objectives, the Peer Review Guidelines which detailed the questions that the reviewers should address, and an overview of the WARMF model. The Peer Review Guidelines were prepared based on the USEPA "Guidance for Conducting External Peer Review of Environmental Regulatory Models" (EPA 100-B-94-001), with additional questions to address TMDL development as well as stakeholder issues. All the reviewers received a CD-ROM with the WARMF model, Truckee River application, as well as copies of the WARMF model documentation and user guide. The reviewers were asked to load and run the model as soon as possible, and to provide comments or ask questions to Systech Engineering as needed. Reviewers were asked to provide their expert opinion on those areas with which they are most familiar, not necessarily on each and every question included in the guidelines.

Their official review of the model was requested for January 31, 2000. The comments from all the reviewers were collected and placed under the various headings by Dr. Arturo Keller and Dana Armanino at the Bren School of Environmental Science and Management at UCSB. The first draft of the Peer Review Report was sent to the reviewers for additional comments by

March 3, 2000. This also served to make sure there were no mistakes in the editing process. Comments and revisions were received from the reviewers up to April 3, 2000. This final draft contains all the comments from the reviewers, with minimal editing to avoid affecting the original intent of the authors. Some reviewers were asked to clarify or expand on certain issues. We also present in Appendix 1 the response by Systech to the Peer Review Report, as well as specific comments from some reviewers.

As a note to the reader, the peer review process is not intended to provide a unified response, since different reviewers have different values and levels of expertise. Rather, the intent is to provide expert opinions on the various issues involved with the use of the WARMF model, highlighting both the advantages and disadvantages. The reader of this report can then determine whether this is an appropriate model for the intended application, and understand the limitations of the model. The peer review process is not intended to be an endorsement of the model, or of the results produced by the model, nor is it intended to be a specific comparison of the model with respect to other existing watershed models.

3. Composition of the Peer Review Panel

Under the auspices of Russell Kinerson (kinerson.russell@epa.gov) at US EPA Headquarters, Tom Henry (henry.thomas@epa.gov) from USEPA Region III and Jim Greenfield (greenfield.jim@epa.gov) from USEPA Region IV, and Dr. Robert Goldstein (rogoldst@epri.com) from the Electric Power Research Institute, Dr. Arturo Keller (keller@bren.ucsb.edu) from the University of California at Santa Barbara was asked to organize the review of WARMF by a group of experts. A Peer Review Panel was convened to evaluate WARMF as an appropriate tool for TMDL development. The following individuals were asked to provide their comments and critical assessment, based on their expertise in watershed management or related areas as discussed briefly here:

Academic Institutions

David Correll, (correll@hitter.net), has thirty years of experience with watershed research, especially effects of geology, weather, and land use on nutrient and sediment fluxes. He is an expert on water quality effects of riparian buffers. He also has experience in the areas of atmospheric deposition and eutrophication of surface waters. Dr. Correll holds a B.S. in Zoology and Chemistry from North Central College, an M.S. in Limnology from Michigan State University, and a Ph.D. in Chemistry and Limnology from Michigan State University. He has been a Postdoctoral Fellow, Marine Biology at Scripps Institution of Oceanography Senior Scientist (Chemistry), and worked from 1962 to 1999 at the Smithsonian Institution, Smithsonian Environmental Research Center in Maryland.

Jerry Fletcher, (jfletch@wvu.edu) is Professor of Environmental and Natural Resource Economics at West Virginia University, and is also Chair of the Agricultural and Resource Economics Program, Natural Resource Analysis Center. His research interests are in Natural resource and environmental economics; quantitative methods; spatial applications in economic analysis; computer applications in applied economic analysis. Dr. Fletcher holds a Ph.D., University of California, Davis, Agricultural Economics, 1982, an M.A., University of

California, Davis, Economics, 1979, and a B.S., University of Wyoming, Mathematics, 1976. (http://www.wvu.edu/~regional/vita/fletcher.htm)

Arturo Keller, (keller@bren.ucsb.edu), is an Assistant Professor of Biogeochemistry at the Bren School of Environmental Science and Management, UC Santa Barbara. Keller's research interests are in the fate and transport of chemical in the environment, and the effects of management practices on fate and transport. Most recently he led the production of a report by a group of UC investigators on the "Health and Environmental Assessment of MTBE" for the State of California. He has also done work with global carbon models, and experimental and modeling work with the fate and transport of chlorinated organic contaminants in groundwater systems. His research group involves a combination of experimentalists and numerical modelers. Keller teaches courses in Biogeochemistry, Fate and Transport of Pollutants, Soil and Water Quality Management, Air Quality Management, Advances in Pollution Prevention, and most recently Watershed Quality Management. Keller is also involved in the research group that recently received a Long-Term Ecological Research (LTER) award from NSF, and will be implementing a watershed model to understand and characterize the chemical loads that discharge into the coastal ecosystems in Mediterranean climates such as those present in Southern California. Keller holds a PhD in Civil (Environmental) Engineering from Stanford University, an M.S. in Civil (Environmental) Engineering from Stanford University, and a B.S. in Chemical Engineering and a B.A. in Chemistry from Cornell University.

John Tracy, (tracy@dri.edu), has worked on a wide range of research and consulting projects in the areas of watershed planning, watershed restoration, the development of modeling tools for environmental systems and remediation of soils contaminated with hazardous chemicals. He has worked in a wide range of watersheds, including the Florida Everglades, agricultural watersheds in the Great Plains, heavily urbanized watersheds in the Great Lakes Region and mountainous watersheds on the western edge of the Great Basin. His most recent work includes: the development of a conceptual model of the integration of physical and socio-economic processes in the Lake Tahoe Basin for the Lake Tahoe Watershed Assessment Report; chairing an American Geological Institute peer review committee to assess the decision making value of models that predict the fate of PCBs in the Lower Fox River (Wisconsin); and the development of watershed scale planning models for use in evaluating plans to restore flows to Walker Lake (Nevada). Dr. Tracy received his B.S. degree in Civil Engineering at Colorado State University in 1980, and his M.S. and Ph.D. degrees in Civil Engineering at the University of California at Davis in 1986 and 1989, respectively. He has held academic positions at Kansas State University, (Civil Engineering Department, 1989-1992) and South Dakota State University, (Civil Engineering Department, 1992-1996). Dr. Tracy is currently an Associate Research Professor in the Division of Hydrologic Sciences at the Desert Research Institute.

Raymond Whittemore, (rwhittem@tufts.edu), is a Principal Research Engineer with the National Council for Air and Stream Improvement, Inc. (NCASI) located at Tufts University in Medford, MA. He graduated from the University of Maine with a Ph.D. degree in Chemical Engineering in 1971 and has been at the NCASI's Northeast Regional Center since that time. Major projects and research interests related to water quality modeling and waste load allocation. Early work focused on developing the ultimate BOD Standard Method, advancing sediment oxygen demand measurement, and demonstrating an innovative nonradioactive krypton gas tracer technique with colleagues at Amherst College. Along with Linfield Brown at Tufts, he was responsible for the evolution of the QUAL-II model into what is now QUAL2E. In recent years, Dr. Whittemore is working with industry foresters in various modeling issues related to TMDL development.

Regulatory Agencies

Mary F. Beck, PE, from USEPA - Region III (Beck.mary@epa.gov). Ms. Beck transferred from the USDA - Soil Conservation Service to the Resource Conservation and Recovery Act (RCRA) program, EPA, Region III, in September 1984, were the water quality issue was contamination of groundwater from hazardous waste. In June 1998 transferred to the Water Protection Division, TMDL Management and Support Unit, where responsibilities include assisting states in developing TMDLs, reviewing states' TMDL development methodologies, reviewing state-submitted TMDLs, reviewing states' section 303(d) listing methodologies, and responding to related TMDL and listing issues. While working for a consultant prior to joining the federal government, Ms. Beck was responsible for all hydrology/hydraulics analysis under four dam safety inspection contracts with the Corps of Engineers, performed dam-break studies using the NWS dam-break computer program, and prepared sedimentation and erosion control plans. Ms. Beck holds a BSCE (Civil Engineering) from Drexel Institute of Technology; a MSCE (Geotechnical Engineering) from Drexel University; and a MSCE (Water Resources) from Villanova University.

Robert K. Hall, (hallswan@juno.com), is the USEPA Region IX Regional Environmental Monitoring and Assessment Program (R-EMAP) coordinator and project manager. Mr. Hall is also the co-bioassessment coordinator and peer review coordinator for USEPA Region IX's Water Division. Mr. Hall provides stream bioassessment training for tribal water monitoring programs and volunteer monitoring groups within the region. Mr. Hall has authored and co-authored several papers on USEPA Region IX's stream bioassessment program. Some recent publications include:

- Hall, R.K., Olsen, A., Stevens, D., Rosenbaum, B., Wolinsky, G., Husby, P., and Heggem, D., in print. River Reach File 3 (RF3) as an EMAP Sample Frame; EMAP Symposium Proceedings.
- Hall, R.K., Wolinsky, G., Husby, P., Harrington, J., Spindler, P., Smith, G., and Vargas, K., in print, Aquatic Bioassessment USEPA Region IX; EMAP Symposium Proceedings.
- Ellsworth, S., Rosamond, C., Hall, R.K., and Husby, P., 1999. Humboldt River REMAP; EMAP Symposium, Abstract with Programs, April. Hall, R.K., Wolinsky, G., Husby, P., Harrington, J., Spindler, P., Smith, G., and Vargas, K., 1999a, Aquatic Bioassessment USEPA Region IX; EMAP Symposium, Abstract with Programs, April.
- Hall, R.K., Olsen, A., Stevens, D., Rosenbaum, B., Wolinsky, G., and Husby, P., 1999. River Reach File 3 (RF3) as an EMAP Sample Frame; EMAP Symposium, Abstract with Programs, April.
- Hill, B., Hall. R.K., Husby, P., Herlihy, A.T., Dunne, M., 1999. Interregional Comparison of Sediment Microbial Respiration in Streams; Ecosystem Health Symposium, Abstract with Programs, August.
- Hill, B., Hall. R.K., Husby, P., Herlihy, A.T., Dunne, M., in press, Interregional Comparison of Sediment Microbial Respiration in Streams; Journal of Environmental Health.

Michelle Woolfolk, is an environmental modeler with the North Carolina Division of Water Quality (michelle.woolfolk@ncmail.net), where she is part of a team of scientists developing wasteload allocations, TMDLs, and water quality management strategies. She is currently working on modeling projects and management strategies for the Upper Catawba River Basin, the Haw River Basin, and the Lumber River Basin, all within North Carolina. Ms. Woolfolk graduated from the University of Virginia with a Master of Science in Civil Engineering and the University of South Carolina with a Bachelor of Science in Mechanical Engineering.

Adele Basham, (abasham@ndep.carson-city.nv.us), is the supervisor of the Water Quality Standards Branch in the Nevada Division of Environmental Protection (NDEP). In addition to water quality standards, the Standards Branch is responsible for the TMDL program. Adele has worked with water quality standards and TMDLs for NDEP for more than 10 years. Her work includes supervising the establishment of TMDLs on the Truckee River. Since a model suitable for addressing the dissolved oxygen problems on the Truckee River was not available, a site specific water quality model that simulates nutrient, water temperature, algal biomass, and dissolved oxygen was developed. This model served as the basis for establishing the TMDLs for nutrients. Adele is a Registered Professional Engineer in the State of Nevada.

Stakeholder Groups

Evan Hansen (downstream@imagixx.net), works as an independent consultant for watershed groups, environmental organizations, consulting companies, and government agencies. Through Downstream Strategies, his work focuses on four areas: TMDLs, water resources and water quality, agriculture and the environment, and energy and greenhouse gases. In his TMDL work, Mr. Hansen primarily works for stakeholder groups and environmental organizations to assess the data and models used to develop TMDLs, and to help incorporate local information into TMDL models to improve their results. From 1988-95, while employed at Tellus Institute/Stockholm Environment Institute-Boston, Mr. Hansen designed and developed WEAP, a water planning tool that provides a comprehensive framework for water resource assessment. He applied WEAP to model water supply and demand in the tributaries to Central Asia's Aral Sea to predict future water level decline, and he provided support for the application of WEAP by the U.S. Army Corps of Engineers. He also designed, developed, applied, and provided training on other resource and environmental computer models. From 1995-97, Mr. Hansen was employed at the Natural Heritage Institute in San Francisco, where he worked on issues related to water resources allocation and consensus building among stakeholders. Mr. Hansen holds a B.S. in Computer Science and Engineering from M.I.T. in 1988, and an M.S. in Energy and Resources from University of California-Berkeley in 1997.

Larry Olmsted, (lolmsted@duke-energy.com), has been employed by Duke Power since 1973 in positions such as Fisheries Team Leader, Manager of Biological Sciences and current position as Director of Scientific Services. In current position he is responsible for planning, budgeting, personnel administration, technical overview and quality assurance for staff of 45. Primary disciplines include plankton, macroinvertebrates, fisheries, wildlife, bioassay, bacteriology, and environmental chemistry. He holds a BA in Biology from Northwest Nazarene University Nampa, Idaho; an MS in Zoology from University of Arkansas, Fayetteville, Arkansas; and a PhD from the University of Arkansas, Fayetteville, Arkansas. Some selected publications are:

- Chen, C.W., J. Herr, L. Ziemelis, M.C. Griggs, L.L. Olmsted, and R.A. Goldstein. 1997. Consensus model to guide watershed management decisions for Catawba River basin. Environmental Professional (19): 75-79.
- Chen, C.W., R.A. Goldstein, J. Herr, L. Ziemelis, and L.L. Olmsted. 1998. Uncertainty analysis for watershed management. Proceedings of watershed management: moving from theory to implementation. Water Environment Federation. Alexandria, VA.
- Chen, C.W., J. Herr, L. Ziemelis, R.A. Goldstein, and L.L. Olmsted. 1998. Translation of water quality to usabilities for the Catawba River Basin. Proc. NWQMC Conference. Monitoring: Critical foundations to protect our waters. U.S. Environmental Protection Agency. Washington, DC. Pp III: 399-407.
- Cox, R.M., R.D. Forsythe, G.E. Vaughan, and L.L. Olmsted. 1998. Assessing water quality in Catawba River reservoirs using Landsat Thematic Mapper satellite data. Land and reservoir management. 14(4): 405-416.

Valerie Nelson, (Valerie508@aol.com), is Director of the Coalition for Alternative Wastewater Treatment, a national organization formed in 1993 to research and analyze federal and state policies and practices in decentralized wastewater treatment, and to provide a forum for grassroots organizations and communities to articulate their needs for education, regulatory reform, and technical assistance in this field. Dr. Nelson is an economist and was a Lecturer and Visiting Assistant Professor in public policy and management at the Kennedy School of Government and M.I.T. She also served for four years as a City Councilor in Gloucester, Massachusetts.

Alan Wood, (arwood@aep.com) is currently the Manager - Water Quality for American Electric Power, headquartered in Columbus, Ohio. His group's responsibilities for corporate environmental compliance activities include preparation of applications and negotiation of permits, interpreting environmental statutes and regulations, reviewing and commenting on proposed federal and state rules, providing guidance and training to field operations. Specific program areas include NPDES and other Clean Water Act regulations, as well as water quality criteria and standards at both the federal level and within a seven state area of the Midwest. He is a 1979 graduate of Clarkson University with a Bachelor of Science degree in Civil & Environmental Engineering. He has been a registered Professional Engineer in the State of Ohio since 1986.

General Comments from Peer Reviewers:

David Correll: WARMF is an impressive model in a number of ways. It is user friendly, can be applied at reasonable cost to large watersheds, and should be of considerable utility in the TMDL process. The graphics interface and outputs are well designed. WARMF should be applicable to many if not all watersheds. It is certainly the best of several models I have seen that were designed for this purpose. However, like all models, WARMF does have some limitations.

Michelle Woolfolk: All of my responses are based on my knowledge of the Catawba River basin model, the stakeholders in North Carolina, and characteristics of all of our river basins that may or may not be reflected in the current Catawba River model.

John Tracy: My primary area of expertise is in systems analysis at the watershed scale, in particular simulating hydrologic, erosion and suspended sediment load processes. Thus, I am going to answer the majority of questions focussing on these areas.

Adele Basham: Nevada has been involved with developing and implementing TMDLs for more than 10 years. As a state regulatory agency, we are interested in whether WARMF is scientifically defensible. Hopefully, this peer review process will determine if WARMF is based on sound science. I have answered only the peer review questions related to the utility of WARMF in setting TMDLs from the state regulatory agency perspective. WARMF may have application to stakeholders in a manner that does not involve the arena of TMDLs such as a tool for assessing opportunities for locally driven watershed improvement or source water assessment required under the Safe Drinking Water Act, but my answers to the questions below are restricted to the TMDL application.

Evan Hansen: Overall, WARMF is an impressive model that allows analysts to assess a wide range of water quality and quantity issues, including TMDLs, using a sophisticated graphical user interface built upon a powerful engineering model. These comments help to answer some of the questions in the Guidelines for Peer Review of WARMF Model by highlighting areas where WARMF can be improved to make the model even more useful.

Jerry Fletcher: I found WARMF to apply to an impressive array of water quality issues. This is both a strength and weakness. It does allow the WARMF model to be used in a wide variety of locations for many issues with little modification. However, the same breadth restricts its ability to address specialized issues that do not fit well into the point source/non-point source dichotomy.

WARMF relies on its own implementation of a graphics interface and GIS functionality. While this makes the model stand alone and applicable without purchasing additional software, it does mean that added functionality from continued development of standard packages cannot be made available without significant investment in software development that is not central to the modeling process.

My biggest single concern with the WARMF implementation is the way it handles uncertainty and the estimation of parameter values for a specific study. Without adequate statistical analyses, I do not feel that the WARMF model (or any current model) can be used or defended in a regulatory framework. This is not to imply that WARMF is a conceptually inadequate. It has put together a wide array of scientific studies and concepts in a reasonable framework. The work is just not yet sufficiently complete for wide scale application. However, I'm not sure there is anything better.

Specific comments follow within the outline provided in the first draft of the review panel comments. I have also inserted a few comments to the write-up sent out. Many of the questions are redundant so hopefully it will be clear that my comments within a section apply to other questions with in the section as well. Some questions I felt were already addressed or that I had insufficient information to comment.

Valerie Nelson: My answers are not based on familiarity with watershed models or, specifically the TMDL process, but rather with the field of decentralized wastewater treatment and the community-level decision making process.

4. Elements of the Model Addressed by the Peer Review Panel

A. Model Purpose/Objectives

The Watershed Analysis Risk Management Framework (WARMF) model was developed as a decision support system to guide stakeholders to a consensus watershed management plan. Specific application of WARMF includes the estimation of Total Maximum Daily Load (TMDLs) of a number of pollutants to receiving water bodies within a particular watershed, in accordance with Section 303(d) of the Clean Water Act (40 CFR Part 130). WARMF simulates flow, pH, temperature, dissolved oxygen, ammonia, nitrate, phosphate, suspended sediments, coliform bacteria, major cations and anions, pesticides (up to three), and three algal types. The model displays spatial distributions of point and non-point loading in a graphical manner. The model can display water quality status of a river or lake segment in terms of suitability for fish habitat, swimming, water supply, recreation or other uses, based on stakeholders' water quality criteria.

i. Does the model fit within the regulatory context for which it is intended, and does it answer the scientific questions that are required?

Keller: The model was developed to support the watershed approach to managing water quality and to assist in TMDL development. It specifically considers the input of the targeted nutrient and pollutant loadings to the watershed via atmospheric deposition, land-use practices (e.g., fertilization, pesticide application, cattle grazing, suburban and urban activities), and point source releases under NPDES permits. The nutrients and pollutants are transported through the watershed via hydrologic processes, while considering their uptake, release and transformation within the various watershed units. Point and non-point sources become contributors of nutrients and pollutants to the receiving streams, rivers and lakes. Using a continuously stirred reactor (CSTR) formulation for each hydrologic unit, the model calculates the concentrations of pollutants and nutrients for each stream or river segment, as well as for the lakes and reservoirs. An energy balance is used to simulate the temperature changes in the waterbodies, based on input from solar heating as well as from point and non-point sources. The daily loading of pollutants and nutrients is simulated using a mechanistic approach, considering the most significant processes in the watershed. The model can be used to estimate the TMDL of particular pollutants to meet water quality criteria set by the stakeholders in a particular catchment, set of catchments or the entire watershed under study. Thus, the model answers the required scientific question, i.e. the TMDL.

Fletcher: The question must be addressed within the context of available data to support modeling and analysis. The WARMF model provides a reasonable assessment of standard pollution issues (non-point from land use, atmospheric discharges, and background geological sources; point sources from NPDES data). The model appears to be less adequate for issues that are not as clear cut such as acid mine drainage given the present state of the science. Development efforts such as WARMF will tend to make clear limitations in both data and scientific understanding of complex systems. It fits within the regulatory context and attempts to answer the scientific questions.

Woolfolk: From a basin wide planning approach, the model is well positioned to be used for predicting changes in water quality due to changes in the atmosphere, land use, and direct discharges. Because the model offers a holistic view of the types and magnitudes of pollutant loads over time (i.e., not steady-state), managers can evaluate different strategies for reducing the impacts of those pollutant loads.

Tracy: In terms of the variables the WARMF model is designed to simulate, its use would fit within a regulatory decision making context.

Wood: I believe that the WARMF framework is an excellent fit with the regulatory issue of TMDL development. It appears to deal with all of the technical issues that TMDL developers will face. And WARMF can be readily modified to add additional routines if necessary.

Whittemore: In principle, WARMF does provide a proper format for doing TMDLs and appears to have provided a credible answer to the task required for the test watersheds. Given that there are thousands of TMDLs remaining to be developed in the years to come, it would be desirable to build a case for alternative modeling frameworks that have been proven effective.

Hansen: WARMF allows users to calculate TMDLs for impaired waters, and to calculate what levels of pollutant load reductions are necessary to meet water quality standards.

The first limitation is due to the fact that WARMF is generally run on a daily time step because most of the relevant parameters are measured at best on a daily basis (e.g., water quality data, general meteorological information, etc.). WARMF therefore produces daily results, but acute water quality standards are written with regard to 1-hour average concentrations in some states, such as West Virginia. Therefore, the model cannot directly compute whether these specific 1-hour acute standards are being met.

One solution proposed by Systech is to use existing data to calculate factors that relate maximum hourly concentrations to average daily concentrations, and then to apply these factors to the WARMF outputs to see whether or not acute standards are likely to be met. It should be acknowledged that this issue is not unique to WARMF; it more generally applies to all models that run with daily time steps. The User's Guide should acknowledge this issue and provide guidance on how to best address it.

A second, admittedly minor, limitation is that WARMF allows standards to be met 100%, 90%, or 80% of the time. Some water quality standards (for example, in West Virginia) allow a single exceedance every three years, which corresponds to meeting water quality standards 99.91% of the time in any three-year period. This issue can be addressed in a number of ways. Modelers can have WARMF meet the standard 100% of the time and consider this to be a conservative assumption, thus adding to the TMDL's margin of safety. Or they can have WARMF meet a water quality standard-set to be slightly more stringent than the real standard-100% of the time, and then examine the results to see if the real standard is exceeded no more than once every three years. Alternatively, WARMF can be enhanced to allow the user to specify any percentage, rather than choosing between the three "hardwired" percentages currently allowed.

Beck: USEPA Region III uses the one-day value when evaluating acute water quality standards which are frequently written based on an one-hour maximum. More importantly, WARMF does not calculate a four-day average concentration for a chronic water quality standard. As Systech Engineering is preparing a mine drainage module for use in West Virginia, perhaps they have could add a four-day average routine to WARMF.

Olmsted: WARMF appears to fit well within the regulatory context of the Carolinas (Michelle Woolfolk would be best judge). Dr. Hank McKellar of the University of South

Carolina has obtained an EPA grant to use WARMF to establish TMDLs in several tributaries of the Catawba River in South Carolina. He is in the initial data gathering phase of the study, but should start application of the model next year. This is being implemented with the full support of the South Carolina Department of Health and Environmental Control. In North Carolina we have shared WARMF with a number of the staff of the Department of Environment and Natural Resources. They have expressed interest in the model and it is our understanding that it will be used to establish TMDLs for a number of impaired streams in the Catawba River.

WARMF does appear to answer the majority of the scientific questions asked. The question is, does it answer them correctly? That is the reason for our work on error analyses. Our preliminary results suggest that WARMF does a very adequate job, probably as well as any of the models available. An unknown is how well it simulates metals. Most of our metal data were obtained using traditional means and with the recent revelations on the importance of clean sampling, I am not sure our data are adequate to test the metals simulations.

ii. What are the model's strengths and weaknesses?

The WARMF model's major strengths are:

a) It relies on a process-based mechanistic description of the fate and transport of pollutants and nutrients in the watershed. Other models use transfer functions to estimate the source term from different land uses. (**Keller**)
b) It uses mostly readily available data such as the USGS Digital Elevation Model (DEM) data, USEPA's information about the land-use in the watershed, NCDC meteorological data, and literature values for process parameter values. It requires little additional data to set up the model (although field data is required to calibrate the model). (**Keller**)
c) It relies on proven hydrologic and biogeochemical models for its formulation. (**Keller**)
d) The model links catchments, river segments and lakes in a seamless watershed model. (**Keller**)
e) It has a very user-friendly interface that allows any user to view most of the input data (see comments below), and provides easily understandable output figures, which can be also downloaded as text files for further processing. (**Keller**)
f) Given the scale of the watersheds (e.g. Truckee River and Catawba River basin), the WARMF model runs in a relatively short time (minutes). (**Keller**)
g) Individual sub-catchments can be run separately, once the entire catchment has been calibrated, saving significant time in developing management scenarios for a particular region of the watershed. This is particularly useful when a basin wide run is not needed, such as when calibrating and evaluating management scenarios for only one portion of the overall river basin. (**Woolfolk**)
h) As delivered to the users (stakeholders, regulators, etc.), the WARMF model of a particular basin can be used immediately to understand watershed processes, evaluate the effect of the point and non-point sources, develop management scenarios, and calculate TMDLs. It requires only a simple (5 minute) installation and relatively little training to navigate through the model. (**Keller**)
i) The model is well documented. (**Keller**)
j) The model saves the different scenarios that are simulated (user's choice) and can display several of them for comparison of model output, both graphically and in spreadsheet format. (**Keller**)

k) Access to the parameter values is clear, and usually requires only a few clicks. Help menus aid the user to understand the various parameters, and can be accessed in each screen. (**Keller**)
l) The TMDL module guides the user through the TMDL development process. (**Keller**)
m) The consensus module provides a very useful framework for tracking all the steps necessary to reach consensus, and is logically laid out. (**Keller**)
n) The Systech help line (email or phone) is well supported, with typically a 24-hour turn around for most issues. (**Keller**)
o) The model can be setup at the required spatial resolution to calculate TMDLs, provided that the input data supports this level of resolution. (**Keller**)
p) The model can be used to determine those areas where data should be collected to improve the simulation process and/or the development of TMDLs. (**Keller**)
q) A key strength is WARMF's scope in that it goes beyond simply being a watershed model by including other elements to support a decision-making process involving multiple parties. (**Wood**)
r) The model is very user-friendly which is both a strength and a weakness. It is a strength because stakeholders from various backgrounds are able to manipulate the model. (**Basham**)
s) If the intended application is to bring stakeholders together and build consensus, WARMF is unique in providing a "road map" in a user-friendly tailored manner. (**Basham**)
t) WARMF's strengths include its graphical user interface and its ability to handle point source, nonpoint source, and atmospheric discharges. (**Olmsted**)
u) The mechanistic approach rather than the use of export coefficients has great appeal. (**Olmsted**)
v) Its user friendliness and its output in an easily understood format are also advantages. (**Olmsted**)
w) The model's major strength is in incorporating a consensus building and tracking process within the decision support tool. The Consensus Tool currently in the WARMF model is an excellent platform to build on. (**Tracy**)
x) The graphical interface is ideal for explaining and presenting the impacts of small areas on the overall water quality, particularly in the case of a downstream reservoir or estuary. (**Woolfolk**)
y) WARMF's strengths include its sophisticated graphical user interface and its integration of point source and non-point source pollution. (**Hansen**)
z) The model strengths lie in the robustness of the fundamental watershed functional representations, characterized by the collection of algorithms and databases presented. The DSS format of WARMF is unique and a definite plus, compared to competing models such as BASINS. (**Whittemore**)
aa) Nutrient loading coefficients from the different land use types were clear in relationship to agricultural lands. (**Hall**)
bb) Buffer strips are an excellent process to have in any watershed model. (**Hall**)
cc) WARMF does provide information and a focus for stakeholders to direct their discussions. (**Hall**)
dd) The strength of this model is that it presents in a clear, visual context the multi-faceted water quality impairments in a watershed. It attempts to identify the sources of pollution -

- but I am not capable of assessing how well that process works, or how it compares to other water quality models. Assuming that the predictions about water quality improvements are reasonably accurate, the results can be useful for stakeholders. The effort to model the watershed in this fashion is a very important stimulus to future research on nonpoint source inputs and remedial. (**Nelson**)

ee) A tremendous advantage is that the model will be handed to the stakeholders on a CD and they can get at all of the data that was used in the model. (**Beck**)

WARMF model weaknesses include:

a) Once the level of spatial resolution is set, it requires significant additional work to reconfigure the framework at a different level of resolution. (**Keller**)
b) The necessary averaging of parameter values (e.g. an average hydraulic conductivity for each sub-catchment soil, an average crop for the agricultural land-use, a simplified "watershed slope" to compute the hydraulic gradient for groundwater flow, zero surface water detention as a default) results in a significant simplification of the complexity of watershed topographical features and soil and land-use heterogeneity. (**Keller**)
c) All the reservoirs are considered Continuously Stirred Tank Reactors (CSTR), which implies that the particular reservoir (e.g. canopy, soil layer, river segment, lake) is completely mixed within a time step, regardless of its size or hydrologic properties. (**Keller**)
d) The model's user-friendliness can be a weakness, since stakeholders who do not understand the science can generate unrealistic or even impossible results. Having stakeholders generating many results may result in an unmanageable situation, which could undermine the consensus process. The model does not contain safeguards for these scenarios. (**Basham**)
e) There is danger of assuming that because the model produced a certain outcome, it must be true. (**Basham**)
f) The over-riding weakness of any watershed model (e.g., WARMF, BASINS) is the amount of input data needed. In many areas the volume of site-specific input data needed to run and calibrate the model are not available. Default values are obtained from general databases and are not necessarily good indicators of a particular watershed. (**Woolfolk**)
g) It is still requires a significant amount of knowledge and experience in knowing what changes to make in the parameters that define a scenario. Making changes in the model is fairly easy. However, I am concerned that stakeholders will begin using WARMF with the impression that the model will guide them through this decision process (which it will not) or that they will unwittingly make so many changes as to get lost in the maze of parameters. It should be clearly stated up front among the stakeholder group that this is still a very technical tool that requires someone with experience to lead them through. (**Wood**)
h) The toxics model is not very useful as currently programmed. It may take a funded toxics project before this is fixed. (**Woolfolk**)
i) Systech must perform the model setup, which involves an expense. (**Woolfolk**)
j) Without in-stream chemistry data to use for calibration, model performance is unknown. (**Woolfolk**)

k) It would be useful to be able to visually present sub-watershed loading though a GIS interface. (**Woolfolk**)

l) Additionally, the model should have enhanced output features so that the results of secondary, in-stream or lake water quality models (e.g., MCM, E-MCM, CE-QUAL-W2, WASP) can be accessed. (**Woolfolk**)

m) The model's major weakness is a lack of perspective of modeling hydrologic and water quality processes at the watershed scale. (**Tracy**)

n) A major improvement need is a very user friendly approach of calculating TMDLs in a nested or sequential nature. A transparent means of "freezing" the values of a TMDL so they can be used as input into TMDL calculations in the next downstream section would be desirable. There is a means of handling this within the current WARMF, but this upgrade would substantially the model's efficiency. (**Olmsted**)

o) A weakness is the lack of a seamless, easy way to calculate nested TMDLs in which upstream pollutant reductions affect those required downstream. (**Hansen**)

p) Unknown uncertainties in data and model parameters. (**Whittemore**)

q) No formal error analysis was done and should be a factor that stakeholders explore before dollars are invested in implementation. A fully established error analysis option would be a useful addition in future releases. (**Whittemore**)

r) Nutrient loading coefficients were not so clear for non-agricultural land cover/land use types. (**Hall**)

s) More information is needed about the quality (i.e., established riparian, cottonwoods, willows, ground cover, etc.), quantity (i.e., mix of different vegetation types indicative of the natural land cover type) and stability (i.e., human influence factors - channelization, levee roads, trails, grazing, etc.) of the vegetation in the buffer zone. For example, a scale of 1-5, or 1-10, which describes how much of the above parameters are present in the buffer zone (e.g., USEPA Rapid Habitat Assessment protocols - available on the USEPA web site). (**Hall**)

t) In terms of applicability to Acid Mine Drainage (AMD) issues, the problem with averaging parameter values combined with set level of spatial resolution are major limitations due to the high spatial variability of driving factors. An additional major weakness is the method (or lack thereof) for dealing with errors and variability. There needs to be a systematic attempt to quantify the effects of alternative parameter values on relative errors. (**Fletcher**)

u) While the model was developed for river/lake TMDL calculations, there is a groundwater component. The value from the model could be substantially increased if these groundwater/surface water models could be used for source water assessments or wellhead protection areas (of drinking water wells) as well. (**Nelson**)

v) The model does not predict septic system inputs. (**Nelson**)

w) The model does not seem to be designed yet for use in coastal estuaries or wetlands. (**Nelson**)

x) The model may be technically sophisticated, but if it is not based on good data and an accurate understanding of what is happening in the watershed, it can lead the community astray. (**Nelson**)

y) In the decentralized field discussions, it has been suggested that it is much better to avoid complex modeling projects such as WARMF, and instead spend money on walking along the river searching for obvious pollution problems and sources and investing in remedial projects. Complex models are only as good as the input assumptions, and if these are overly generalized or not well understood, the results of WARMF will give a false sense of security about predictions? (**Nelson**)

z) Based on other comments from other reviewers, it might make sense to conduct a comparative study in a watershed: how does WARMF perform, how does BASINS perform, how does a more simplified assessment process perform? Evaluation criteria could include accuracy of simulations, user-friendliness, and cost. (**Nelson**)

iii. How well does the model fit its intended application niche compared to existing models?

Keller: The most applicable model that can be compared to WARMF is the BASINS v.2.0 model developed by TetraTech, Inc. for USEPA. Both models are used to develop TMDLs, and consider point and non-point sources within the watershed processes. The underlying formulation of both modeling frameworks is very similar (e.g., hydrologic and biogeochemistry models, DEM data, meteorological data, land-use data). Systech delivers WARMF as a pre-setup, calibrated package, which can then be used by the stakeholders to understand the watershed, perform simulations and develop TMDLs and consensus. BASINS is available free of charge from USEPA, requiring significant expertise on the part of the user(s) in setting it up correctly, performing the calibration, and then proceeding to simulate the watershed processes and develop TMDLs. In both cases, the users (stakeholders) are required to provide watershed specific data for calibration and comparison of model output, as well as for the input of point source loading.

There are significant limitations in the BASINS model which are not the subject of this review. For example, using the NPSM (Non-Point Source Model) in BASINS lakes cannot be modeled, the groundwater algorithm is much more simplistic, the parameter values are not accessible to the user for the most part, the documentation does not provide sufficient detail for a complete evaluation, etc. Although the objective is similar, the potential user of BASINS should do a significant amount of "background check" to make sure that BASINS is really the right model for the particular application.

To date, few watersheds have been modeled with either WARMF or BASINS. Both models fit the intended application niche (TMDL development), with their limitations. Due to its more sophisticated TMDL development module, WARMF provides an easier approach to TMDL development, once the model is setup by Systech.

Tracy: The most applicable model that WARMF could be compared to at this time is the EPA BASINS package. However, neither of these packages is capable of modeling non-point source pollutants for TMDL issues for Sediment/Temperature/Nutrients at the current time. At the current time, the best models for simulating these TMDL issues are site and process specific, and large integrated models do not to perform as well. My experience with BASINS is limited, however if faced with a choice between WARMF and BASINS, I would select BASINS for developing models at the watershed scale. The reason for this choice is not so much that simulation routines in BASINS inherently provide a platform to better simulate the quantity and quality of water flowing in streams. Rather, the reason for this choice is that the routines in BASINS are non-proprietary and the source codes can be readily obtained and modified by experienced professionals. This allows BASINS to be better tailored for site specific issues and physical conditions by the inclusion or exclusion of processes that better represent the conditions in a watershed. There are several examples where this type of code modification has occurred, such as the modification of WASP5 to better simulate the fate of PCBs in the Lower Fox River. This type of modification is not readily accomplished using a proprietary code such as WARMF, and even if the modifications could be made, they typically have to be described to the model developers, who then implement the changes. This has the possibility of resulting in a misinterpretation of the needed changes, and thus producing a less functional model.

Wood: While I have no direct experience with other models used for similar purposes, I believe WARMF is an excellent fit in this niche. I believe WARMF has a distinct advantage over BASINS in that it does not require that a third party software be purchased (e.g., Arcview) in order to be functional. It is delivered as a self-contained package.

Basham: In terms of defending a TMDL, other existing models, especially EPA supported models in the public domain, have the advantage of case history and being tested, defended and successfully accepted. Models that are available in the public domain are preferred because they can be obtained free of charge.

Olmsted: My experience with other models is limited but as a result of other researchers using a multitude of models it appears WARMF is very user-friendly and produces very good results.

Whittemore: WARMF, unlike the EPA-sponsored BASINS v 2.0 product, is decidedly more user-friendly and better documented. Unfortunately, the philosophy of WARMF's creation means that it cannot be easily applied to another watershed (as is the case for BASINS). Although the water quality models in BASINS (HSPF, QUAL2E, and TOXIROUTE) are well known to many modelers, only QUAL2E currently is robust in terms of its usage and fundamental understandings. Similarly, many users find HSPF difficult to routinely use, requires substantial training to effectively use, and problematic with its reliance upon abstract and numerous parameters. These factors alone have made its use in the public stakeholder TMDL regime suspect since its fundamental constructs are based in abstract ideas and relationships initially developed in the 1960's Stanford Watershed Model. In my limited experiences, WARMF has addressed these issues and uses a suite of models that is more user-friendly and understandable to more users.

B. Major Defining and Limiting Considerations

Keller: Similar to BASINS, the WARMF model for a particular watershed is built from a Digital Elevation Map (DEM), which is created using USGS data. The watershed sub-catchments are delineated, typically at a resolution of 11 digit hydrologic units, as defined by the USGS. If a certain section has diverse land-use patterns, topography or monitoring data, the land catchments and stream segments can be divided into a finer resolution. Each land catchment can have a mixture of land uses (e.g., deciduous forest, grassland, agriculture, suburban, urban, etc.). The hydrologic model is driven by daily meteorological data (from NCDC), which provides precipitation and temperature. Precipitation (distinguished as rain or snow based on the daily temperature) is routed through the canopy and/or snowpack, which can serve as storage reservoirs. Rainfall infiltration and snowmelt permeate into the subsurface, which is modeled typically with four or five soil layers of variable thickness and soil properties. Excess water can flow as surface runoff down to surface detention storage, streams, rivers or lakes. Groundwater flows towards the receiving water bodies based on an average hydraulic gradient (computed using topography), and the effective (saturated or unsaturated) hydraulic conductivity of each layer.

Atmospheric pollutants are deposited on the catchment via dry or wet deposition. Biogeochemical cycling within the watershed intercepts and/or transforms some of the nutrients and pollutants, but a certain amount is transported to the receiving stream, river or lake segments, either via surface runoff or groundwater flow. These chemicals are then transported downgradient, accounting for transformation in each water reservoir. The model accounts for concentration changes due to sources (including point and non-point sources), sinks (reactions, sedimentation) and change in the volume of water in which the chemicals are mixed. A similar energy balance is performed to simulate temperature changes in the various reservoirs, which may affect water temperature in a particular stream or lake segment.

Each sub-catchment consists of a number of compartments for water, sediments and the various chemical species. These include the canopy, snowpack, surface detention storage, 4 or 5 soil layers, vegetation (leaves, fine litter, coarse litter, humus and fulvic acids), eroded particles (in three sizes: clay, silt and sand), stream segment and lake layers and segments. Each sub-catchment considers more than a dozen different land-uses. There are typically dozens of sub-catchments in a watershed. However, even with this fairly detailed description of watershed processes and spatial distribution, the areas that are considered in each sub-catchment typically represent hundreds or thousands of hectares, many more distinct land-uses (e.g., vegetation types, population density, agricultural or silvicultural types), and very diverse topographic and geologic conditions. Independent models have been constructed for a particular aspect (e.g., surface hydrology, groundwater flow, nutrient cycling, sediment transport), which are individually more complete than the models that are used in WARMF (or BASINS v. 2.0 for that matter). These models may consider a finer spatial and temporal resolution than WARMF. It is in principle possible to setup WARMF at a much finer spatial resolution, and the time step could be reduced to hours. The trade-off is much longer simulation times. In addition, the typical datasets available for initialization and calibration of WARMF are sparse and usually rather coarse (e.g., few streams segments have flow gages, even fewer have frequent monitoring of water quality, and the frequency with which water quality is monitored is typically much less than once a day).

i. Does the model consider all the relevant processes (e.g., transport, diffusion, chemical reactions, removal mechanisms, etc.) for developing TMDLs?

Keller: The WARMF model considers atmospheric deposition, advective transport, diffusion/dispersion in lakes, chemical reactions, removal mechanisms, biological uptake, adsorption, desorption, cation exchange, oxygen reaeration of streams and lakes, and all relevant hydrologic processes. As described above, in several instances the model makes simplifications with respect to the mathematical representation of these processes, or a simplification is used with respect to the spatial resolution.

Woolfolk: Based on a review of the documentation, it appears that the most common processes are represented for conventional pollutants. The toxics model is severely limited - conservative modeling without partitioning, transformations (e.g., hydrolysis, biodegradation, analysis or retention of daughter products) or transfers (e.g., volatilization). Also, it is unclear how the model deals with heavily sewered systems in metropolitan areas.

Whittemore: A module to deal more completely with toxic fate and bioaccumulation in relevant food chains would make WARMF amenable to several issues known to exist in some waterbodies would be welcomed.

Tracy: The WARMF model does develop equations to describe the necessary processes within a watershed, but in many cases these equations are applied at an inappropriate time and spatial scale. In addition, virtually no documentation is provided on the mechanism of process model integration. Thus, some of these issues can only be answered by model use. For example, the watershed diagrams in the WARMF user interface give the impression that a fairly refined hydrologic discretization is used, but it is quite clear from running the model that only a coarse sub-catchment representation is used to simulate processes in the watershed, with average lumped parameters used to represent the physical processes within each sub-catchment.

Basham: For algal dynamics, WARMF simulates three types of algae (e.g. diatom, green, and bluegreen). In the Truckee River, research and previous water quality modeling has shown that attached algae, which is not modeled by WARMF, plays a significant role in the nutrient and dissolved oxygen dynamics. For attached algae, additional processes are important such as the effect of flow on algal growth. Modeling of the Truckee has shown that grazing by zooplankton has a significant effect on algae, but WARMF does not simulate zooplankton grazing. Biological cycling of phosphorus is not clearly explained in the documentation so it is difficult to determine if this process has been adequately addressed. A daily time step is not adequate for simulating minimum dissolved oxygen.

Olmsted: Based on my experience the model seems to include the relevant processes. For our work, we would like to see algorithms added for internal cycling of phosphorus.

Hall: In the Truckee River Watershed, different runoff coefficients will be essential to understand and estimate accurately loadings from NPS (Non-Point Sources).

Fletcher: WARMF can (or could) include all relevant processes. The question is how well from a spatial and temporal perspective?

ii. Are relevant temporal and spatial scales considered?

Keller: The spatial scale (watershed scale) is relevant to the development of TMDLs. In addition, a TMDL can be developed for each stream segment, or for a combination of segments within the watershed. The spatial resolution must be defined upfront between the users (stakeholders and regulators) and Systech. In principle, Systech can provide the level of spatial resolution desired by the customers, provided they understand the implications with respect to simulation time and quality of data required. In practice, the resolution is somewhat coarse, to accelerate the simulation time, and taking into consideration the relatively sparse data sets. The model should not be applied at too small a scale (for example a single reservoir), or where the particular TMDL would depend significantly on groundwater movement, which might be better described using a more detailed groundwater model (e.g. MOC3D and MODFLOW).

The temporal scale (typically one day time step) is relevant for developing TMDLs, which are by definition daily loads. The use of WARMF at less than one-day timestep is possible, but not warranted by the meteorological data. Although some states (e.g. West Virginia) have set 1-hour acute toxicity standards, these are based on standard USEPA and ASTM methodology which calls for 24-, 48- or 96-hour acute toxicity protocols. Since the issue is the dose, converting a 24-hour test to a 1-hour standard will result in a higher allowed concentration, which in principle is easier to meet. Thus, the one-day timestep will in general produce TMDLs that are more restrictive than the 1-hr timestep would indicate. Also, there are no non-point source models that accurately reflect processes with diurnal variation at the watershed scale.

Woolfolk: Temporally - WARMF currently steps daily in time. This time step is likely due to the ease of computation as well as the temporal variation of available data sets. In the case of larger creeks or rivers that are not "flashy" (i.e., the hydrograph peaks and falls back to normal quickly, within a 24-hour period) and lakes, this is probably adequate. However, in the cases of determining pollutant loads from systems that are flashy, the daily time step may not be adequate. The bigger question is the focus of the current and future modeling. If WARMF will be used for overall watershed planning with focus on larger water bodies that are used recreationally or for water supply, a daily time step is more than adequate. However, if the model will be used to develop TMDLs in smaller creeks that have significant amounts of impervious surfaces, the daily time step is less desirable. With respect to toxics modeling (e.g., metals or organic chemicals), again the focus of the modeling is important. If acute toxicity is an issue, then the daily time step may not be adequate. The daily time step may also not be adequate if evaluating mercury/methylmercury cycling to any serious degree. If chronic toxicity or long-term fate and transformation is an issue, the daily time step is likely adequate.

Spatially - Systech can set up the spatial levels of the model according to user preference (or client preference). However, once the model is spatially configured, only Systech currently has the expertise to change the spatial configuration (i.e., adding additional streams).

Correll: Precipitation is entered in the model as cm/day. This temporal scale severely limits the models ability to accurately predict the proportion of precipitation that becomes overland flow versus infiltration to groundwater. There also seems to be no way to calibrate or verify how well the model predicts these outcomes for individual storms or over seasons and years. This is a very serious shortcoming, since these two routings for water movement have very different effects in terms of water quality. I did note that in chapter 3, page 14, soil detachment by rain drops has an intensity term (mm/min), which is needed, but intensity is not a variable in the model. Am I missing something here? Precipitation intensity is often not available for a study area, but it is certainly important, especially for a "mechanistic" model.

Tracy: The option for using varying time steps in the model simulations is not functional, thus not allowing for any type of analysis to determine the impacts of time averaging on the variables being simulated in the engineering module. Thus, at the current time, the issue of temporal resolution of the model simulations cannot be addressed. The developers of WARMF need to provide much more detailed documentation on what averaging routines are used in the WARMF model and make the variable time step functional in the program to allow for an effective evaluation of this issue.

Olmsted: For our purposes the temporal and spatial scales are adequate, or can be provided. The daily time step is adequate for our needs and generally exceeds the frequency of data collection. We are in the process of taking WARMF down to a much smaller (100 sq. mi) subwatershed of the Catawba River. It appears going to a finer scale will be a reasonably simple task.

Fletcher: The temporal scale (daily) is quite adequate given the data available. The potential for finer temporal scale is severely limited. When finer scale is required, it would seem better to use specific models for specific local problems. It would seem that there are significant gains to be made using a longer time step for initial analysis. The spatial scale is more problematic. While WARMF can deal with the spatial scale, it is quite inflexible for change.

Whittemore: Yes, I believe so.

iii. Is the grid resolution appropriate for the problem?

Keller: WARMF does not use a regular grid, but rather the watershed is divided into subcatchments based on diversity of topography, land uses, and level of detail required by the user for a particular stream or river segment. Lakes are also partitioned into several segments when they contain several branches. The resolution of the subcatchments can be adjusted by Systech based on the stakeholder needs.

Woolfolk: Grid resolution will be dependent upon the watershed considered. Generally, for watershed-wide TMDLs (e.g., estuary or lake at the watershed outlet), this model is ideal for evaluating the fate and transport of sources throughout the watershed. Systech can always reconfigure the model to a smaller watershed resolution, if needed.

Whittemore: Yes, because in the few cases where greater resolution might have been desirable, it would only confuse some stakeholders. If finer resolution is warranted, then a different model should be considered.

Fletcher: WARMF use of grid models is only in the initial development of subcatchments and possible for data development. This does not appear to be a limiting factor and could improved if better DEMs were available.

iv. Is the level of aggregation adequate for the problem?

Keller: WARMF has been designed to deal with entire watersheds, so the common level of aggregation (subcatchments forming a catchment) is adequate. WARMF could also be applied to smaller systems, provided a finer resolution was considered. It would however be inadequate for a very small scale where some of the simplifying assumptions (e.g., groundwater flow) would not be adequate.

Correll: Most parameters are estimates or measurements of the average for a given subwatershed. For example, soil texture and infiltration rate. Of course, in reality soil texture and infiltration rates vary considerably and non-randomly within each small subwatershed. Typically, soil texture will exhibit a gradient from the upper boundaries of the basin to the stream channel. Similarly, land use is input as a percentage for each category for the subwatershed. Land use cannot be arrayed within the subwatershed. Slope is entered as an average. Of course, land use is usually correlated with slope to some extent and slopes change as one moves down the watershed. Thus, the model performance is ultimately limited by this approximation of reality.

Woolfolk: This depends upon the intended use. For larger systems where a number of smaller streams are sources to either larger rivers or lakes, the level of aggregation is adequate. For smaller first order streams only, the model is likely not as useful.

Whittemore: Yes, although my comment in iii applies here as well.

Fletcher: Not sure how to answer this. WARMF is sufficiently flexible. The issue is one of implementation, not capabilities.

C. Theoretical Basis for the Model

Keller: The basic numerical computation engine is the same as the Integrated Lake-Watershed Acidification Study (ILWAS) model, with algorithms for sediment erosion and pollutant transport from ANSWERS and the Storm Water Management Model (SWWM). The mass balance equations for water quality parameters and algal-nutrient dynamics are adapted from WASP5. All rivers, lake layers and aquifers are considered Continuously Stirred Tank Reactors (CSTR), which implies they are completely mixed within the daily time step.

The use of a CSTR formulation is adequate for small reservoirs or short river segments where mixing can be expected to occur within a relatively small time (i.e. one time step). However, even for small reservoirs or short river segments, complete mixing on a daily basis is at best an approximation. This simplifying assumption becomes more of an issue for larger reservoirs or long river segments. For the longer river segments, a Plug Flow Reactor (PFR) is a better approximation. The PFR formulation would assume that as a slug of nutrients, BOD or pollutants enters the river, it travels essentially as a plug, with some longitudinal and transverse dispersion, but does not mix completely in the entire river segment. The difficulty in using a PFR model under the current framework is that the spatial location of the various land uses in the subcatchment are not tracked, so it is not possible to identify the probable points of entry of non-point source loading. For the larger reservoirs, the use of layers with advective and dispersive transport is a reasonable approximation, although ideally the circulation patterns would be taken into consideration, rather than assume that each layer is completely mixed within a time step. A more sophisticated lake model would be more realistic, but would have much greater data needs (e.g., wind direction, circulation patterns, etc.), which are typically not available.

The CSTR formulation also has implications for the groundwater model. Again, the assumption in WARMF is that once nutrients or pollutants enter a particular soil layer, there is complete mixing within a time step, and the concentrations increase uniformly. This has the effect of "averaging out" the pollutant loading throughout the watershed. This again is related to the method in which land uses in a subcatchment are considered, with no particular location. More sophisticated groundwater models (e.g., MODFLOW) would do a better job of predicting the fate and transport of pollutants through the subcatchment, but then a much higher level of resolution for the land uses within a watershed would be required, increasing the computation time and the data needs exponentially.

Basham: The computing engine for WARMF is taken from the Integrated Lake-Watershed Acidification Study (ILWAS). The source code of ILWAS has been updated to simulate river basins with multiple reservoirs, by splitting the river basin into the sub-watersheds draining to each reservoir. It is not clear from the model documentation that ILWAS is appropriate for use on long segments of river where no reservoir is involved such as the Truckee River. Without further documentation justifying the application of a "Lake Acidification" model to river systems, the theoretical basis for the model is subject to criticism.

i. Is the conceptual model adequate for addressing TMDLs?

Keller: The conceptual model is adequate, with meteorology driving the hydrologic cycle within the watershed, and with atmospheric deposition and land uses as the main sources of nutrients and pollutants to the streams and rivers. The relevant hydrologic and biogeochemical processes are considered for the various compartments of the watershed (e.g. groundwater, surface runoff, canopy, snowpack, streams, rivers and lakes). Although there is no specific diagram in the model's documentation describing the linkage between the various systems, the text is quite clear about how the various systems become sources for the next system in the watershed. There are some deficiencies in the model's documentation (addressed in more detail in section I of this review), including the lack of more schematic representations of the processes within various systems and the linkages between systems. The reader is required to work through the mathematical description to discover the conceptual model(s). It should be noted that this deficiency is even more pronounced in the BASINS model documentation.

The buffer strip model seems adequate for certain simple grass buffer strips, but might be inadequate for more complex forest buffer strips.

Olmsted: The conceptual model appears to be adequate for addressing the TMDLs we have worked with.

Tracy: The conceptual model of the processes appears adequate, however, there is no conceptual model of system integration, other than that given in Figure 3-1 of the WARMF documentation manual, which is at much too general of a scale to provide adequate detail for evaluation. Thus, I would conclude that the conceptual model at the watershed scale is inadequate.

Correll: Buffer zones are given slope, width, and percentage of water frontage buffered. There are no parameters for type of vegetation (e.g. grass, deciduous forest, coniferous forest, etc.). The formulation of the model seems to be for grass buffer strips and their effects on overland storm flows. In most of the world forested buffer strips are being restored, protected, enhanced and may be used in conjunction with an outer (upslope) grass buffer strip. These forested buffers main role is in treating shallow ground water as it moves laterally to the stream channel. The trees have deeper rooting zones and help foster denitrification in the ground water.

In other cases, such as the riparian vegetation, the model is much too simplistic and needs to be able to specify vegetation type, depth of rooting zone, etc. It also needs to be able to predict the effects of the riparian zone on ground water quality. This is a defect in every watershed scale model that I have seen and it needs to be addressed.

Whittemore: Yes, this effort provides a clearer perspective on land-based processes than does HSPF, for example. In general, much more could have been done (per Dr. Correll's comments).

Hall: As I understand it, mining was not necessarily a part of this review. From the manuals it's apparent that this module is not set up for hard rock mining operations (abandoned mines, open pit, heap leach, waste rock, pit lakes and pit lake overflow) found in the west and in the Truckee River Watershed. If at some point this module is completed it should be reviewed by Mining Industry, Nevada Bureau Mines, USGS, USEPA and Researchers at the University of Nevada, Reno.

Fletcher: This is not my area of primary expertise and cannot address this in general. I tend to think that the conceptual model is adequate in general. While I am not fully informed, I am concerned with my perception of the conceptual approach to AMD from either coal or hard rock mining. The approach seems much more problematic for such issues.

ii. Are algorithms used within the model based on sound scientific principles?

Keller: The algorithms are presented in the documentation in terms of their mathematical representation, with explanations given as needed. Appendix 2 presents the literature references that have been used in the development of the algorithms in WARMF. The algorithms are based on commonly applied, sound scientific principles. For example, groundwater flow is based on Darcy's Law, snowmelt hydrology is based on Corps of Engineers models, sediment transport by runoff and in the river is based on Manning's model, stream reaeration follows the traditional Streeter-Phelps algorithm, etc. All of these algorithms have been used extensively in other models to simulate hydrologic and biogeochemical processes. More sophisticated algorithms have been developed in some instances, but typically these algorithms are for a specific application (and thus not applicable for a model that is intended for wide application), and require several more parameters, which are typically not available.

Correll: There is no provision for things like macropores in the model. During the calibration process, how is this lack accommodated? In other words, how is the lack of interflow parameters accommodated?

Tracy: There are very few algorithms presented, mainly just the equations that govern the behavior for each process. Thus, at this time, there is no real information available to answer this question.

Olmsted: The algorithms are largely taken from existing models that have received peer review and seem adequately based on scientific principles.

Whittemore: Yes, the manual provided to the reviewers was sufficiently detailed to answer many/most of these questions that might arise.

Fletcher: All models are based on published research and are an acceptable approach.

iii. Is the mechanistic basis adequate?

Keller: As opposed to other models that simply consider transfer functions or emission factors from the various land uses, the WARMF model is based on a detailed mechanistic representation of watershed processes. The mechanistic basis is adequate; however, as expressed above and in the comments that follow from Dr. Tracy, the averaging processes that is necessary to produce a short computation time and reasonable input data requirements results in some important simplifications, which in some cases might produce inadequate results, for example the issues discussed below by Dr. Tracy with respect to surface runoff and sediment transport in heterogeneous land surfaces.

Tracy: The series of equations used to represent the fraction of precipitation reaching the stream as overland flow versus abstraction and infiltration are wholly inadequate for use at the watershed scale. Eqs. 3-12 through 3-19 (in the EPRI TR-110709 document) were primarily developed for use in understanding infiltration at the field scale in homogenous land use and soil type situations (i.e. agricultural watersheds). When used on much larger scale with more heterogeneous land covers and soil types, the averaged behavior of these equations becomes highly non-linear. That is, use of averaged parameters in the equation does not equal the averaged conditions using spatially explicit parameters. This can be seen in Figure 1. [Editor's note: this Figure was prepared by Dr. Tracy].

I used the simplest form of Eq. 3-15 on Page 3-8 of the WARMF documentation, assuming that the lower soil layers never fill up, that is the upper soil layer always drains to field capacity, and then running the simulation for a one day time period with varying amounts of available water. The properties used in the equation are known to vary significantly throughout a watershed, these being the saturated porosity and the field capacity. If a uniform depth of soil layer 1 is assumed as 15 cm, the properties of saturated porosity are assumed to have a mean of 0.35 and a standard deviation of 0.1, and the field capacity is assumed to have a mean of 0.15 and a standard deviation of 0.05, then the average infiltration and runoff for the sub-watershed can be computed assuming a group of randomly sized soil segments (I used a mean size of 10 sq. m with a standard deviation of 3 sq. m). Using 1,000 realizations (soil segments), I arrived at the mean behavior of the watershed as shown in Figure 1. What the equation does well is simulate the overland flow under conditions of large amounts of available water. However, what the equation does not do well is simulate the overland flow during low available water. This is significant in that many water quality regulatory standards are related to low flow conditions, and not properly accounting for where the water is coming from in low flow conditions will skew model results. For example, the only way to account for stream flow if no overland flow is simulated is to induce flow to the stream from the subsurface environment. If the area has many septic tanks, this could result in the model overpredicting the movement of nutrients to the stream, which might not actually be the case.

Other modelers have attempted to use these types of equations at the watershed scale, but the simulation results are typically poor, and thus they should not really be used to simulate the hydrology at the watershed scale, especially in mountainous watersheds. In addition, it is obvious that using Eqs. 3-12 through 3-19 at the temporal scale set in WARMF (1 day) will result in no overland flow in watersheds except for a handful of days. Viewing the output from WARMF, this result can be seen for the upper sub-catchments of the Truckee River Basin (e.g. the Upper Truckee River in the Lake Tahoe Basin), where there is only overland flow for a few days each year. However, overland flow exists in these catchments for a great number of days throughout the year, especially during the spring melt period. Failing to simulate the overland flow reaching the river accurately will result in highly skewed predictions of suspended sediment loads in the river throughout the year.

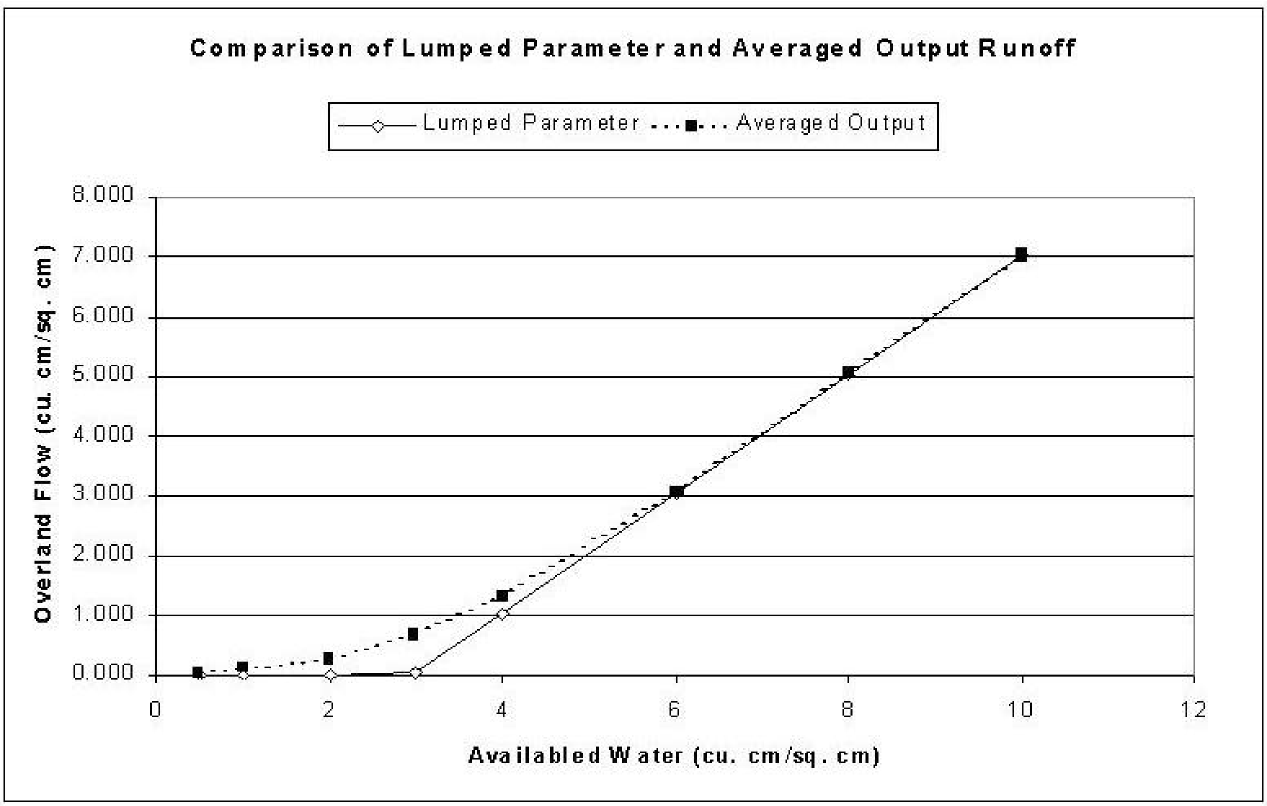

Figure 1. Comparison of Lumped Parameter (WARMF) and Average Output Runoff predictions for a hypothetical watershed

The hydraulic routing equations used in the WARMF model tend not to be the best method to estimate streamflow velocities in river systems. The kinematic wave equations were originally developed to route flood flows in gradually varied flow systems. Since most streams only have flood waves moving through them infrequently, the kinematic wave equations are not appropriate for describing the streamflow hydraulics for most periods of time. The use of this approach neglects the impacts that backwater effects will have on streamflows, thus under lower flow conditions, the depth of flow in mildly sloping streams with downstream controls will be underestimated, and the streamflow velocities overestimated. A better representation of the stream hydraulics would be a dual approach, where flood waves are simulated using the Kinematic Wave equation and a transient direct step method used to simulate flow at other times. In addition, groundwater flow pathways are poorly represented in the WARMF models. In mountainous watersheds, baseflow from groundwater is the dominant source of stream flow for the late summer and early fall. Failing to simulate these flow conditions can significantly affect predictions of stream temperature, nutrient concentrations, and TDS concentrations in the stream. Thus, a much better representation of the groundwater contribution to streamflow is needed. Finally, the equations used to predict sediment erosion are again not appropriate for use at the watershed scale. The equations developed are based on the ANSWERS model, which are more applicable to highly disturbed soil systems at the field scale. In mountainous watersheds, these equations typically do not apply, especially when the parameters in Eq. 3-34 to 3-43 are averaged over the watershed. The developers of WARMF should have simply used more rudimentary representations of erosion processes that are developed for the watershed scale, such as modifications of the USLE or the WEPP program. Although, these models are not perfect, they tend to be more easily calibrated at the watershed scale. As it currently stands, the algorithms used by the WARMF engineering models to predict the behavior of the hydrology, soil erosion and transport cannot provide a reasonable simulation capacity unless the spatial and temporal scales of the modeling exercises are drastically reduced, which would result in a huge increase in computational effort and simulation time in the models.

Fletcher: I do not think we know enough for this approach to all issues, especially AMD. I worked a great deal with ANSWERS in the past and concur with Tracy's comments. Field scale, grid type relationships seem inadequate for a catchment approach.

iv. Is the method of numerical solution stable and robust?

Keller: The method of numerical solution appears stable and robust, from the information presented in the documentation of the model. Most users, including stakeholders with little training, have not experienced problems running the model. The simulation results appear stable, and the simulation consistently reaches convergence. Two of the reviewers experienced problems setting up the model or running simulations, but unfortunately they did not contact the Systech helpline to determine the cause of the problem(s). One of the shortcomings of the WARMF model is that there is no provision for catching irrational input parameter values, potentially leading to very erroneous results, which might not be evident to the average user, or to incomplete termination. The model does not provide very useful feedback when a simulation ends before completing all the calculations.

Tracy: When I was running the model under a variety of scenarios, the model failed to fully execute the simulation approximately 75% of the time. Thus I would conclude that the numerical solution is not stable, nor robust. The major problem seemed to occur when full simulations of the Truckee river basin were executed. Typically the model would stop execution when it was trying to simulate basin 7, which is the largest basin in the Truckee Watershed model. This problem could be due to wide variety of reasons, but since it only seemed to happen in the largest basin, it most likely is a memory handling problem. There were several other instances when the model execution just stopped with an error in both the Catawba and Truckee Watershed models, but the one mentioned above was the most consistent. I was using the model on a Windows 95 platform.

Whittemore: While this goes beyond my experience, I didn't sense any problems while manipulating and running the models, when simple changes were made to existing parameter sets and modeling frameworks. I did not examine whole-scale changes.

Fletcher: Not sufficient information for comment.

v. How does the basis for problem solving compare to existing models?

Keller: The basis for problem solving (conceptual model, scale, numerical solution) used in WARMF is very similar to that used in BASINS, which is one of the few widely available comparable models for TMDL development. There is also the USGS MMS and proprietary models such as Battelle's DHSVM and WAM from a Florida consultant, but are not as widely available at this point. BASINS and WARMF are based on very similar data sets, and use similar models for hydrologic and biogeochemical processes. The same issues are valid for both models. The conceptual models are sound, but of course higher spatial and temporal resolution would be highly desirable, although there are the trade-offs mentioned above. The CSTR issue is valid in both cases. One great advantage of WARMF is the TMDL development module, which greatly simplifies the task of narrowing in on the maximum daily loads; this is not available in BASINS.

The implementation of these models is quite different. The philosophy behind WARMF is that linking the models and exchanging the data sets required for each model is a complicated process, best left for very experienced modelers. Thus, Systech takes on that responsibility completely and delivers a running model. BASINS is based on a more open architecture, which provides guidelines for potential users to choose the models they consider more appropriate, as well as determine the spatial resolution and data exchange interfaces. An experienced modeler might be able to handle these choices and decisions, but there is more room for error in the model implementation.

Tracy: See Question iii, above

Whittemore: I found the WARMF model innately powerful and intuitive. In this sense, it is far superior to BASINS (my only point of reference) which provides NO decision support framework other than a Watershed Report Generator.

Fletcher: I think WARMF compares well to Basins but there is a long way to go.

vi. What are the shortcomings of the modeling approach (e.g., missing or oversimplification of key processes, restrictive dimensionality, etc.)?

Keller: Most of the shortcomings have been discussed in A ii. The key issues that have been identified are spatial resolution, and the related issue of using a CSTR formulation (complete mixing) for long rivers, large reservoirs, or aquifers. This is an inherent problem when such large scales are considered.

Tracy: See Question iii, above

Whittemore: The only item that I would have liked to see was a more formal treatment of error propagation and discussion amongst the stakeholders on its significance. In all fairness to Systech, this topic is not routinely developed in modeling studies and may be only of research interest. While the topic is of regulatory relevance, little state or national guidance is available to provide structure. Traditional error analyses such as Monte Carlo simulation and first-order methods may be too computationally intense for nonpoint source models (of any type). The topic needs research attention to craft new software that provides such essential information. In the short-term, the two example case studies could be probed with a 'modified sensitivity study' that looks at some critical model parameters or inputs to ascertain their impact on water quality. Some examples include:

What impact does uncertainty have for 4-5 key water balance and/or fate parameters?

What impact does uncertainty in precipitation or flow monitoring have?

I suspect that these uncertainties may be minor when compared to the management activities prescribed by the stakeholders. Whether a buffer strip is 50', 75', or even 100' or additional waste treatment removals are some incremental fraction greater is not really the key question. The key question that must be ascertained is: Are any of these management action decisions sufficiently altered by model input (parameters or forcing functions) uncertainties?

Fletcher: AMD again.

Nelson: Other processes -- no septic system inputs, not applicable in coastal areas or wetlands, no riparian zones, insufficient complexity of land use inputs (density of housing, location of housing, etc.) Also, in inputting point and nonpoint source data, it seems to be built on assumptions rather than documentation. In the decentralized field, there is a lot of interest now in "tracer" studies -- for example, identifying whether fecal coliform is coming from wildlife, farm animals (by type), dogs and cats, humans, etc. Wouldn't it make sense to think about conducting such studies and using results to provide for accurate representation of sources in water quality impairments?

vii. What are the major potential sources of error in the model?

Keller: There can be errors in the conceptual model (i.e. not considering all the relevant processes), the mathematical description of the processes, the numerical formulation of the algorithms, the scale chosen (temporal and spatial), the method of calculation, the input data, and in the interpretation of the results. Of these, the most important potential sources of error in the WARMF model are the spatial and temporal scales (if they are chosen too coarse) and the input data, which is discussed in the next section.

Tracy: See Question iii, above

viii. Can the magnitude of the error(s) be estimated?

Keller: The current formulation (i.e. spatial and temporal resolution set by Systech in coordination with the stakeholders) does not allow a method for estimating the potential error in the predicted concentrations or maximum daily loads. If there is some concern about an error in a parameter value, or the initial conditions, a sensitivity analysis can easily be done to determine whether this will have a large effect on concentrations or TMDLs.

Tracy: With the information given, the magnitude of the errors cannot be estimated a-priori.

ix. Can the error or uncertainty be tracked in the model to provide a basis for estimating the uncertainty in the calculated TMDLs?

Keller: Detected errors in parameter values can be tracked through the model to provide a basis for estimating the uncertainty in the calculated TMDLs, by performing sensitivity analysis. The model can also be used to cross-check the input data, by comparing the results to measured values, when these values are available. Uncertainty can be tracked by running various simulations exploring the range of parameter values in question.

Tracy: As far as I can tell, the error uncertainty cannot be tracked in the model for the way the WARMF model is currently constructed.

Fletcher: Handling of uncertainty and errors appear to be a major limitation in the WARMF implementation.

x. Are there particular processes that the current WARMF model does not address adequately, for example in the case of the Truckee River? For other cases (e.g. acid mine drainage, estuaries, etc.)? These processes should be identified so that the WARMF model is applied correctly in other situations, and so that the developers of WARMF can make the necessary upgrades.

Keller: The model is suitable for the Truckee River, considering the limitations described above in terms of resolution. An Acid Mine Drainage (AMD) module is being developed for the Cheat River (WV), which will extend the applicability of WARMF to watersheds with AMD. The simulation of toxics might not contain all the necessary processes, and thus care should be taken to review the model formulation if this is the intended use. WARMF is not designed to deal with estuaries or coastal contamination issues at this time. The model does not consider wetlands.

Tracy: As discussed above, the basic hydrology and sediment erosion processes are not adequately simulated or addressed within the WARMF model.

Fletcher: AMD again.

D. Key Assumptions

i. What are the key assumptions?

As described by Systech, the key assumptions of the model are:

1. Physically, it is assumed that a river basin can be divided into catchments, stream segments, and lake segments. A long and narrow reservoir can have several lake segments.
2. For catchments, they are further sub-divided vertically into canopy, land surface, and soil layers. For lake segments, they are further sub-divided into layers.
3. Each of the sub-divided segments is treated as a CSTR (continuously stirred tank reactor) in which various physical, chemical, and biological processes occur.
4. Water can move from one CSTR to another according to hydrodynamics equations, i.e. from land surface to soil layer 1, from soil layer 1 to soil layer 2, from land surface to a

stream segment, from an upstream stream segment to a downstream stream segment, and from a stream segment to one or more lake layers.

5. Chemical and physical constituents, dissolved or suspended in the water, are transported from one CSTR to another by advection. Between lake layers, constituents can be transported from one CSTR to another by diffusion. Diffusion between stream segments is assumed to be negligible.
6. Processes that occur in each CSTR are approximated by kinetic expressions. For example, BOD decay, coliform die-off, and the nitrification of ammonia are represented by first order kinetic equations. Atmospheric deposition of aerosols, that may contain ammonia, sulfate, cations, anions etc., are calculated by a product of deposition velocity, air concentrations, and receptor area (i.e. leaf area index). Algae growth rate is determined as a function of temperature, light, ammonia, nitrate, phosphorus, and a maximum growth rate. Algal growth removes an equivalent amount of nutrients from the water for conversion to biomass. Algae, being suspended particles, settle at a specified velocity. The kinetic expressions generate sink and source terms for various chemical constituents in the water.
7. In each CSTR, it is assumed that chemical equilibrium for pH calculations is reached within the simulation time step.
8. In the soil layers, there are air, water, and solid fractions. The solid fraction contains minerals which are weathered to release ions to the water. Anions in the water are adsorbed to the solid fraction according to an isotherm. Cations in the water are subjected to competitive exchange with cation exchange sites of the solid fraction. All of these processes generate sink and source terms for various chemical constituents.
9. The mass transfer into and out of a CSTR equals the sum of all the advection, diffusion, sink, and source terms for each constituent.
10. A similar approach is used to calculate the heat that enters soil layers, rivers, and lake layers. The heat (temperature) transfer into and out of a CSTR equals the sum of advection, diffusion, sink, and source terms for temperature (heat).
11. Mass transfer contributes to the change of mass in each CSTR that occurs during a time step. Mass is volume times concentration. In a dynamic system, both volume and concentration can change. So, a differential equation is established to relate the change in volume and concentration to the mass transfer due to advection, diffusion, sinks, and sources. The equation is solved numerically by the computer to calculate the concentration of the chemical constituent in each CSTR.
12. By the same procedure, a heat balance equation is set up to calculate the temperature of the water in each CSTR.
13. WARMF is neither a runoff coefficient model for hydrology nor an export coefficient model for nonpoint loading. The mass of water and each chemical and physical constituent is tracked within and between catchments, rivers, and lake layers.

Thus, one of the key assumptions of the WARMF model is that the use of a mechanistic description of watershed processes is more robust than a probabilistic, runoff coefficient, export coefficient or response function (e.g. emission factors) formulation. Given that WARMF is intended for TMDL development across a variety of watershed conditions, this key assumption is valid. Probabilistic or response function models are usually only valid for very similar conditions to those in which these models were developed, since they rely on a statistical interpretation of the data, without a process-based explanation. Extrapolating these much simpler models to conditions different than the original basis can lead to large errors in prediction. The mechanistic basis on which WARMF is built has general acceptance in the hydrologic and biogeochemical communities. Linking the various models (hydrologic, sediment transport, biogeochemical) at every time step is a valid formulation, and is much better than running the various models independently and using one model output as the basis for the next model.

Another key assumption is the spatial scale at which the model is discretized. Since this has a significant impact on the averaging of subcatchment properties, care must be taken to use a spatial resolution adequate to the nature of the watershed and its subcatchments, as well as the diversity of land-uses, topography and other important properties.

A third key assumption is the CSTR formulation, which is valid only for short river segments and small reservoirs or aquifers.

Whittemore: The key assumptions are inherently related to the appropriateness of the models used and their supporting data. The documentation manual provides sufficient detail here that supports the notion that these models are reasonable, state-of-the-art choices that would be hard to refute. While modelers have different preferences and biases, they all can be justified at some level because a model is just an abstraction of reality devised to provide important environmental insights. A debate based on - My model is better than your model! - is inappropriate as they both can be right if they give useful management answers. In these cases WARMF does and cannot be faulted or summarily dismissed. Sensitivity studies should be performed and used to evaluate the model's performance. For certain this was not addressed to any significant degree.

Tracy: In my opinion, the key assumption made in developing the WARMF model is that mechanistic equations can be strung together to provide simulations of hydrology and water quality processes at the watershed scale. The basis for this assumption is most likely rooted in the earlier promotion and use of deterministic and mechanistic models to simulate water quality conditions in streams and lakes from point sources of pollution. The implications of this assumption are huge and leads to models that are highly sensitive to what data they are being calibrated to, and the judgment of the modeler. As understood by most hydrologists, processes at a watershed scale cannot be described deterministically. This is why most hydrologic modeling has always been performed using stochastic, probabilistic, response function, or land form characteristic modeling approaches. These approaches have proved extremely useful for a wide range of water resource problems and should be explored for use in a modeling package such as WARMF.

Fletcher: I tend to agree with Tracy. While I think the WARMF approach provides a useful basis, it is very weak in margin of safety and uncertainty in general. It cannot be expected to work where there is not a scientific literature to base the model on (e.g., AMD).

ii. What is the basis for each key assumption and what is the range of possible alternatives?

Keller: The basis for using a mechanistic description of the watershed processes is the intention to apply the WARMF model across many different watersheds. If a probabilistic or response function had been embedded in WARMF, it would be limited to only those few watersheds which share similar conditions with the watershed from which the statistics or responses were obtained. Probabilistic (statistically derived) hydrologic models (e.g., models used to predict 100 year floods) are extremely dependent on land-use changes, and thus are not even good predictors of flows after a few years for the same watershed. Response function models are useful as a simple first-cut analysis, but cannot be expected to capture the interactions between different chemicals, for example BOD, nitrogen, phosphate, DO, etc.

The only possibilities are to use either a deterministic or stochastic process based model. One possible alternative to WARMF's current implementation would be a stochastic model, but that would require significantly greater input data sets (to capture all the uncertainty and variability in input parameter values) and much longer simulation times (to run multiple realizations). It would also involve a much more sophisticated user to interpret the output of such a model, well beyond the expected expertise of most stakeholders. To our knowledge, there are no watershed-scale biogeochemical models which have been developed using a fully stochastic implementation.

The basis for the spatial resolution is the availability of hydrologic and water quality control points and their corresponding data. The resolution is also based on stakeholders' needs and the expected computation time. Clearly, the model can be discretized to a finer resolution, but then one needs to consider the trade-offs discussed earlier.

The final key assumption is the CSTR formulation. The basis is the simplicity of this formulation, which does not require very detailed tracking of "plumes" of pollutant in aquifers or rivers. An alternative would be to use a PFR model, and to consider both advective and dispersive transport.

Whittemore: (comments on ii. and iii.) The supplemental information addresses some questions about parameter sensitivity but could go further to address the actual stakeholder decision - would a different consensus decision flow from alternative assumptions or models? I seriously doubt that this would be the case.

iii. How sensitive is the model toward modifying key assumptions?

Keller: One would need to develop an alternate model(s), modifying each of the key assumptions, to evaluate the sensitivity of the model to modifying these key assumptions. This is beyond the scope of the current peer review process.

E. Parameter Value Estimation

Keller: The main parameters used in the model are presented in Appendix 3, which was provided by Systech at the request of the Peer Review Panel. Parameters related to topography are estimated using the Digital Elevation Map (DEM) data from USGS. The USGS data is used to generate a map of the watershed, define subcatchments, stream segments and reservoirs. Reservoir bathymetry is provided by the reservoir operator (utility company or USBR). The DEM data is also used to calculate the slope and aspect angle of the subcatchment. Meteorological data is obtained from the National Climate Data Center (NCDC) for all stations in and close to the watershed. Atmospheric concentrations of pollutants are obtained from US EPA or Regional Air Quality Monitoring Stations. Land-use data is obtained from the BASINS data set developed by US EPA, or directly from stakeholders if it is more recent or at higher resolution. Soil data (e.g. soil type, hydraulic properties, mineral composition) is obtained from NRCS data or from stakeholder data available for the various subcatchments. Point source discharges and concentrations are obtained from the NPDES permits available from the regional or local water quality agencies. These sets of data correspond to the main drivers of hydrology and chemical loading to the watershed.

In addition, parameter values which refer to specific land-use processes (e.g., leaf area index, primary productivity, litter fraction, etc.) or for transport processes (e.g. sediment transport, erosion, resuspension, dispersion in lakes) are derived from published literature values. References are provided in the WARMF documentation for most of these literature values.

It should be noted that one of the strong points of the WARMF model is that most of the parameter values are accessible to any user for review, through the various screens, which is not common in most modeling frameworks. In addition to reviewing the parameter values, the users can input changes to the parameter values to test the effect on the watershed.

A number of parameters have default values (e.g. surface detention storage), which are adjusted during the calibration process. WARMF has a built in auto-calibration function that helps to calibrate hydrology. Thus, a small number of parameters is adjusted in this way to fit the observed data. Hydrology is calibrated first, and then simulated water quality data is compared to observed water quality. If the water quality parameter values derived from the initial simulation are significantly far from the observed values, a review of the input data and a small set of parameter values is done to obtain a better fit. The model provides output screens (graphs and tables) that allow any user to compare observed vs. simulated values, for each hydrologic or water quality control point where data is available.

Hansen: The User's Guide and the online help provide valid ranges for many parameters. These are very useful, and could be expanded to guide the user in selecting a reasonable number from the given range. For example, the online help suggests that the surface roughness parameter ranges between 0.05 and 0.4. New users, or those unfamiliar with Manning's n, would benefit from a description of what type of terrain would most likely correspond to a value of 0.05, and what would correspond to 0.4. It would also be useful for the User's Guide and online help to specify which variables are most sensitive, and therefore need the most care when selecting a value. Also, when a user enters a value that falls outside of the recommended range, WARMF should provide a warning.

Whittemore: In my view, Hansen's comments highlight the dangers of inappropriate modeling by inexperienced personnel. A model is not a model until the parameters have been populated, resulting in the calibrated model. Until this point is achieved, it is just a collection of organized computer code.

i. Are the methods used for parameter value estimation valid?

Keller: The methods used to estimate parameter values are valid. Most parameter values are obtained from peer-reviewed databases or from peer-reviewed literature. A few parameter values are obtained from calibration.

Basham: According to additional information supplied by Systech, algae coefficients used in the model are those that have been developed for lakes. If WARMF is to be applied to rivers, coefficients may need to be modified.

Olmsted: The methods used for parameter estimation include measured values, literature derived values and calibration values. These all seem valid means of parameter estimation.

Whittemore: These all seem valid means of parameter estimation, but like anything else there are degrees of appropriateness and validity.

Tracy: As stated in the WARMF manual and in the presentation, the method of parameter estimation used to develop the Truckee and Catawba models is by trial and error with a visual inspection of how well the data fits the modeled variables. If a modeler has an extremely good understanding of the watershed and an extremely thorough understanding of WARMF, a reasonable model calibration can be developed. However, if both of these understandings are not available, the model calibration will most likely be poor. The approach used in the WARMF package is a highly risky estimation procedure that could result in erroneous predictions of the behavior of watershed processes. Thus, more objective parameter estimation and model calibration procedures should be developed and included in the WARMF package.

Fletcher: I have no problem with parameters taken from appropriate prior studies. The method for calibration, as I understand it, relies on trial and error combined with visual inspection of complex graphs and output. This seems totally inadequate. There are numerous approaches to error minimization that should be applied.

ii. Is there adequate data available for parameter value estimation?

Keller: For most watersheds in the US, there is adequate data available from USGS, US EPA, NCDC and other agencies for parameter value estimation. Similar data sets are becoming available in many parts of the world. Usually, the biggest problem is the sparseness of hydrologic or water quality data to make comparisons and/or to calibrate the model.

Care must be taken when parameter values are taken from the literature for conditions that are significantly different from those in a particular watershed. Systech must work with the stakeholders in each watershed to make sure that the parameter values are valid for that particular application.

Olmsted: Whether there are enough measured values is a site-by-site consideration. Generally, adequate data are provided within the model for parameter estimation.

Whittemore: I agree strongly with Olmsted's comment/observation.

Fletcher: I expect this to vary greatly across areas and by parameter. Many yes, some no.

iii. For those parameters for which there is no data, is the method used to estimate parameter values valid?

Keller: There is data available in the literature for all the parameters, although some parameter values may be extrapolated from the conditions in which the original data was obtained. The methods used are valid (peer-reviewed literature values), although validation through calibration and comparison with observed water quality is strongly recommended in all applications.

Olmsted: The User's Guide and the online help provide ranges for values. These are useful but more rationale and guidance for the user on selecting the appropriate value would be good.

iv. Is the reliability of parameter value estimates acceptable?

Keller: All of the parameter values taken from the literature have been available for several years, and have been used in many water quality or hydrologic models. These parameter values have proven reliable for modeling purposes. The peer review panel did not attempt to verify the reliability of the estimates.

v. Are the boundary conditions appropriate?

Keller: The watershed applications developed to date (e.g., Truckee River, Catawba River, Cheat River) have all considered the entire watershed, such that all the precipitation that falls within the watershed is accounted for in the model. Thus, the lateral boundary conditions are no flow boundaries, except for the outflow at the lowest point of the watershed. The watershed is bounded at the top by the atmosphere, which is considered a meteorologically-driven flux boundary (water and chemicals). The boundary at the bottom of the deepest soil layer is considered to be a saturated soil layer or impermeable bedrock, with no flow further down into the deeper subsurface environment. These are all appropriate boundary conditions for the watershed.

F. Data Quality/Quantity

Keller: Systech relies on the various "owners" of the published data sets (DEM, meteorology, land-use, soil classification, etc.) to have done appropriate quality assurance and quality control (QA/QC) of the data they provide. The same is true for data provided by stakeholders. Systech also relies on the peer-review process for the parameter values that are obtained from the literature. However, the WARMF model is a useful tool for determining whether there are gross errors in these data sets that result in illogical or unexpected results. These gross errors are generally found during the calibration process, and are adjusted manually.

The quantity of data that is required for the set up the model is adequate. However, the hydrologic and water quality data needed to calibrate the model is usually less than desirable, which may result in an extensive data collection program.

Whittemore: Gross errors are generally found during the calibration process. This approach is what EPA has stated for the use of BASINS and may or may not be appropriate as PCS and STORET errors still may exist, albeit minor and obvious in most cases. Ultimately, the individual dischargers must assume responsibility as a stakeholder to seek out and resolve questionable data sets. This, however, is not necessarily trivial and could become quite labor intensive in some extreme cases.

Hansen: When Systech provides a calibrated model to stakeholder groups or to the agency that will be calculating the TMDL, one natural task that the recipients will want to do will be to gain confidence in the model by spot checking some of the data that has been loaded. This process would be greatly facilitated if Systech were to describe, in as much detail as feasible, the source for each piece of data. Sources are already documented within WARMF for some types of data (e.g., water quality and streamflow monitoring data). But sources are not well documented for "coefficients," in other words, the data that describe the physical characteristics of each catchment and river segment.

Tracy: The WARMF package does an adequate job of describing, categorizing and qualifying the data that is used to parameterize and calibrate the engineering models. However, one significant data type was absent from the Truckee model that should be included. This is the SNOTEL data that records snow depths, snow water equivalent, etc. There are at least 5 SNOTEL gages in the Truckee watershed that I know of that can be used to more accurately describe the meteorological conditions within the upper reaches of the watershed. The use of SNOTEL data should be incorporated into the WARMF model.

Fletcher: Data issues are key. I find it a bit difficult to break down in the specific questions that follow in general although I agree with the comments of many of the other reviewers. For a specific case each question could be addressed more readily. My overall view of data is not independent of the analyses performed. I don't see how WARMF (or any model) can address this without a systematic analysis of the errors (difference between predicted and observed values). Adequacy must be based on statistical measures to be defensible.

i. Can the adequacy of the data be defined in terms of quality, quantity, and spatial and temporal applicability taking into account the regulatory objectives of the model?

Keller: The data used to setup the model is adequate in terms of quality, quantity, and spatial and temporal applicability. The data needed to calibrate the model is not always adequate in terms of quantity. Appropriate QA/QC procedures should be implemented to collect such data, following US EPA guidelines.

ii. What kinds of data are required to apply the model?

Keller: The main data sets needed are:

- Topography
- Meteorology
- Atmospheric concentrations
- Soil types and coefficients
- Land-use types and coefficients
- Biogeochemical process coefficients (e.g., reaction rates, equilibrium coefficients, microbial and algal growth and decay rates)
- Point source discharges
- Hydrologic monitoring
- Water quality monitoring

Olmsted: Digital Elevation Maps, land use, fertilizer, point source, meteorology, and atmospheric chemistry are required to apply the model, and gaged flow, monitored water quality and nonpoint source data are required to calibrate the model.

iii. To what extent are these data available and what are the key data gaps?

Keller: The first seven sets in the section above are generally available, or can be estimated from literature values. The last two data sets may be sparse for the different watersheds, and are usually the key data gaps.

Olmsted: These data are generally available in federal, state, and local data bases. The key data gap is nonpoint source data.

iv. Are data quality objectives defined?

Keller: Systech does not collect hydrologic or water quality data, but relies on the information from the stakeholders or regulatory agencies. Thus, Systech does not define data quality objectives (DQO). It is up to the regulatory agencies involved in the development of a particular TMDL to develop DQO.

Fletcher: The data requirements are outlined but the quality issues are less clear. I am not sure how this should be addressed.

v. Is the quantity of data sufficient to address the likely variability?

Keller: The quantity of data available is sufficient to set up the model. The data needed to calibrate the model is not sufficient or adequate to address all the likely variability.

Whittemore: This is likely a site-specific situation and, since I am unfamiliar with the watersheds involved, I cannot intelligently respond. As a general statement, data availability is crucial to any credible model development. In BASINS, for example, EPA requires extensive intensive use of STORET to retrieve the necessary data for calibration and made some arbitrary decision relative to what was packaged with the BASINS CDs and the downloading site.

Woolfolk: No. This model, and most others developed using existing data, will depend upon established sampling programs by states, other agencies (e.g., USGS), and selected stakeholders (e.g., electric power companies). State programs will typically have monthly or quarterly monitoring for a selected group of pollutants at a selected number of sites. The monitoring may be conducted when the weather is nice (i.e., missing storm flows) or a fixed day each month regardless of flow (e.g., every second Tuesday). Storm flows are often missed in part due to sampling with the weather is nice and because the 305(b) and 303(d) lists are based on the same data that is used to populate models such as WARMF and BASINS. Clearly, when evaluating a stream for use support or overall conditions, storm flows are not as desireable as "normal" flow conditions, particularly when monitoring is only conducted once per month.

Olmsted: This is a site-by-site determination. However, in view of the fact that a predominant amount of what we are interested in occurs in relation to storm flow, and traditionally sampling is done under near base flow conditions, the answer will often be no. This is obviously not a problem associated with the model, but rather the data input.

Fletcher: I doubt if the data are adequate but it is clear that WARMF does not try. Statistical analysis is woefully inadequate.

vi. What statistical analyses were/can be performed and are they appropriate?

Keller: There are no statistical analyses that Systech or WARMF can perform to determine whether the hydrologic or water quality data is suitable or appropriate; that has to be done by the appropriate agencies that own the input data sets or the agencies and/or stakeholders involved with the collection of hydrologic and water quality monitoring data. However, the WARMF model can be used to determine gross errors in the input or monitoring data sets, when a comparison between simulation and observation is made.

There are statistical tools that could be applied to determine the "goodness of fit" between simulation and observation. This is not a tool provided by the model, nor is it regularly applied by Systech to determine how well the model fits the observed data.

Whittemore: At the present time, the availability of criteria to determine when a model is adequately calibrated do not exist. As a corollary, complex watershed models may contain too many parameters and inputs to subject to traditional error analysis techniques. "Goodness of fit" statistics for continuous simulations, by themselves, are problematic.

Olmsted: Time series analyses are provided. They are appropriate. It may be that providing some means of looking graphically at error analyses would be informative.

Fletcher: None and NO

vii. Do additional data need to be collected and for what purpose?

Keller: Typically, additional hydrologic or water quality data needs to be collected. Occasionally, more resolution is needed for land-use data. The model provides the users the ability to input new hydrologic or water quality data as it becomes available. However, the recalibration of the model should be done by Systech or a very qualified WARMF user.

Woolfolk: Yes. Storm data is needed for the calibration of the models at the subwatershed level. This includes flows and water quality.

Fletcher: This is not an easy question. I expect the answer to vary greatly among applications. However, the answer needs, in part, to come out of the analysis using the WARMF model. Without adequate objectives for fit/calibration, how can data needs be assessed?

viii. What techniques may be most appropriate for data collection?

Keller: The WARMF model can be (and has been) used to determine new hydrologic or water quality monitoring stations, or to strengthen sampling programs, either in their frequency or the number of water quality parameters that are collected on a regular basis. The methods of data collection are standard USGS, US EPA or ASTM methods.

Woolfolk: Targeted field studies for physiographic regions or land use combinations within the watershed should be conducted, particularly those associated with storm events. These studies could be conducted after the initial model configuration so that strategic locations can be evaluated. Certainly, previous studies may aid in the initial setup of the model. For example, although the Catawba River model is currently set up, storm event field studies in the Lake James watershed (uppermost watershed) and the Lake Wateree watershed (bottom-most watershed) are ongoing. These studies include sampling with automatic samplers and more frequent trips to established sampling sites.

ix. Are all the land uses relevant to a particular watershed considered (e.g. agriculture, urban, golf courses, septic tanks, pastures, grazing)?

Keller: Systech works with the stakeholders to incorporate the land-uses that are considered relevant for a particular watershed. There are however certain land uses that cannot at present be modeled, such as wetlands or septic tanks. WARMF considers the land uses that exist within the time frame of the input data (usually determined by meteorological data). The user can modify the composition of the land use to explore future land use changes.

Hansen: Deep mines and surface mines are not modelled.

Woolfolk: Wetlands have not been mentioned as a relevant watershed land use. Wetlands are an important part of North Carolina hydrology, particularly moving closer to the coast where entire subwatersheds may be wetlands. Additionally, the current algorithms for predicting overland flow and associated water quality may be inadequate for wetlands since wetlands are usually sinks of pollution, not sources.

Tracy: One major issue that is not included in the WARMF package is the temporal characteristics of the land uses. Many land characteristics are temporal in nature, and should be simulated as such. An example of this is the natural progression of Pine forests in the upper watershed of the Truckee River. The cycle progresses from surface conditions that are denuded due to fire (either natural or anthropogenic in nature), to shrubs colonizing the bare soil, to the regrowth of the pine forests. These land cover changes over time significantly affect the runoff and erosive characteristics of the watershed, yet there is no capability within WARMF to simulate this process. Thus, some type of temporal parameterization of model parameters needs to be developed to provide a better predictive simulation of the effects of land management practices on stream water quality within a watershed.

Basham: Do the deciduous and coniferous land uses include the impact of logging? The golf course land use appears to be combined with farming. Golf courses and farming probably have different impacts on the watershed and should be separate categories. Are septic tanks included in one of the residential land uses, as there is no separate category for them?

Fletcher: Land use issues will be specific to the question.

G. Model Performance Measures

i. What criteria have been used to assess model performance?

Keller: Systech relies on visual comparison of simulated versus observed hydrologic and water quality data. WARMF does not perform any specific statistical analysis of simulated versus observed data. The peer review panel was not provided with any additional means of assessing model performance.

Woolfolk: Visual evaluation of model predictability using time series plots. I haven't done (or at least I haven't seen) statistical tests or additional visual tests other than time series plots.

Tracy: No model performance measures were presented by the developers of WARMF, except for a visual inspection of the comparison between the simulated and measured water quality parameters. As discussed above, this is not a robust performance measure. The reason stated by the developers for using a visual performance measure is that the model simulations may not match up temporally to the measured data for a number of reasons. I understand this problem, but there are a variety of ways to still develop model performance measures. The most useful of these for determining the applicability of a model in a regulatory context is by comparing some basic statistics of the simulated and measured variables. These statistics can be basic, such as the mean, standard deviation, maximum and minimum values, or they can be a bit more complex, such as frequency-exceedance relationships. Since most stream water quality standards are described by statistics (e.g. minimum DO over a specified time period, or suspended sediment concentrations not to be exceeded over a certain percentage of time), the comparison of the statistical characteristics of the simulated and measured data would be highly appropriate for this type of model. Using the results of the WARMF calibrated model for the Truckee River, I performed a few of these comparisons. I chose the Upper Truckee River in the Lake Tahoe basin to compare statistics of predicted and measured stream flows and sediment loads, and the Truckee River at Reno/Sparks, Stream ID-099. I chose the Upper Truckee River for comparison because I have recently done a great deal of work in this watershed related to understanding streamflow and suspended sediment loads in the river. However, I chose Stream ID-099 purely at random.

Figure 2 shows a comparison of the simulated and reported suspended sediment concentration frequency-exceedance curves in the Upper Truckee River. Figure 3 shows a comparison of the simulated and reported daily streamflow frequency-exceedance curves in the Upper Truckee River. As can be seen in these figures, the frequency-exceedance curves produced by the WARMF model do not provide reasonable simulations of the reported concentrations for either suspended sediment concentrations or stream flows. Although the characteristics of stream flows are better represented that sediment loads. Viewing these figures I would conclude that the WARMF model could not really be used as a regulatory decision making tool in the upper portions of the Truckee watershed in its current form.

Figure 4 shows a comparison of the simulated and reported daily streamflow frequency-exceedance curves in the Truckee River near Reno/Sparks (Stream ID-099). In addition Table 2 compares some basic simulated and measured daily streamflow statistics. As can be seen in this figure, again the WARMF model does not represent the flow characteristics well at all. This misrepresentation is especially bad at the low flow events, which tend to be the most critical periods of meeting regulatory water quality criteria.

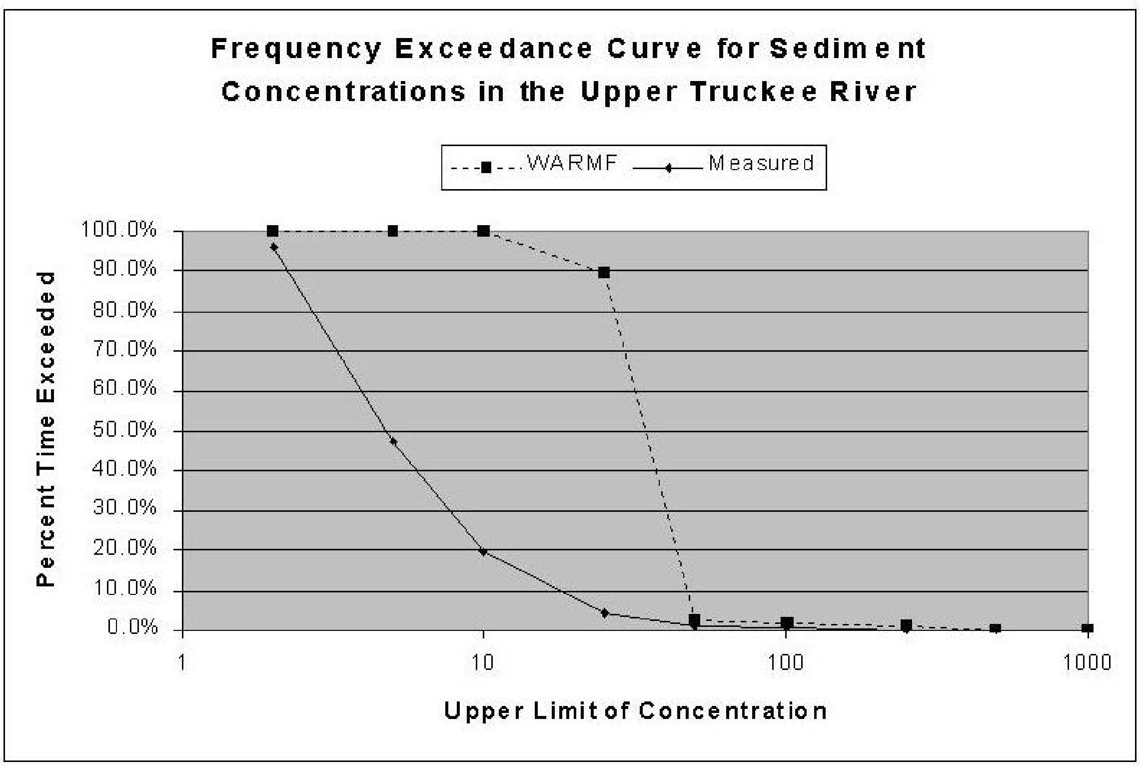

Figure 2. Exceedance Frequency Relationships For Simulated And Modeled Sediment Loads In The Upper Truckee River

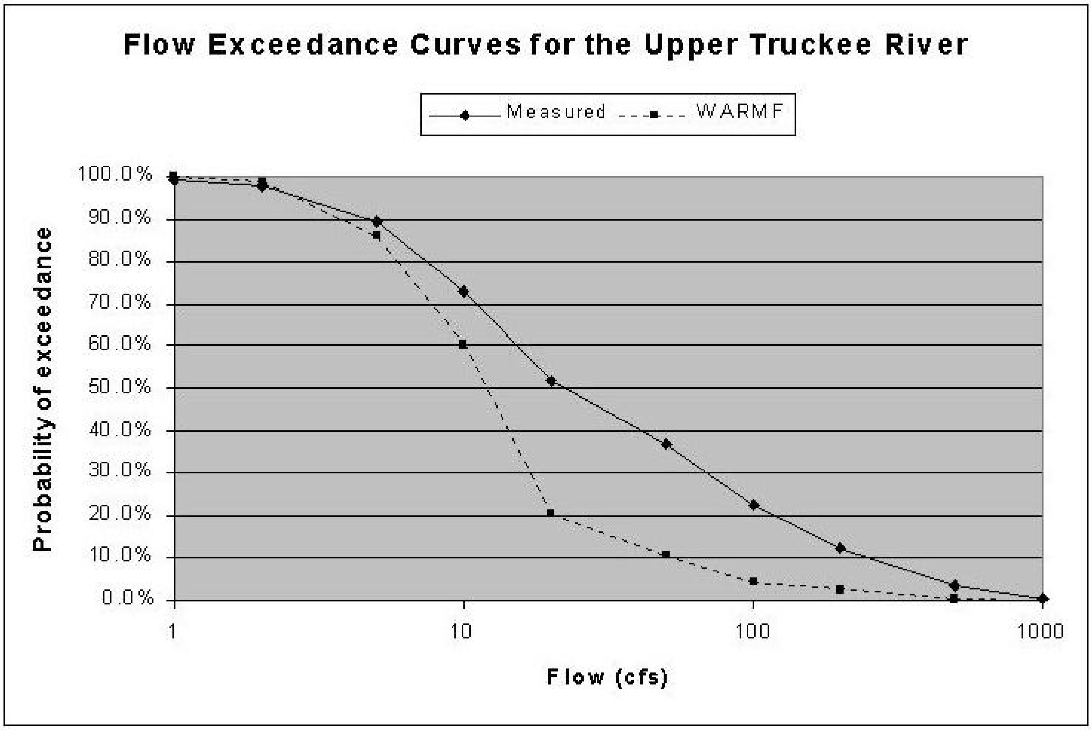

Figure 3. Exceedance Frequency Relationships For Simulated And Modeled Flows In The Upper Truckee River

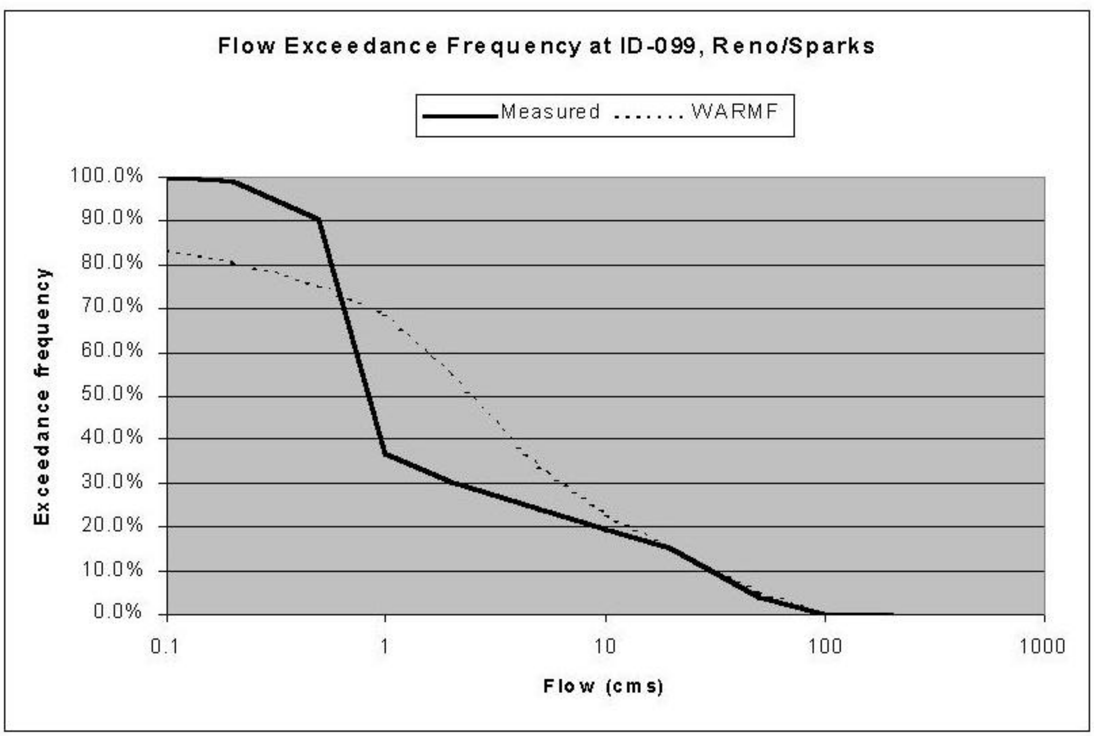

Figure 4. Exceedance Frequency Relationships For Simulated And Modeled Flows At Stream ID-099 In Truckee River

Also, as shown in Table 2, the log-flow statistics are quite different for the simulated and measured daily flows, with the WARMF model predicting a much lower average log-flow condition. This leads me to conclude that WARMF in its present form could not be used for regulatory decision-making in the Truckee River watershed.

Table 2. Comparison of Simulated and Measured Flow Statistics in the Truckee River near Reno/Sparks at Stream ID 99.

Statistic	WARMF	Measured	WARMF-Log	Measured-Log
Maximum	146.59	154.60	2.17	2.19
Minimum	0.00	0.09	-4.46	-1.03
Average	9.70	7.91	0.10	0.23
St. Dev	17.80	16.43	1.31	0.69

Fletcher: Agree with Tracy. There needs to be work in this area. This is not independent of the data needs question. Model performance depends on both the theoretical relationships and the data to calibrate coefficients. Criteria for neither are clear. I would expect to see summary statistics such as sum of squared errors or sum of absolute errors for overall model performance as well as for calibration of specific parameters or sets of parameters.

Olmsted: In general, I view the simulated vs. measured flow results in Table 2 to be fairly close. Considering you can have a fair amount of error in the gage, these results may not be that unacceptable.

ii. Did the performance evaluation provide an adequate test of the model in terms of applicability to the modeling niche?

Keller: The WARMF model applications for the Truckee River and Catawba basin depict a very close match between simulated and observed hydrologic parameters. With respect to water quality, WARMF does a very good job of matching temperature and dissolved oxygen in general. Comparison of other water quality parameters is complicated by the sparseness of the observed data, but in general WARMF is at most within a factor of two of the observed data. The model does not always predict some apparent outliers in the observed data.

iii. How accurate can the model be expected to perform?

Keller: The model depends to a large extent on the quality of the input data. Simulated values are also a function of the spatial resolution used for the particular application. Given high quality input data such as meteorology, diversions, point sources, etc., Systech expects WARMF to simulate hydrology within ±10% and water quality within ± 30% of observed values, as seen in the Truckee River application for most stream segments. Although different watersheds exhibit more or less complexity, it is expected that WARMF can predict the observed values in general with this level of accuracy.

Olmsted: This is a key question and is likely to differ parameter by parameter and site by site. Work that we have done in simulating total suspended sediment and phosphorus suggest WARMF yields good estimates and is far superior to Eutromod. There is so much variability and error in sampling data that it is hard to determine what "truth" is and therefore to determine how accurate the predictions are. We will be doing work that should provide valuable insight into this concern.

Woolfolk: As accurate as the input and performance datasets. Having good input data (i.e., GIS coverages, land use estimations, soil types, precipitation, discharge data) is critical to run the model. Input data should be the best available in order to have some confidence in the model's predictive ability under reduction scenarios. If calibration/performance data are only for normal to low flow conditions, the most accurate portion of the model output will be associated with those conditions.

Fletcher: A deterministic model can never perform better than the natural stochastic processes internal to the system. That is, the best performance is an unbiased predictor of the expected value of the system at any point in time conditional upon the information available. Without adequate measures of the stochastic factors, such performance measures cannot be developed.

iv. Does the model exhibit any overall bias throughout the range of its predictions?

Keller: There is no apparent bias to over or underpredict hydrologic or water quality parameters. The only small bias is that in some cases the observed values are ahead of the simulated values by one or two days.

Woolfolk: There doesn't appear to be a bias in the range of predictions, particularly with flow. Realizing that the Catawba River water quality model is only moderately calibrated, WARMF appears to overpredict in some subwatersheds and underpredict in others. At this point it is difficult to say if there is an inherent model bias, if the input data is flawed, or if calibration should continue. For example, in the Little Sugar Creek watershed, the model appears to underpredict ammonia and total phosphorus. This is a completely urban watershed (Charlotte Metropolitan area) dominated by sewer lines and a large municipal WWTP. Part of the problem with the "calibration" in this watershed may be that the NPDES data were entered using annual average data. However, in rural watersheds, the model appears to overpredict ammonia (e.g., Wilson Creek).

Fletcher: No evidence of consistent bias.

v. How well does the model address, distinguish, and report variability and uncertainty in its output?

Keller: There is currently no provision within WARMF to address, distinguish, and report variability and uncertainty in its output.

Woolfolk: Clearly additional routines, reports and plots could be provided within the model structure. This is a shortcoming of most water quality models, thus relying upon the user to generate reports outside of the model structure. It would be an asset to have this type of analysis within the model. However, since one of the goals of WARMF was to be able to run the model in a reasonably short amount of time, significant statistical routines to evaluate variability in inputs and outputs may increase the processing time to an undesirable level.

Fletcher: Not! See other comments.

vi. Which parameters and key assumptions are most significant in determining the model's variability and uncertainty?

Keller: Appendix 3 presents Systech's assessment of the parameters which are most significant in terms of output sensitivity to parameter values. In addition, it is likely that spatial resolution also is important in controlling the uncertainty in model output.

Fletcher: This is an important question but it cannot be assessed without additional output manipulation.

vii. How does the model perform relative to other models in this application niche?

Keller: It is difficult to compare the BASINS and WARMF models in this respect, since to date there has not been an application of both models to the same watershed. Given that the resolution of each watershed is specific, it is almost impossible to compare them in terms of performance. In addition, the few applications that have been completed with BASINS are not generally available, and no one in the peer review group has had first-hand experience in this regard.

Beck: Systech Engineering has a side-by-side comparison of BASINS and WARMF. As of the peer review meeting, they had not written up the report. Region III has requested the report.

viii. Is the model reasonably calibrated against the observed hydrologic data?

Keller: The model appears reasonably calibrated against the observed hydrologic data in both the Truckee River and Catawba watershed. The method used for the calibration should be more obvious in the WARMF model documentation.

Hansen: WARMF does not calibrate automatically; instead, the WARMF user is responsible for calibrating the model as well as possible based primarily on visual comparisons between graphs of simulated versus observed flow data (Users can also export simulated and observed data to spreadsheets for further analysis). This process leaves some room for variation in what is considered to be a fully and adequately calibrated model. If more objective methods for calibrating the model are available, they should be incorporated into WARMF and provided as an option.

Woolfolk: The Catawba River Basin model does appear to be reasonably calibrated against observed in stream flow data. The model formulation in this regard appears to be satisfactory.

Fletcher: This seems to be a relative strength of WARMF.

ix. Is the model reasonably calibrated against the observed water quality data?

Keller: This has been discussed in section G. iii. above.

Woolfolk: Again, since the water quality portion of the Catawba River Basin model is only moderately calibrated, this is a judgment call. As stated above in item iv, the model appears to predict reasonably well in some cases/pollutants and not as well in other cases/pollutants. Nutrient levels (evaluated as ammonia and phosphorus) appear to predict reasonably well in mixed use watersheds (based on Clark Creek/Lake Wylie subwatershed and Lower Creek/Lake Rhodhiss subwatershed). This was less apparent in rural watersheds (based on Wilson Creek/Lake Rhodhiss subwatershed and Jacobs Fork/Lake Wylie subwatershed) and urban watersheds (based on Little Sugar Creek/Fishing Creek watershed). The urban and mixed use watersheds evaluated have large (>1 MGD) NPDES discharges to the streams. Part of the discrepancy between modeled and measured nutrient levels in urban watersheds may be due to the nature of the NPDES input data (annual average). When a more detailed NPDES dataset was input to the model for the Clark Creek watershed, the predicted nutrient levels were more in line with observed data. Yet, the model calibration is still dependent upon the available observed data, which generally was not collected during the peak of storm hydrographs.

x. Are the WARMF model's parameter values adjusted in a scientifically sound basis to match the observed data?

Keller: The method of calibration is not described in enough detail in the documentation to be able to comment on its scientific soundness.

Whittemore: I must agree.

Fletcher: I would like more information to assess this question.

H. TMDL and Consensus Process

Keller: The WARMF model is unique among watershed management tools in providing a clear process for developing TMDLs, and in providing tools for building consensus among stakeholders. Of course, having the tools and being able to use them are two separate issues, and thus the TMDL development process depends largely on the ability of the leaders to direct the process. WARMF provides the scientific and technical support, in a very user-friendly and graphical manner.

Basham: The underlying assumption in WARMF and the "consensus process" is that there is sufficient leadership and resources for setting up the model and entering the correct information. Additionally, the "consensus process" assumes there is commitment from the stakeholders to invest time in checking model inputs.

Wood: Yes, the process path is quite clear. As stated in A.ii above, one aspect of the process that needs further clarification is the judgment in knowing what changes to make in the parameters that define each scenario.

Fletcher: WARMF includes a module to manage public input and outlines the steps for a consensus process. It does not explicitly deal with prioritization or other approaches that would guide discussion through an analysis of the alternatives.

i. Are the TMDL and consensus processes clear?

Keller: The WARMF documentation provides clear explanation of the use of the TMDL and consensus modules, and even provides simple exercises for developing a TMDL. However, TMDL development is not a simple matter, requiring sufficient stakeholder knowledge and experience to address all the physical processes as well as the regulatory issues. WARMF provides a clear framework for a complex process.

Whittemore: There are typically many issues to resolve when developing a TMDL so its inappropriate to expect a 'model' to produce a TMDL. Rather, the DSS in WARMF aids in this process, since achieving the acceptable mix of PS controls and/or management actions is essentially an iterative process with input from many. I too would have appreciated more discussion here.

Woolfolk: The processes for the TMDL and consensus modules are understood after some consideration. The way each module functions and the interconnectivity between modules is not necessarily intuitive, but after reading the manual and experimenting with the software, the functions are more easily understood.

Basham: It is not clear how WARMF "calculates" TMDLs. Perhaps all that is needed is an explanation in the documentation. If the basis for calculating TMDLs is not explained, the TMDLs could not be approved by the state. The consensus process is clear.

Hansen: The TMDL Module provides a powerful tool for calculating TMDLs and for investigating alternative pollutant reduction scenarios that will meet the TMDLs and bring impaired waters into compliance with water quality standards. However, in watersheds with many impaired segments and with many different order tributaries that are impaired, WARMF's TMDL calculations may be hindered for two reasons.

First, when a TMDL is calculated for a particular control point, WARMF calculates average daily loadings required in the control segment and all upstream segments in order to meet water quality standards at the control point. These loadings do not account for TMDLs that may already have been calculated for upstream segments. To address this issue, WARMF should allow the user to link previously calculated TMDL scenarios for upstream segments to TMDL calculations at downstream control points.

A second issue is that downstream TMDLs do not account for the possibility that some upstream segments may already meet water quality standards. In other words, on segments that already meet standards, WARMF does not preserve existing loadings if they are lower than necessary; instead, WARMF increases loadings until the standards are exactly met. To address this concern, WARMF should allow the option for existing loadings to continue when a TMDL is calculated for a segment that already meets water quality standards.

Beck: A TMDL is required for each waterbody listing on the section 303(d) list, therefore, each listed waterbody is required to meet water quality standards. TMDLs need to be calculated for the upper most waterbody, that loading preserved, and a TMDL calculated for the next downstream waterbody. Some states, Pennsylvania, have chosen to list very short segments on their section 303(d) list while other states may have segments 20 miles long. One disadvantage to preserving existing loading in an upstream section is that future growth is then precluded in that section.

Wood: WARMF is readily tailored to any watershed/TMDL situation. One area that will most certainly need additional development is in the modeling of heavy metals for TMDL derivation. Many of the impaired streams with which I am familiar are listed due to failure to meet standards for heavy metals. The version of WARMF that was subject of this review was limited to aluminum in this category of pollutants.

Correll: It is not clear how a TMDL is found. There is no information in the documentation on how to take a calcualted TMDL into another module. They seem very separate. It would be good to discuss how TMDL links to loading that is obtained in the consensus module. Stakeholders should be warned that the TMDL is not “THE” answer, and that in fact one may not achieve the water quality goal even if the loading is done according to the TMDL.

ii. Are the TMDL and consensus processes adequate for a variety of situations and/or stakeholder groups?

Keller: The TMDL development process and the consensus process appear adequate for a variety of watersheds and/or stakeholder groups. Their understanding and use by the stakeholders has to be monitored to ensure that the final management strategy is adequate.

Woolfolk: The TMDL and consensus processes are good for a variety of situations, including TMDLs and watershed management strategies that are not necessarily part of a state or federal government effort. Since the TMDL module only considers one pollutant at a time, it will require some additional knowledge of the system and sources to develop a TMDL that incorporates all critical pollutants (e.g., for DO both BOD and ammonia should be considered, for algal growth nitrogen, phosphorus, turbidity/TSS, should be considered). As far as using the model across stakeholder groups, it appears able to do this. Additionally, since previous TMDLs are stored within the TMDL module, antagonistic and synergistic TMDLs/management strategies can be evaluated as needed.

Basham: TMDLs are required when water quality standards are not met. Therefore, where there are standards in place which include uses and criteria, stakeholder selection of "water quality issues", "intended uses" and criteria is not optional, but instead must be based on water quality standards if TMDLs are involved. Unless there is strong leadership and buy in to WARMF from the stakeholders group, application of the consensus process will have limited success.

Hansen: The TMDL and consensus processes address a variety of pollutants and help guide stakeholder groups through the process of evaluating alternatives and reaching consensus. However, despite the sophisticated user interface, a significant amount of complexity is hidden beneath the graphics. For stakeholder groups to use the model correctly, the User's Guide will need to be improved and, most likely, training will have to be provided. Stakeholder groups that are working with someone with at least a rudimentary understanding and experience with modeling have a greater chance at using WARMF correctly; those without technical expertise are less likely to be able to use the model correctly.

Hall: The aquatic community is the ultimate end user of the river. Maintaining a viable fishery in the Truckee River is a goal of the tribe and to the other stakeholders. Controlling algal growth in the Truckee River watershed will be important for managing and maintaining a healthy aquatic community within the river. The Cost Benefits/Cost Benefit Analysis (CBA) should be attached more to the health of the river (i.e., support potential for threatened species) as well as the economic viability of the watershed users.

Fletcher: At the present time it requires a very sophisticated support structure to use the consensus module. While the thought is good and the basic layout a good first cut, there is an opportunity for significant improvement in this area. This does not appear to be an engineering based module and requires other inputs. Perhaps other decision support modules could be tied to WARMF.

Nelson: I am not convinced that the current model is as useful as other simpler approaches. For example, in the Upper Shenandoah River (where a TMDL analysis and agreement has been made) in Virginia a lot of useful information has been generated from visual identification of likely pollutant sources and from subsequent tracer studies of fecal coliform sources. It was determined that beef cattle were the primary source. Some straight pipes from homes were identified. These particular problems were addressed in the initial stages. Now of the remaining pollution, human sources are dominant and the most obvious of the dense housing areas will have septic system upgrades. The WARMF model would not have been helpful in this instance. Similarly, in a Massachusetts watershed, the most useful information has been visual inspections of the river, in terms of identifying broken sewer pipes, etc.

Further, I think that the stakeholder process could be improved to fit better with our experiences of the community-based decision-making process. We have found that a small group of stakeholders is much, much better than a very large group. The stakeholders like to see where the sensitive environmental or natural resources are in the community (shellfish beds, water supplies), and where water quality problems are evident (failing septic systems, water quality impairments). They are very, very concerned about the future of the community, in particular land use concerns. They worry about preserving open space, excessive growth, etc. They worry about the burden on the tax base if they grow too fast. They look at options such as sewering, low-density development, advanced on-site treatment or cluster systems, or cluster housing.

If WARMF were to be used for watershed or community-based decision-making, it would have to incorporate much better predictive models for these aspects. Otherwise it will miss what the community really cares about.

Correll: The model should list which scenario was used to create the TMDL.

iii. Does WARMF provide adequate documentation of stakeholder interests for future reference?

Keller: The model has specific provisions for documenting stakeholders' interests individually, for future reference during the TMDL development or implementation process.

Woolfolk: Certainly, priorities of a particular stakeholder organization are recorded in the model and are available to any who desire to see how those priorities are ranked. However, priorities change over time and a case could exist where a stakeholder organization changes its mission statement and thus priorities. Although the model accepts this change fairly easily, there is no way within the model to track a change in priorities. This type of situation may or may not happen often, but the models' ability to track this is less than desirable.

Basham: Yes.

Hansen: The Consensus Module provides a field for the stakeholders to list their names, contact information, interests, expertise, and committees. This documentation should be adequate for future reference.

Wood: WARMF seems to allow for sufficient documentation of interests, although there still needs to be a process mechanism to consolidate the response from multiple stakeholders into a single update, which would then be re-issued to stakeholders.

Nelson: I found the stakeholder interest categories unhelpful. It's not clear how public awareness is met by different scenarios. Water quality protection, natural resource protection -- these are mom and apple pie statements and will get casual answers, I would think. In an actual stakeholder process, it is likely that actual shellfish beds, wetlands, etc. in the watershed or community will be identified as priorities. Land use options (dense development, no development, village development, etc.) will be the most important value for the community!

Not only have we found that in the decentralized field, but EPA's community-based environmental protection projects have found that as well. In the TMDL process, no consensus will be reached if these concerns are not addressed as well.

iv. Is the process for evaluating different scenarios adequate?

Keller: WARMF specifically provides a tool to manage different scenarios, keeping track of all the data files (input and output) associated with the scenario, as well as notes and comments that the user(s) may wish to keep with each scenario. The output graphs include means for visually comparison of the various scenarios. This information is also available in tabular format for export to another data analysis software (e.g. spreadsheet).

Woolfolk: Yes. Particularly renaming alternate scenarios to show overall effects of each alternative and the ability to change point and nonpoint sources within an individual scenario.

Wood: The process of evaluating different scenarios seems to be the most complex part of the WARMF process. The model seems to allow for a very robust menu of changes.

Basham: Yes.

Hansen: WARMF provides three visual methods for evaluating different scenarios: graphs of pollutant concentrations and flow over time for a given river segment, bar charts that show average pollutant loadings in a given subwatershed, and maps of all river segments colored green or red depending on whether or not water quality standards are met. WARMF also allows daily pollutant concentrations and flows as well as average daily loadings to be exported to spreadsheet programs for further analysis. Together, these methods provide powerful tools for evaluating alternative scenarios.

Beck: The TMDL module includes a spreadsheet to keep track of the calculated TMDLs. However, a large watershed such as the Cheat River, WV, has more than one stream with the same name, e.g., Beaver, Glade. It is suggested that the unique steam identifier be included with the name of the control point.

Nelson: Are the scenarios too broad? Do all farms need buffer zones? Do the buffer zones only deal with fertilizers, or do they also address farm animals? Are there other scenarios to consider? Could the bars for point source and nonpoint source contributions be expanded to include a variety of land use contributions, such as stormwater, farms, septic systems, etc.? Are there ways to include on the maps more than just stream segments and lakes? Could particular resource areas such as wellhead protection areas, or shellfish beds be highlighted as well? I was quite uncomfortable with the consensus process. Why should each group get one vote? As it is now, the stakeholder/public-input process may be a too simplistic effort at what really needs to happen. A smaller group needs to work through the particulars of their watershed or community-level problem, get to know what is important to the community and why, where water quality impairments are threatening public health or the environment, etc. Then the model can come in, if it properly reflects the values and the scenarios, and the stakeholder group can see what happens under various approaches. Costs will be important at that point, along with other aspects such as loss of open space, equity, possible subsidy programs, etc. Perhaps new combinations of scenarios will be generated. This stakeholder group would be very unlikely to use the quantitative weighting of values and calculation of scenarios approach presented in WARMF, is my guess.

Hall: It would be useful to be able to display the graphs in output mode. It would also be better to be able to link the point source changes to the scenarios instead of having to go back and change it back after running a scenario. It is actually rather dangerous that changes to point sources are made to the original data file- if the simulator does not document the original values properly, the information could be lost. In addition, if the simulator does not remember to change the values back, it can affect subsequent simulations.

v. Are the WARMF model output files and graphics sufficient to convey the information to the various stakeholders?

Keller: WARMF generates output files and graphics which are very useful for the stakeholders. For more advanced users (e.g. academic research) and for trouble-shooting, it would be useful to be able to request (via an on-off switch in a simulation module) the generation of tables with intermediate values calculated by the model which are not as useful to stakeholders. For example, snowpack depth, soil moisture content, surface water detention storage, nitrogen and phosphate reservoir sizes in each compartment, etc. The analysis of these intermediate parameters would be quite useful for specific applications.

Woolfolk: Good, but maybe not entirely sufficient. Water quality maps and loading charts are helpful in showing stakeholders the effects of various load reduction strategies on the water quality and what it means in real numbers. However, if there is an educated stakeholder group, they will want to know exactly how much the water quality parameter of interest is affected by changes in loading. Thus, a direct tie to time series plots similar to those in the output portion of the Engineering module would be desirable. Evaluating nonpoint source loads by subwatersheds would be easier if these loads were mapped by WARMF. The graphical framework can be used to color subwatersheds differently based upon the magnitude of nonpoint or total pollutant loads.

Basham: Yes.

Hansen: Same as previous question.

Wood: The "traffic light" (red/yellow/green) indicators are very user-friendly. One strong criticism that I have, however, is that the model does not contain an "audit" function that would easily allow the user to determine what has been changed from one scenario to the next. Currently, users must rely on keeping manual record of the changes made to coefficients, etc. that define each individual scenario. I suggest that functionality be added to the model which would allow the user to generate a table or spreadsheet which would list all (or some user-specified subset) of the scenarios comparing them to the base case. To keep the list manageable, the table could be limited to show only those parameters, coefficients, etc. that change from one scenario to the next. This functionality would go a tremendous way towards maintaining the necessary trust between stakeholders. It would easily allow them to see what others have manipulated.

Nelson: I found it extremely hard to compare the scenarios. The instructions are to compare a base and other scenario in terms of river segments going from red to green. This was not at all user-friendly! Couldn't a map appear that showed, for example, streams that still stayed red, streams that were already green, and say in purple, segments that were now in compliance based on the scenario? In addition, how can one person remember all the different pollutant measures and how well the scenarios will improve them? Is there any way to get a "composite" or at least a fecal composite and a nutrient composite?

Hall: The loading charts are not very user-friendly: it is often hard to tell which bar chart goes with which segment, and it is hard to turn certain segments on and off.

vi. Is the WARMF model sufficiently "user-friendly" for use by the various stakeholders?

Keller: WARMF is very user-friendly once Systech has set it up. In a couple of hours, most computer-literate stakeholders can navigate through the various menus. A word of caution is that the user-friendliness of the model may be dangerous, for stakeholders that do not understand the complexity of the processes underlying the model.

Whittemore: Inexperienced personnel SHOULD NOT BE DOING MODELING, regardless of the user-friendly nature of the software. While 'user-friendliness may result in greater stakeholder comfort, the modeling should be done by professionals who understand the limitations of the model and what parameter changes actual mean in a physical sense.

Woolfolk: For many stakeholders the model is sufficiently "user-friendly". Those with some computer aptitude or technical training should be able to use the TMDL/consensus modules without significant effort. However, the interpretation of the output from these models may be the more important question. Thus, even if non-technical stakeholders choose to run the model, the results and methods should be verified with a modeler.

Basham: Yes.

Hansen: Compared with other models that attempt to do similar things, WARMF is perhaps the most user friendly of all. If stakeholders are to use the model simply as a tool for displaying results, then WARMF is most likely sufficiently user-friendly. But if stakeholders are to use the model to evaluate alternative scenarios in order to participate fully in the TMDL process, then an improved User's Guide and, most likely, training, will be required to make sure that WARMF is being used properly.

Wood: As stated in other comments, neither the model nor the documentation provides any assistance to the user to guide them through the decision-making process on what to change from scenario to scenario. While the interaction with the model is fairly user-friendly, it remains a very complex machine that requires good technical decisions regarding model input of coefficients, etc.. I am concerned that non-technical stakeholders will still feel "left out" due to an inability make meaningful decisions when they want to "play" with the model.

Also, it would be useful to be able to choose people from the list of participants when populating committees, rather than retyping all their names.

At several points in the various modules, small windows are generated which contain tables. It is very difficult to grasp the information contained in these tables since you must scroll horizontally and vertically through them. Further, the user is unable to resize the window to attempt to show more of the information on-screen. Similarly, there are pull-down lists which do not show the complete name of the entry (i.e., it is truncated). For example, selecting pollutants to calculate a TMDL in the TMDL module for the Truckee.

Beck: In spite of the many reviewers' comments that WARMF is user friendly, I found a steep learning curve. The public should not think that they can run simulations after an hour's playing with the program. I found difficulty in determining which stream segment a loading chart was attached to (Cheat River version).

Nelson: The WARMF model is only usable by technically proficient computer types. One simulation took forever on my e-machine, my machine froze on several tries, and the instructions were not simple for an introductory computer type like me. I can see that what would happen is that a technically sophisticated person would run these models for the stakeholder group, but that hardly anyone else would ever do anything directly with the model. One suggestion would be to present a case study of a stream segment -- where the stakeholder could go right in, get a simplified description (in words and in the model) of the water quality impairment and sources, and play with several scenario changes with a map as described above. Then the particulars for their community could be incorporated by a technically sophisticated consultant.

Hall: The model is very user-friendly, but it can be overwhelming when you don't know what to change in a scenario. Perhaps better documentation and a tutorial program with more exercises (a la ESRI).

vii. Are stakeholders able to input new data to the model as it becomes available?

Keller: WARMF provides additional space and/or tools to input new data to the model as it becomes available, which is a very useful feature not commonly found in similar models. However, if the new data is going to be used to recalibrate the model, it is recommended that this be done by an experienced user from the stakeholder group, or directly by Systech.

Woolfolk: I only tried to enter additional ambient data and NPDES data - this was much easier in version 4.6 than in version 4. Modelers and technical persons should have no problem with this. I have not attempted to get meta data or GIS coverages into the model, so no comments with regards to those.

Basham: Yes.

Hansen: After Systech delivers the calibrated model, new data can still be entered. This is a powerful feature, but one with potential pitfalls that should be addressed. If possible, WARMF should allow the source for each parameter to be loaded into the model. The source could be a value taken directly from a published report or database, a calculated value based on one or more sources, or an estimate based on a reasonable range. The value could then be altered through calibration. WARMF should allow the user to fully document each parameter so that a clear record is preserved.

WARMF should also be able to compare the input data between scenarios and to create reports that show differences. This capability would be absolutely essential if stakeholders are to submit consensus-based scenarios to the regulatory agencies that are developing the TMDLs. Agencies would need to confirm that the scenarios are based on the same data used in the original calibrated model, or on approved adjusted data, before they could incorporate stakeholder-generated scenarios into a draft TMDL. With such a large database contained in each scenario, it is extremely important to be able to perform these comparisons automatically.

In addition, if the previous suggestion is implemented so that each parameter is clearly documented, the most useful comparison report would not only show differences in data values, but would also show the sources used to generate the different values.

Wood: Yes, the model should be fairly easy to keep current with new data and instructions are provided to do so.

Beck: With respect to "new" data and recalibration: if the new data is "new" with respect to time, and the model was adequately calibrated and adequately describes the processes taking place, then calibration should not be necessary. If whole new data sets covering the original time frame, then calibration may be necessary. Mr. Hansen's comments regarding documentation of a scenario's parameters are valid. Region III has had discussion with Systech Engineering regarding documentation but no decisions have been made.

viii. Are stakeholders able to recalibrate the model as needed?

Keller: Although WARMF provides a tool for automatically recalibrating the hydrologic model, it is strongly recommended that only very experienced users (or Systech) perform such a calibration.

Whittemore: I strongly agree!

Woolfolk: Stakeholders who are modelers or technical persons should be able to recalibrate the model, as additional data becomes available. However, if it is difficult to update some of the new input data (e.g., coverage); assistance from Systech may be needed (see user's guide, items deactivated for general use).

Basham: Yes.

Hansen: Stakeholders are able to recalibrate the model. This involves changing data and re-running the model until the stakeholders are convinced that it is calibrated properly. The suggestions in the previous question for addressing potential pitfalls in entering new data apply to this question as well.

Wood: While I did not attempt to recalibrate the model, the documentation indicates that this can be done.

Fletcher: I doubt it - at least not without significant help.

I. Model Documentation and User's Guide

Keller: The WARMF model is documented in:

- Watershed Analysis Risk Management Framework. A Decision Support System for Watershed Approach and Total Maximum Daily Load Calculation. 1998. EPRI Report Number TR-110709. (Referred to below as technical document)
- User's Guide to WARMF (Documentation of Graphical User Interface). DRAFT. 1999. Systech Engineering Inc. San Ramon, CA. (Referred to below as user's guide)

This section discusses the material covered in the technical document and user's guide.

Tracy: The User's Guide is fine, it could be a bit more polished, but I found it useful in using the WARMF model. The Model Documentation needs to be much more detailed in describing how the models are linked together, and in describing how spatial and temporal scaling issues were handled.

Fletcher: The documentation varies in quality. Some parts seem adequate. Issues on calibration are quite weak. This makes verification difficult as well.

Whittemore: The manual was better than some I have seen and can be improved by the comments noted by me and others throughout this document.

Hall: I don’t think the help menu is descriptive enough – it usually gives a very superficial description of the item, which is not what I need at that point. I think the User’s Guide could be expanded considerably, with more discussion of the modules and how they are linked.

i. Model applicability and limitations?

Keller: The documentation explains that WARMF is designed to develop TMDLs, its intended application. The model does not explicitly describe the model limitations, nor those watershed conditions where it has not been fully developed (e.g. estuarine environments, wetlands, etc.).

Woolfolk: The model niche, and thus intended applicability, is briefly described in the introduction of the technical document. However, model limitations are not explicitly described in either piece of documentation.

Basham: The limitations of the model are not discussed in the documentation.

Wood: The applicability is well documented, however, a cautionary note addressing my comments in A.ii and H.vi. above should be added. Perhaps more focus should be given to the exercises for new users as I found that working through them was more beneficial than attempting to learn the program while following along in the user instructions.

ii. Data input?

Keller: Both documents do a very good job of describing data input. There are specific examples for most data entry screens, as well as how to add new data once the model has been setup by Systech.

Woolfolk: The user's guide describes the input of additional or new data into the model in several places. The user's guide does a good job of describing how to input the data and where it is best to input the data. The technical document briefly describes data input and units needed (note: there is a discrepancy between units in the technical document and units in the data module). Parameter codes are listed in the technical document, however, there are some codes that are missing (e.g., 24 for BOD).

Basham: It would be helpful to include a list of the minimum data required to run WARMF and expect realistic results.

iii. Interpretation of results?

Keller: The documentation discusses the output screens, and in particular how to view the TMDL and consensus module output. Examples are provided for the user to compare. There is no additional discussion beyond the presentation of results, for example, how to go about making changes in the non-point sources in the watershed to actually meet the TMDL. Knowledgeable stakeholders are expected to make the interpretation of the results.

Woolfolk: There isn't a noticeable amount of paper dedicated to results interpretation, with the exception of the tools that can be used to interpret results (e.g., plotting, loading bar charts by watershed, colored segments based on meeting intended uses). In this regard, the model documentation has fulfilled necessary duties in providing instruction on how to use the available tools. Additional interpretation of results should be the responsibility of the modeler/user. As previously mentioned, stakeholders without modeling/technical training may mis-interpret results or place more confidence in model results than a technical person. Without an uncertainty module built into WARMF that describes model confidence, this could happen often with non-technical people.

Basham: The documentation did not specifically discuss the interpretation of results. It is my impression that the interpretation of results is a stakeholder function.

iv. Mathematical formulation?

Keller: The mathematical formulation is presented in the technical document, in a very clear manner, with sections and subsections for the various components of the watershed. The mathematical description of the hydrologic cycle is very complete, although a few details and typographical errors were detected during the review process. The sediment transport equations are also clearly presented and are quite complete.

There is a major gap in the mathematical formulation of the flow of chemicals (nutrients and pollutants) through the watershed, and in particular the cycling of nutrients within a particular land-use. Although there is a general description of the processes, there are no mathematical equations presented in these sections. Even if these equations are available in some of the references cited, it would be extremely useful for WARMF advanced users to know the specific model formulations.

In addition, the equations are presented without any discussion of their limitations. This would be a useful addition, to at least provide a warning to users about the applicability of the model and submodels.

It would be useful to include a glossary describing each parameter and the specific literature reference(s) from which the values were obtained (where applicable). There are a few variables that share the same symbol, which makes it somewhat confusing to the untrained reader.

Hall: In chapter 3, pages 19-20 of the technical document, nutrient uptake refers to tree productivity, canopy dynamics, and root respiration. Is the watershed vegetation assumed to be forest? This section is not at all clearly written. Many parts of the country have grassland or desert vegetation.

Woolfolk: The technical document presents a large number of governing equations for the model. These are organized into flow or water quality groups. The "Engineering Models" portion of the technical document is a quick introduction to the underlying concepts. There may need to be a more detailed description of the mathematic formulation, including the numerical solution techniques. In many stakeholder groups a justification of the model formulation will be needed and it will be difficult to do with only the technical document. Additionally, instead of just presenting equations, more accompanying text should be added to tie the equations to each other. The text is currently written for someone who either already understands the interconnectivity of the equations or has time to figure it out. Stakeholders may check the documentation to see if a process is simulated or generally what is involved in that simulation. Currently, it may be difficult to find these types of processes or to understand how they are connected to the overall model.

Basham: Yes, limited formulations.

v. Numerical solution algorithms?

Keller: The discussion on the various methods of numerical solution is very brief. Besides mentioning using Runge-Kutta, there is little discussion of what parameters are explicit or implicit, what is the order of calculation, or how in general are mathematical expressions interpreted numerically. It would also be extremely useful to provide a set of diagrams indicating how the models are linked.

There is a discussion in page 3-20 of the technical document about the calculation of root respiration which discusses possible methods of solution, but which indicates that a rather simple method is used. Although CO_2 is not a major concern, this could be indicative of some deficiencies in the implementation of the nutrient cycling algorithm.

Woolfolk: I didn't find very much about numerical solutions (except a reference or two about Runge-Kutta techniques). Certainly a general discussion on numerical solutions should accompany the technical document.

Whittemore: Are the algorithms used by Systech known to be robust in other cases? Has the code been verified against known solutions? This is not discussed in the documentation.

vi. Calibration procedures?

Keller: The discussion on the calibration procedures is limited. It would be very valuable to include a section describing how the model is calibrated. Although this could give some users an incorrect signal (that calibration can be easily undertaken), there is more value in knowing how this is done. Appropriate caveats can be included if this is a concern.

Woolfolk: Calibration and verification (below, item vii) are two steps in developing a model. These steps should probably not be referred to in the context of the model documentation. Calibration and verification methods are varied and are best left to the modeler to determine which is more appropriate. These are subjects best covered in a water quality-modeling textbook where the subject can be covered in more detail. On the other hand, if Systech knows of common calibration mistakes, it may be useful to have these presented in the technical document.

Basham: Calibration is discussed in the documentation in general terms. It would be helpful to include suggestions about which calibration coefficients to start with first.

Whittemore: Calibration might be difficult since the process is not straightforward and requires some professional judgment. In any event more discussion or justification would be helpful.

vii. Other key aspects such as verification testing?

Keller: The discussion on verification testing is limited. It would be very valuable to include a section describing how this is done.

Woolfolk: (see above comment for calibration)

viii. User-friendly instructions for all stakeholders?

Keller: The User's Manual provides very user-friendly instructions for stakeholders, and the language is written in a very clear manner. Most computer literate stakeholders should be able to surf through the various input and output screens just by reading the manual, and could perform simulations and TMDLs after following the exercises. A recommendation is to include output screens for the exercises, since there is no way for the user to know if they have done the exercise correctly. There are some sections of the User's Manual which need to be completed.

Woolfolk: The language in the user's guide is written in such a way that most stakeholders with some computer knowledge will be able to run the model. The user's manual definitely needs to be completed and there appears to be some organizational changes that should happen in the later chapters (5 and 6).

Basham: In my opinion, the instructions are user-friendly especially in providing step by step "point and click" instructions.

Wood: Instructions are fairly user-friendly. More specific comments include:

- The instructions are somewhat unclear on adding new stakeholders to the list. I inadvertently erased some by overtyping. Need to explain that you must click on a blank line to enter new stakeholders.

- The instructions dealing with running simulations should more clearly communicate the fact that individual runs may take a long time, depending upon the timeframe and areal extent chosen.

J. General

i. Does the model satisfy its intended scientific and regulatory objectives?

Keller: The model satisfies the intended regulatory objective, the development of TMDLs, and is based on sound science. There are some weaknesses that can be corrected, and others that are inherent in the development of any watershed-scale model, which need to be considered while developing TMDLs (e.g. spatial resolution, averaging process). It is the just as sound as the only comparable model, BASINS, and it is the most user-friendly tool for the development of TMDLs.

Woolfolk: Yes. While not perfect, WARMF offers a user-friendly alternative to models such as BASINS. The model can be used for TMDLs, watershed management strategies, evaluations of BMPs, etc. The developers should continue to push for wider use of the model to make it more widely accepted.

Basham: Satisfaction of the regulatory objective is dependent on satisfaction of the scientific objective.

Olmsted: Numerous suggestions and comments have been proffered during this peer review process that will improve WARMF. Indeed, the model should never be considered fully developed as improvements and upgrades are constantly being made. However, in its present form I believe that it meets the regulatory objectives in the Carolinas (Woolfolk would be a better judge of this), and the scientific objectives on an ecosystem basis. Some people have been interested in pushing WARMF beyond its intended ecosystem focus and look at scenarios on a microscale. WARMF was not intended for these purposes and would not meet the scientific objectives of such efforts.

Tracy: In its present form I would not recommend that the WARMF model be used in a regulatory decision making environment. I feel that the Consensus and TMDL modules are a good platform to further develop WARMF, but that a significant number of changes need to made to the engineering module. The model developers should investigate other methods that are available to simulate water quantity and water quality processes at the watershed scale and focus less on linking together existing mechanistic models and focus more on developing procedures that can predict the integrated behavior of water quantity and quality processes at the watershed scale.

Wood: Overall, I would say that WARMF is quite satisfactory for accomplishing the goal of developing TMDLs in a stakeholder setting. The stakeholders need to realize that, while the model has been made to be quite user-friendly, this is still a very technical process and has not necessarily been simplified to the point of playing a computer game.

Fletcher: WARMF satisfies the primary scientific objectives in a preliminary way. It can provide an initial assessment for TMDL analysis. I doubt if it is currently adequate for implementation and certainly would have major problems for AMD issues. It would seem that the issues with uncertainty and error must be addressed to meet these goals.

ii. Is there any available scientific evidence to suggest changes to either the model design and/or key parameters and assumptions prior to its use for regulatory purposes?

Keller: The peer review process has resulted in a number of suggestions and comments which are being incorporated into a new version of the model. Systech should carefully evaluate the recommendations and comments in this document and assess the difficulty inherent in making these changes.

Basham: The algal and DO processes need refinement before the model could be used for regulatory purposes in Nevada.

Fletcher: This most likely depends on the issue to be addressed. For implementation, this may apply to most if not all of the pollutants. Issues such as AMD may require major structural changes in the way WARMF operates.

iii. How robust (i.e., not overly sensitive toward small changes in modifying key assumptions or input data) are the model predictions?

Keller: The sensitivity of model predictions to input data is indicated in Appendix 3 for the various parameters. This information was provided by Systech, and was not evaluated specifically by the reviewers.

iv. How well does the model output quantify the overall uncertainty resulting from limitations/simplifications in its design: use of standard assumptions; availability of supporting data; etc.?

Keller: The model does not quantify overall uncertainty.

Basham: As far as I could tell, the model does not quantify overall uncertainty.

v. What key research is necessary to refine or improve the model and/or the data bases upon which it relies?

Woolfolk:

1. Flexibility to reduce the time step when needed.
2. Additional field studies to quantify storm flow pollutant loads and/or water quality for smaller watersheds. Actually, for the Catawba a future sampling plan can be designed around the model.
3. Test in a variety of situations (e.g.,. wetlands, blackwater, estuaries) and for a wider variety of pollutants (e.g., metals, organic chemicals).

Basham: As mentioned earlier, attached algae needs to be addressed.

Fletcher: The adequacy of the final WARMF model for AMD needs to be assessed. The data, in general, could be improved but there should be a clear indication of the value of additional information.

vi. Does the WARMF model address the management questions of interest?

Keller: WARMF directly addresses the management question of interest, which is the development of TMDLs. The user must then work with the Engineering Module to determine how to implement the TMDL.

Woolfolk: For the question of determining a TMDL for a higher order stream or river, or a lake, yes, it appears so. One shortcoming of the model is the ability to do loading allocations. Once the TMDL is determined at a control point for point and nonpoint sources, different allocation schemes may be considered that are not easily done from the TMDL or consensus modules. For example, Source A may be considered for a higher limit for BOD simply because it is further from the critical segment. This type of analysis will probably have to be done through the engineering module, which is more difficult than through the TMDL or consensus modules.

Basham: WARMF appears to be useful for evaluating different scenarios and evaluating the impact of nonpoint source controls.

vii. Since WARMF is a framework that combines several models that interchange intermediate answers, is this done seamlessly?

Keller: The exchange of intermediate answers is seamless. There is no need for the user to concern him/herself with the linkage between modules. This is an outstanding feature of WARMF. It would be very useful to detail in the technical document how this is done.

Woolfolk: From the user perspective, this does appear seamless. From the programming/numerical solution perspective, decline comment.

Wood: WARMF appears to function between its modules quite seamlessly.

Olmsted: This is one of the beauties of WARMF. It is easy to switch between the engineering and TMDL modules. The transition is seamless. No attention has been given during this review to the consensus module, but I believe that is one of the unique features of this model. The transition from consensus to engineering and TMDL is also seamless. The consensus module has yet to be fully tested but we are in the early stages of using it in a small subwatershed of the Catawba River. I expect it to work well, but I also expect to find areas for improvement. Systech is in the process of developing web-based capabilities to handle stakeholder input and this will be a powerful addition to the model.

Hall: I don’t see how this is done. How is the TMDL module linked to the others?

viii. How easy is it to add new modules to the WARMF framework?

Keller: This question is beyond the scope of the reviewers' work. However, the current implementation of the Acid Mine Drainage module appears to require a few months of Systech's time, which seems like a reasonable timeframe.

Appendix 1. Systech Response to the Peer Review

A) General Response to the Peer Review

Appreciation of Effort

We would first like to thank the peer reviewers for taking time and effort to conduct the review of WARMF. The reviewers have provided constructive comments indicative of their interest and thorough understandings of WARMF. Dr. Arturo Keller should be congratulated for organizing such an outstanding review panel and guiding them through the review. This is possibly the only model review that has been performed according to the EPA guidance manual. We are honored to be a part of the effort.

Lessons Learned

We were wrong in thinking that error analysis should be performed outside of WARMF. We originally thought that there was no accepted statistical procedure to measure the "goodness of fit" between simulated and observed time series of data. For that reason, we designed WARMF to export the simulated and observed time series data to text files. The users could then analize the data with their favorite statistical program, outside of WARMF. Clearly, the reviewers want the built-in statistical tools.

We developed WARMF as a decision support system for practical applications. To be practical, we knew the computation had to be fast and the data requirements had to be realistic. To be acceptable, WARMF had to have a good scientific basis. As a compromise, our original concept of a catchment, containing uniform characteristics, was refined to include multiple land uses. When the model is reviewed by people with a research background, it is criticized for being too coarse and therefore not realistic. WARMF stands in the middle of practical and research models. It will continue to be criticized for being too detailed and requiring too much data on one hand and too coarse to be realistic on the other.

The philosophical difference between stochastic modelers and mechanistic modelers is large and probably not reconcilable. Stochastic modelers would never accept the notion that a complex watershed can be reduced to a few equations purported to represent key processes controlling its behavior. They believe that the watershed responses can only be measured directly and only the measured data can be used to develop the stochastic model. The mechanistic modelers would never accept the notion that a statistical equation, developed with data collected at one location and one time, could be applied to any other location or the same location at another time. They believe that the complex hydrologic process can be studied stepwise by canopy interception, throughfall, snow melt, infiltration, evapotranspiration, lateral flow, etc. and that the water quality can be studied in terms of advection, diffusion, sinks, sources, mass balance and heat balance.

Some reviewers felt that the user friendliness of WARMF may lead to model misuse. We designed WARMF so that ordinary stakeholders with some minor training could use it. As long as the model is set up and calibrated by experienced modelers, there is less chance for misuse. This may not be the case as time will tell. Even with the user-friendly features of WARMF, the stakeholder group may still need a more technically inclined person to help run the model. For example, Mr. Evan Hansen of Friends of the Cheat has been very helpful to the stakeholders of the Cheat River TMDL project.

We have known all along that WARMF will be used to evaluate many management scenarios. We developed a scenario manager and a voluntary documentation tool to facilitate this process. To prevent abuse and/or confusion, we plan to make the scenario documentation mandatory and create a tool for assessing differences between scenarios.

New Enhancements

Larry Olmsted of Duke Energy has correctly pointed out that WARMF is a work in progress. Based on the suggestions of the reviewers, we plan to make some enhancements to WARMF in the year 2000. The following features will be added in the next upgrade:

1. Statistical tools: In addition to time series plots, we will add frequency distribution plots. We will also output mean, range, standard deviation, mean error, and mean absolute error of both simulated and observed data.
2. Benthic algae: For river segments, we will add an algorithm to simulate benthic algae and its impact on dissolved oxygen and nutrients.
3. Scenario documentation: We will make scenario documentation a mandatory step to initiate a simulation. We will also provide a tool for comparing the input data of different scenarios.
4. Nested TMDLs: Due to the questions raised by peer reviewers, we discovered that WARMF does have the capability to do nested TMDLs. The TMDL solution for an upstream control point can be frozen during the calculation of TMDL for the downstream control point. We will add new dialogues to facilitate this process and make it more clear to the user.
5. Multiple parameter TMDL: We will add the capability to calculate the TMDLs of multiple consituents (e.g. BOD, ammonia, and nutrients) that affect a single criteria (e.g. chlorophyll-a, dissovled oxygen).
6. Reservoir 1D, Pseudo-2D, CE-QUAL-W2 options: Three options will be offered for the reservoir model. For round lakes, users can choose the 1D vertically stratified model. For long and narrow reservoirs, users can choose either the Pseudo-2D or CE-QUAL-W2 models. Pseudo-2D will divide the reservoir into multiple segments, each of which is vertically stratified. CE-QUAL-W2 is the fully hydrodynamic two dimensional reservoir model developed by the US Army Corps of Engineers.
7. Revised documentation: We will add sections describing nutrient cycling in catchments, how to interpret model results, how to formulate various management scenarios, and how to recalibrate the model with new data.
8. Revise user's guide: We will update the user's guide to be current with the latest verion of WARMF and add additional exercise examples to guide first time users.

A proposal has been submitted to add septic systems to WARMF. When it is funded, WARMF will have the capability to assess the impact of septic systems on local water supply wells and downstream lakes.

At the present time, we have no plans to include toxicants that go through the chemical processes of hydrolysis, volatilization, methylation etc. If they become an important issue for TMDL, we may consider adding these processes in later years.

WARMF will do simulations for such toxicants as pesticides and heavy metals, which interact with suspended sediments. WARMF has been enhanced to simulate acid mine drainage, which leaches out ferric iron, ferrous iron, aluminum, manganese, and zinc. The transport and fate of the metals in the receiving water due to pH equilibrium, precipitation and adsorption are considered.

The 1-hour acute toxicity standard is a regulatory decision which can be arbitrary in many cases. As pointed out by a reviewer, the criterion was derived from bioassay experiments, based on 24, 48, and 96 hours of exposure. To meet the 1-hour acute toxicity standard, one has to consider the mixing zone (i.e. initial dilution), which is not considered in WARMF. We think that TMDL and WARMF should use water quality criterion based on chronic toxicity.

In order to view model results more quickly, percent compliance computations are done during the simulation run through the engineering module. The percent compliances have been pre-set at 80, 90, and 100% and the user cannot ask for a different compliance level after the simulation. If there is a consensus on the issue, we can change the pre-set compliance levels. We can also change the 7 day average water quality criteria to 4 day averages.

Clarifications

Lake Acidification Model

There was a question about whether a lake acidification model could be applied to a river. ILWAS stands for Integrated Lake Watershed Acidification Study. Its model includes the algorithms for catchments, stream segments, and lake segments.

Buffer Zone

The algorithm for buffer zones was derived from field studies that monitored the removal of suspended sediment and associated nutrients (e.g. phosphorus) from the overland flow. The type of vegetation in the buffer strip should be reflected by the Manning's flow resistence. Furthermore, it is assumed that the buffer zone is maintained. The model does not track the accumulation of sediment, which may cause channelization etc.

The forest buffer can be simulated in two parts. The trees, which remove nutrients from groundwater, should be included in the landuse coverage of catchment. The buffer zone should be used to simulate overland flow and sediment removal.

Vegetation

Vegetation on catchment surfaces can be crops in farmland, coniferous and deciduous trees in park land or forests, or herbaceous grasses in pasture land. The model requires the input data of annual growth rate for each land use type and a seasonal pattern of nutrient uptake to satisfy the growth. The difference between the fertilizer and atmospheric application and the nutrient uptake by vegetation is the nutrient pool available for transport to the river segments, either through surface runoff or groundwater seepage.

Land Use Changes

WARMF assumes that land use changes are gradual. GIS land use covers are generally updated only every 3 to 10 years. WARMF provides a warm start capability, in which WARMF simulates a time period with one land use scenario and then prepares the results of the last day as the initial condition for the next time period with a new land use scenario.

Stakeholder Group

WARMF is a decision support system which facilitates the stakeholder process. It does not specify the demographics of the group or how the vote of each member should be counted. In general, we do encourage diverse stakeholder groups that include industries, environmentalists, home owners etc. WARMF can be used by a focus group or a single individual of the regulatory agency.

With a diverse stakeholder group, it is not surprising to see various types of stakeholder concerns. One of the reviewers commented that some of the stakeholder concerns, such as public awareness, seemed too general. However, public awareness could be a likely concern raised if an individual feels that every management alternative must have an education program to win his/her support. Local home owners interested in growth control may specify growth control as one of their concerns. When considering different alternatives, they will watch the effect of land use changes on the water quality, which WARMF was designed to evaluate. They can vote down alternatives that allow for too much growth and too much water quality deterioration. WARMF is open-ended and users have the ability to enter any stakeholder concern they have. The list is not limited to the default categories that were entered for the peer review version.

When we first applied WARMF to the Catawba River Basin, we envisioned a basinwide stakeholder group with representatives from both North and South Carolina. However, we found that there was no infrastructure to support such an effort. Our focus has now shifted to working with smaller community based groups (e.g. Muddy Creek Restoration, South Fork Catawba Restoration, etc.) dealing with localized issues. We are modifying WARMF to support the local groups and at the same time using WARMF to track the cumulative impacts.

Walking the River

We do not think that information gained by visual inspection of the river and application of WARMF should be mutually exclusive. WARMF can be used to calculate TMDLs to protect the river for its intended use. By walking along the river and making visual inspections, stakeholders can define fixes to meet the TMDL requirements. These two approaches complement each other.

In fact, we recommend the stakeholders form an activities committee to arrange field trips where stakeholders can gain knowledge of the river system. For example, when the stakeholders identify shellfish beds in certain parts of the river, they can come back and designate “shellfish bed” as the intended use for those river segments. The water quality criteria to protect the intended use can then be specified.

When the stakeholders identify discharge pipes along the river, they can ask the regulatory agencies about what they are and make sure that they are included in the point or nonpoint sources discharges in WARMF. In addition to obvious pollution that can be identified by naked eyes during the field trips, WARMF may include other sources of pollution that is not so obvious.

Sensitivity of parameters

Michelle Woolfolk of North Carolina Division of Water Quality pointed out that she saw an improvement in model result by replacing NPDES data from annual average to monthly values. Her statement contains 3 important messages:

1. Forcing functions and boundary conditions are driving the model. If they are not acurate, there is no way to make a good fit by adjusting model coefficients.
2. Observed data is measured in real time. WARMF is a dynamic model that simulates real time data. To be comparable, we need real time forcing functions as well (i.e. NPDES, diversions in finer time resolution).
3. WARMF predictions will improve with better data input. This is where the stakeholders can provide most significant help.

Our experience in model calibration indicates that forcing functions and boundary conditions are often more important than model coefficients. Therefore, we always place an emphasis on collecting good input data for meteorology, point source data, land use, flow diversion and fertilizer application. We have identified that the reason for not being able to predict the low flow as observed in the Truckee River system was due to the lack of accurate diversion data, rather than the errors of model coefficients or formulations.

Model limitations

At this time, WARMF cannot simulate estuaries and septic systems. But, the framework is suitable for including them in the future.

Data Quality Objective

We do not specify data quality objective to preclude any data. The purpose is to encourage people to give us all available data for the watershed. WARMF can be used to search for outliers and test whether the data is consistent with other data.

B) Systech Response to Dr. Fletcher's Comments

We reviewed the comments by Dr. Fletcher of the University of West Virginia. We are in general agreement with his constructive critique. We offer the following responses.

Uncertainty Analysis

Previously, we thought that there was no generally accepted statistical technique for the comparison of observed and simulated time series data. Besides the provision for a visual comparison, we provide WARMF with the capability to export observed and simulated values to a spreadsheet so that the users can analyze them with their own favorite statistical programs.

Many reviewers advocated for a built-in capability for statistical analyses. In year 2000, we plan to add this component to WARMF. In version 5.0, WARMF will calculate mean errors and mean absolute errors. In addition to the time series plot, WARMF will display the frequency distribution of observed and simulated values.

Regulatory Framework

Dr. Fletcher suggests that, without adequate statistical analyses, the model can never be used or defended in a regulatory framework. We might add that in an adversarial setting, statistics can be used and abused by both sides to support opposite viewpoints. Court is not the best place to judge science and WARMF is designed to help prevent this scenario.

Under the old command and control mode of operation, EPA would perform analyses and issue regulations. The regulated would challenge them in court. Under the new EPA guidelines, the TMDL decision is to be made by consensus of stakeholders, which should include all adversary parties. EPA only asks that the decision be based on good science, not on arbitrary opinions. As long as WARMF is shown to have a sound scientific basis and to match the observed data reasonably well, the stakeholders may be satisfied and willing to use it as a planning tool.

In this peer review, we are asking fellow scientists to evaluate whether the modeling framework has synthesized the current understanding in a scientifically defensible way. The fellow scientists would make such evaluations by checking the formulation against science. They would also compare the model results to the observed data. If the match is not good, they have to find out whether the source of errors is from model, data, or both.

Acid Mine Drainage (AMD)

Dr. Fletcher has raised concerns about the ability to incorporate the AMD algorithms into WARMF. This is understandable, because no information was available about the AMD results at the time of peer review.

Recently, we completed a technical report on the application of WARMF to simulate AMD for the Cheat River Basin in West Virginia. In the report, we showed how well WARMF simulated the hydrology, pH, iron, sulfate, aluminum, and manganese observed at various stations in the Cheat River. Both time series plots and frequency distribution curves were used in the comparison.

We did confirm a fear of Dr. Fletcher. When a catchment has complex land uses including very localized phenomena, we have experienced difficulties in matching the observed data. This is a limitation of all lumped parameter models.

C) Systech Response to Dr. Tracy's Comments

We reviewed the comments by Dr. Tracy of DRI, which were generally critical of WARMF. Some of the criticism is based on fundamental philosophical differences between his own methods and WARMF. Other criticism is based on misunderstandings.

Fundamental Differences

1. Dr. Tracy seems to favor a stochastic modeling approach. WARMF is a lumped parameter, mechanistic model. He said repeatedly that a large-scale integrated watershed

model is not good for calculating TMDLs. Given this opinion, it is difficult to convince him that a lumped parameter model can simulate hydrology, water quality and TMDL.

2. Dr. Tracy seems to prefer BASINS over WARMF, despite his own admission of inexperience with BASINS. The comments would be more constructive if he could give us the specific reasons. Since he does not believe in a large integrated model (such as BASINS or WARMF), one wonders if his stated preference is based largely on his greater familiarity with WARMF.
3. Dr. Tracy says that kinematic wave routing cannot account for backwater effects and is therefore not suitable for mountainous watersheds like the Truckee River basin. However, the theory behind kinematics wave routing is best suited for a mountainous watershed where backwater effects are insignificant. We cannot follow his line of reasoning.
4. Dr. Tracy thinks that we cannot put a number of equations together to make a model. We disagree. First, we did not simply slap the equations together to create WARMF. We have appropriately put the equations together for a simultaneous solution to calculate runoff and to route the flow and pollutants through soil layers, surface runoff, river segments, and lake layers. Second, we followed the Cannon law of mechanistic modeling. Science tells us that mass must be conserved. So, we write a differential equation for each parameter (quantity and quality) according to the mass conservation principle. This equation contains the mass (concentration times volume) at time t+1 on the left hand side. It also contains three terms on the right hand side, i.e. the mass at time t, sinks, and sources. The equations for flow and quality are then solved to advance the prediction for a time series output.
5. Dr. Tracy believes in including a statistical procedure to perform error analysis. We have a different idea. There are no standard statistical procedures for error estimation. Instead of a built-in statistical function, which nobody will agree upon, WARMF provides the capability to export the data into a text file. The users can then use their favorite statistical programs to perform error analysis, outside of WARMF. Perhaps, we should have said that the user is encouraged to make a visual comparison as the first step of error analysis. If there are sufficient observed values for comparison, the user should export the data to a spreadsheet for further error analysis. We do it ourselves.
6. Dr. Tracy thinks that ANSWERS is only appropriate for a disturbed watershed, and therefore not applicable to the Truckee River Basin. He favors the universal soil loss equation (USLE) instead. First of all, the ANSWERS algorithm includes USLE. Secondly, the equations for soil erosion and sediment transport include coefficients that are a function of land use (disturbed or not) and soil type, which can vary from catchment to catchment.

Misunderstandings

1. Dr. Tracy made a comparison of simulation results for a river segment at the Upper Truckee River upstream of Lake Tahoe. In our contract, which was paid for by Reno and Sparks, we were asked not to perform model calibration for the Upper Truckee River. Because of Lake Tahoe's size, we do not think it necessary to calibrate for the Upper Truckee River. Since it is not calibrated, we are not surprised that the comparison

between simulated and observed data was poor. We mentioned this during the first peer reviewer meeting, but we apologize for not making it clearer. We fear this might have tainted Dr. Tracy's overall view of WARMF.

2. Dr. Tracy said that SNOTEL data was not used. Actually, the meteorology data for Mt. Rose and Big Meadow is from the SNOTEL database.
3. Dr. Tracy indicated that he had problems running WARMF in 75% of time. It is unfortunate that he did not contact us. We could have provided technical support to help him out. Under a normal procedure, we would conduct a training workshop before turning over the WARMF CD. During the training, we would teach people how to use WARMF and how to contact us for technical support. We did not do that for the peer reviewers. To our knowledge, Dr. Tracy was the only person with so many problems running WARMF. We can understand his frustration. We hope it did not prejudice his opinion of WARMF.

Appendix 2. References for Algorithms in WARMF

During the first meeting of the peer review, Systech stated that they reviewed many models and picked the best formulations and incorporated them into WARMF. The reviewers asked Systech to provide a list of references for the source of algorithms used in WARMF. The core of WARMF comes from the ILWAS (Integrated Lake Watershed Acidification Study) model, whose algorithms are described in the ILWAS manual. This list of sources emphasizes those portions of the model simulator that use algorithms from other sources and key algorithms from ILWAS. In some cases, WARMF uses a dynamic equation for the process instead of the original steady state equation.

1. CSTR (continuously stirred tank reactor) concept was derived from:

Levenspiel, O., 1991. "Chemical reaction engineering," Wiley, New York.

Chen, C.W., 1970. "Concepts and Utilities of Ecologic Model", Journal of Sanitary Engineering Division, ASCE, Vol. 96, No SA5, pp. 1085-1907.

Chen, C.W. and G.T. Orlob. 1975. "Ecologic Simulation for Aquatic Environments", in Systems Analysis and Simulation in Ecology, Vol. III, B.C. Patten, Editor, Academic Press, New York, NY. pp. 475-588.

Ambrose, R.B., T.A. Wool, J.L. Martin, J.P. Connolly and R.W. Schanz, 1991. "WASP5x, a Hydrodynamic and Water Quality Model - Model Theory, User's Manual, and Programmer's Guide", Environmental Research Laboratory, Environmental Protection Agency, Athens, GA

2. Soil erosion and sediment transport algorithms were derived from:

Beasley, D.B. and L.F. Huggins, 1991. "ANSWERS User's Manual", Publication No. 5, Agricultural Engineering Department, University of Georgia, Coastal Plain Experiment Station, Tifton, GA.

Beasley, D.B., L.F. Huggins, and E.J. Monke,"ANSWERS - a model for watershed planning", Transaction of ASAE, 23(4): 938-944.

Meyer, L.D. and W.H. Wischmeier, 1969. "Mathematical Simulation of the Processes of Soil Erosion by Water", Transaction of ASAE, 12(6): 754-758.

Wilson, B.N., B.J. Barfield, A.D. Ward, and I.D. Moore, 1984. "A Hydrology and Sedimentology Watershed Model, Part I: Operational Format and Hydrologic Component", Transaction of ASAE, 27 (5): 1370-1377.

Wilson, B.N., B.J. Barfield, I.D. Moore, and R.C. Warner, 1984."A Hydrology and Sedimentology Watershed Model, Part II: Sedimentology Component", Transaction of ASAE, 27 (5): 1378-1384.

Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw-Hill Book Company, New York, NY, p. 96.

3. Buffer strip algorithms were derived from:

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee, 1989. "Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control", Transaction of ASAE, 32 (2): 513-519.

Landry, M.S. and T. L. Thurow, 1997. "Function and Design of Vegetation Filter Strips: An Annotated Bibliography", Bulletin No. 97-1, Texas State Soil and Water Conservation Board, Temple, Texas.

Hayes, J.C, B.J. Barfield, R.I. Barnhisel, 1984. "Performance of Grass Filters Under Laboratory and Field Conditions", Transaction of ASAE, 27 (4): 1321-1333.

Comerford, N.B., D.G. Neary, and R.S. Mansell, 1992. "The Effectiveness of Buffer Strips for Ameliorating Offsite Transport of Sediment, Nutrients, and Pesticides from Silvicultural Operations", Technical Bulletin No. 631, National Council of the Paper Industry for Air and Stream Improvement (NCASI), Inc., Research Triangle Park, NC.

Lee, D., T.A. Dillaha, and J.H. Sherard, 1989 "Modeling Phosphorus Transport in Grass Buffer Strips", Journal of Environmental Engineering, ASCE, Vol. 115 (2): 409-427.

4. AMD algorithms were based on the review of following literature:

Morth, A.H., E.E. Smith, and K.S. Shumate. 1972. Pyrite Systems: A Mathematical Model. EPA-R2-72-002, EPA Office of Research and Monitoring, Washington D.C.

The Ohio State University Research Foundation., 1971. "Acid Mine Drainage Formation and Abatement", Final Report to EPA, FWPCA Grant No. 14010 FPR.

Evangelou, V. P. 1995. Pyrite Oxidation and Its Control, CRC Press, New York.

Skousen, J. G. 1996. Acid Mine Drainage Control and Treatment. Second Edition, West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV.

Jaynes, D.B., A.S. Rogowski, and H.B. Pionke. 1984. "Acid Mine Drainage From Reclaimed Coal Strip Mines 1. Model Description", Water Resources Research, Vol. 20, No. 2, pp. 233-242.

Jaynes, D.B., H.B. Pionke, and A.S. Rogowski. 1984. "Acid Mine Drainage From Reclaimed Coal Strip Mines. 2. Simulation Results of Model", Water Resources Research, Vol. 20, No. 2, pp 243-250.

Bronswijk, J.J.B. and J.E. Groenenberg. 1993. "A simulation model for acid sulphate soils, I: basic principles", in Dent and van Mensvoort, editors, Institute for Land Reclamation and Improvement, Wageningen, the Netherlands. Publication 53, pp. 341-355.

Van Wijk, A.L.M., I.Putu Gedjer Widjaja-Adhi, C.J. Ritsema and C.J.M. Konsten. II: Validation and application", in Dent and van Mensvoort, editors, Institute for Land Reclamation and Improvement, Wageningen, the Netherlands. Publication 53, pp. 357-367.

5. Snow hydrology algorithms were derived from:

Chow, V.T., 1964. Handbook of Applied Hydrology. McGraw-Hill Book Co., New York, NY.

Corps of Engineers. 1960. "Runoff from Snowmelt", Engineering and Design Manual, EM11102-2-1406, US Army Corps of Engineers.

6. Wet and dry atmospheric deposition were based on the following references:

Fowler, D., 1978. "Dry Deposition of SO2 on Agricultural Crops". Atmospheric Environment. Volume 12, pp. 369-373.

Fowler, D., 1980. "Dry Removal of Sulfur and Nitrogen Compounds from the Atmosphere in Rain and by Dry Deposition". In Proceedings of the International Conference on the Ecological Impacts of Acid Precipitation. Sandefjord, Norway, March 11-14, 1980.

Garland, J.A., 1978. "Dry and Wet Removal of Sulfur from the Atmosphere". Atmospheric Environment. Volume 12, pp. 349-362.

Chamberlain, A.C., 1970. "Interception and Retention of Radioactive Aerosols by Vegetation". Atmospheric Environment 4:57-78.

Chen, C.W., R.J.M. Hudson, S.A. Gherini, J.D. Dean, and R.A. Goldstein. 1982. "Acid Rain Model: Canopy Module", Journal of Environmental Engineering, ASCE, Vol. 109, No. 3, pp 585-603.

Chen, C.W., S.A. Gherini, R.J.M. Judson, and J. D. Dean, 1983 "Integrated Lake-Watershed Acidification Study, Volume 1: Model Principles and Application Procedures", Final Report, Electric Power Research Institute, Palo Alto, California, EA-3221, Volume 1.

Gherini, S.A., L. Mok, R.J. Hudson, G. Davis, C.W. Chen, and R.A. Goldstein, 1985. "The ILWAS Model: Formulation and Application, Water, Air, and Soil Pollution 26: 425-459.

7. Algorithms for runoff simulation were derived from the following references:

Chen, C.W., J.D. Dean, S.A. Gherini, and R.A. Goldstein, 1982 "Acid Rain Model - Hydrologic Module". Journal of Environmental Engineering, ASCE, Vol 108, EE3: 455-472.

Environmental Protection Agency, 1992. "SWMM: Storm Water Management Model, Version 4.2", Center of Exposure Assessment Modeling, EPA, Athens, GA.

Chen, C.W. and R.P. Shubinski., 1971. "Computer Simulation of Urban Storm Water Runoff", Journal of Hydraulic Division, ASCE, Vol. 97, No. HY2, pp. 289-301.

8. Algorithms for cation exchange in soil were derived from:

Bolt, G.H., M.G.M. Bruggenwert, Editors. 1976. Soil Chemistry: A. Basic Elements. Elsevier Scientific Publishing Company, Amsterdam.

Teague, W.R. 1977. Finite-Difference Modeling of Transport and Chemical Interaction of Several Ions in Soil Solution. Ph.D. Thesis, Texas A & M University.

Dutt, G.R., M. Shaffer, W.J. Moore. 1972. Computer Simulation Model of Dynamic Bio-Physical-Chemical Processes in Soil. Technical Bulletin 196. Arizona Experiment Station, University of Arizona.

9. Algorithms for lake/reservoir stratification were derived from:

US Army Corps of Engineers. 1978. Water Quality for River-Reservoir Systems. Hydrologic Engineering Center, Davis, CA.

10. Algorithms for nitrogen species uptake by algae were derived from:

Ambrose, R.B., T.A. Wool, J.L. Martin, J.P. Connolly and R.W. Schanz, 1991. "WASP5x, a Hydrodynamic and Water Quality Model - Model Theory, User's Manual, and Programmer's Guide", Environmental Research Laboratory, Environmental Protection Agency, Athens, Georgia.

11. Algorithms for lake/reservoir outlet withdrawal were derived from:

Environmental and Hydraulics Laboratories. 1986. CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality; User's Manual. Instruction Report E-86-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

12. Kinetic expressions for various chemical and biological processes were derived from:

Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, First and Second Editions, EPA Report EPA/600/3-85/040 Environmental Research Laboratory, Athens, GA. June, 1985.

Thomann, R.V. and J.A. Mueller, 1987. Principles of Surface Water Quality Modeling and Control. Harper Collins Publishers, Inc., New York, NY.

Jorgensen, S. E. 1979. Handbook of Environmental Data and Ecological Parameters. International Society for Ecological Modeling.

13. Consensus building process was developed in part from:

South Carolina Department of Natural Resources. 1994. Catawba River Corridor Plan, September 1994.

Fisher, R., W. Ury, and B. Patton. 1991. Getting to Yes, Second Edition, Penguin Books, New York, N.Y.

Fisher, R. and D. Ertel. 1995. Getting Ready to Negotiate, Penguin Books, New York, N.Y.

Chen, C.W., J. Herr, L. Ziemelis, M. C. Griggs, L.L. Olmsted, and R.A. Goldstein, 1997. "Consensus Module to Guide Watershed Management Decisions for Catawba River Basin". The Environmental Professional, Vol. 19, pp. 75-79.

14. Cost sharing concept was developed in part from:

Podar, M.K., R.M. Kashmania, D.J. Brady, H.D.H. Herzi, and T. Tuano, 1996. "Market Incentives: Effluent Trading in Watersheds", in Proceedings of Watershed 96 a National Conference on Watershed Management, Baltimore, Maryland, June 8-12, 1996, pp. 148-150.

Hall, J.C. and C.M. Howett, 1996. "The Tar-Pamlico Experience: Innovative Approaches to Water Quality Management", in Proceedings of Watershed 96 a National Conference on Watershed Management, Baltimore, Maryland, June 8-12, 1996, pp. 151-153.

McCarthy M., R. Dodd, J.P. Tippett, and D. Harding, 1996. "Cost Effectiveness and Targeting of Agricultural BMPs for the Tar-Pamlico Nutrient Trading Program", in Proceedings of Watershed 96 a National Conference on Watershed Management, Baltimore, Maryland, June 8-12, 1996, pp. 154-156.

15. Method for uncertainty analysis was derived in part from:

Yoe, C.E., 1996. "An Introduction to Risk and Uncertainty in the Evaluation of Environmental Investments", US Army Corps of Engineers, Institute for Water Resources, Alexandria, Virginia, IWR Report 96-R-9.

Yoe, C.E., 1996. "Incorporating Risk and Uncertainty into Environmental Evaluation: an Annotated Bibliography", US Army Corps of Engineers, Institute for Water Resources, Alexandria, Virginia, IWR Report 96-R-9.

Efron, B., 1982. "The Jackknife, the Bootstrap, and Other Resampling Plans", Society of Industrial and Applied Mathematics, Philadelphia, Pennsylvania.

Efron, B. and G. Gong, 1983. "A Leisure Look at the Bootstrap, the Jackknife, and Cross-Validation", American Statisticians, Vol. 37, No.1, pp 36-48.

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Appendix 3. Sensitivity of Parameters used in WARMF

Systech separated the WARMF parameters into three categories:

1. The parameters in the sensitivity category 1 are those which have a profound effect on simulation results. These are the key parameters that we adjusted during the set up and calibration of WARMF to a river basin.
2. The parameters in the sensitivity category 2 are those which may have substantial effects on simulation results. Their parameter values may or may not be adjusted during the model set up.
3. The parameters in the sensitivity category 3 are those which may not have a significant effect on simulation results. Most likely, these parameter values are not adjusted after the model set up.

Following is a list of parameters, their sensitivity categories and the source. There are many sources of parameter values. If the source is data, it means that we have compiled and imported the site specific data from various sources in the WARMF CD. If the source is from a referenced manual/ literature, it means that the referenced manual has compiled typical values from the literature. The bibliography of references is provided in the previous section of this report.

Parameter	**Sensitivity**	**Source of parameter values**
Meteorology Parameters		
Precipitation	1	Data from NCDC
Minimum Temperature	1	Data
Maximum Temperature	1	Data
Cloud Cover	2 (lakes)	Data
Dewpoint Temperature	2	Data
Air Pressure	3 (lakes)	Data
Wind Speed	2 (lakes)	Data
Air/Rain Chemistry		
Rain Chemistry	1	Data from NADP
Air Quality	2	Data

Parameter	Sensitivity	Source of parameter values
Physical Data		
Latitude	2	Data from USGS
Longitude	3	Data
Elevation	3	Data
Watershed Area	1	Data
Wind Speed Factor	2 (lakes)	Literature / calibration
Atmospheric Turbidity	3 (lakes)	ILWAS manual
Anoxic Limit	3	Engineering estimate
Evaporation Magnitude	2	Literature / calibration
Evaporation Skewness	2	Literature / calibration
Soil Thermal Convection Factor	2	
Snow Thermal Convection Factor	3	
Ice Thermal Convection Factor	3 (lakes)	ILWAS manual / literature
Land Use Parameters		
Open in Winter	2	Engineering estimate
Cropping Factor	2	ANSWERS manual / literature
Rainfall Detachment Factor	2	ANSWERS manual
Flow Detachment Factor	2	ANSWERS manual
Fraction Impervious	2	GIS Data and engineering estimate
Interception Storage	3	ILWAS manual
Long-term Growth	3	ILWAS manual
Leaf Growth Factor	3	ILWAS manual
Productivity	3	ILWAS manual / Handbook of Environmental Data and Ecological Parameters
Active Respiration	3	ILWAS manual / literature
Maintenance Respiration	3	ILWAS manual
Dry Collection Efficiency	2	ILWAS manual
Wet Collection Efficiency	2	ILWAS manual
Leaf Weight/Area	3	ILWAS manual / literature
Canopy Height	3	Engineering estimate
Stomatal Resistance	3	ILWAS manual/ literature
Leaf Area Index	2	ILWAS manual / Handbook of Env. Data and Ecological Parameters
Annual Uptake Distribution	3	Rationale estimate
Litter Fall Rate	2	ILWAS manual / literature
Exudation Rate	2	ILWAS manual / literature
Leaf Composition	2	ILWAS manual / literature
Trunk Composition	3	ILWAS manual / literature

Parameter	Sensitivity	Source of parameter values
Snow Coefficients		
Snow Formation Temperature	2	Corps of Engineers Snow Hydrology manual
Snow Melting Temperature	2	Corps of Engineers Snow Hydrology manual
Open Area Melting Rate	2	Corps of Engineers Snow Hydrology manual
Forested Area Melting Rate	2	Corps of Engineers Snow Hydrology manual
Rain Induced Melting Rate	2	Corps of Engineers Snow Hydrology manual
Solute Fraction in Ice	3 (lakes)	ILWAS manual
Snowmelt Leaching	2	ILWAS manual
Snow Field Capacity	2	Corps of Engineers Snow Hydrology manual
Snow Nitrification	3	Zero snow nitrification is assumed
Open Area Sublimation Rate	3	ILWAS manual
Forested Area Sublimation Rate	3	ILWAS manual
Algae Coefficients		
(Algae types)	2 (lakes)	
Maximum Growth Rate	2 (lakes)	Thomann & Mueller
Respiration Rate	2 (lakes)	Thomann & Mueller
Mortality Rate	2 (lakes)	Thomann & Mueller
Settling Rate	2 (lakes)	Thomann & Mueller
Lower Temperature Limit	2 (lakes)	Literature
Upper Temperature Limit	2 (lakes)	Literature
Optimum Temperature	2 (lakes)	Literature
Chl-a/Carbon	3 (lakes)	Handbook of Env. Data and Ecological Parameters
Nitrogen Half Saturation	2 (lakes)	Thomann & Mueller
Phosphorus Half Saturation	2 (lakes)	Thomann & Mueller
Silica Half Saturation	3 (lakes)	
Light Saturation	2 (lakes)	Thomann & Mueller
Litter Coefficients		
Litter Decay Rate	2	ILWAS manual/ literature
Fine Litter Decay Rate	2	ILWAS manual
Humus Decay Rate	2	
Organic Acid Decay Rate	2	ILWAS manual
Leachable Ions: Litter	3	ILWAS manual
Leachable Ions: Fine Litter	3	ILWAS manual
Leachable Ions: Humus	3	ILWAS manual
Leachable Ions: Nonstructural	3	
Soil Nitrification Rate	2	ILWAS manual
Soil Denitrification Rate	3	
Soil Sulfate Reduction Rate	3	
Canopy Coefficients		
Foliar Nitrification	2	
Standing Biomass	3	ILWAS manual / literature
Particle Deposition Velocity	2	ILWAS manual / literature
Gas Deposition Velocity	2	ILWAS manual / literature
Gas Uptake Velocity	2	ILWAS manual

Parameter	Sensitivity	Source of parameter values
Sediment & Detritus		
Particle Size	2	ANSWERS manual / literature
Particle Gravity	2	ANSWERS manual
Settling Velocity	2	ANSWERS manual
Sediment Shading	2 (lakes)	Thomann & Mueller
Algae Shading	2 (lakes)	Thomann & Mueller
Detritus Shading	2 (lakes)	Thomann & Mueller
Detritus Settling	2 (lakes)	
Detritus Decay	2 (lakes)	
Pesticides		
Decay Rate: Trees	2-3	Literature value for chosen pesticides
Decay Rate: Land	2-3	Literature value for chosen pesticides
Decay Rate: Water	2-3	Literature value for chosen pesticides
Minerals		
(Mineral Types)	2	
Molecular Weight	2	ILWAS manual /measured
Weathering Rate	2	ILWAS manual / measured
pH Dependence	2	ILWAS manual
Oxygen	2	Chemical reaction stoichiometry for each mineral
Reaction Product	2	ILWAS manual / measured

Parameter	Sensitivity	Source of parameter values
Physical Data		
Area	1	DEM data from USGS
Aspect	2	DEM data from USGS
Slope	1	DEM data from USGS
Width	1	DEM data from USGS
Detention Storage	3	Zero by default / calibrated
Surface Roughness	3	ILWAS manual / literature
Meteorology		
Meteorology File	1	Data from NCDC
Precipitation Weighting	1	Estimated / calibrated
Average Temperature Lapse	2	Estimated / calibrated
Altitude Lapse	2	Estimated / calibrated
Land Use		
Land Use	1	Data from BASINS and local agency

Parameter	Sensitivity	Source of parameter values
Erosion		
Soil Erosivity Factor	2	NRCS soil data
Primary Clay	2	NRCS soil data
Primary Silt	2	NRCS soil data
Primary Sand	2	NRCS soil data
Irrigation		
(Irrigation Files)	2	Data from Irrigation District
Fertilization		
(Loading Rates)	2	NRCS
Buffer Zone		
Percent Buffered	2	GIS data / estimated
Width	2	GIS data / estimated
Slope	2	GIS data / estimated
Roughness	2	GIS data / estimated
Soil Coefficients		
Number of Soil Layers	1	Data / estimated
Hydrology		
Area	1	Data
Thickness	1	Data
Initial Moisture	2	Estimated
Field Capacity	1	ILWAS manual / literature / calibrated
Saturation Moisture	1	ILWAS manual / literature / calibrated
Horizontal Conductivity	1	ILWAS manual / literature / calibrated
Vertical Conductivity	3	ILWAS manual / literature / calibrated
Root Distribution	2	Data/ estimated
Tortuosity	3	
Density	3	
Solution		
Initial Temperature	3	Estimated
Initial Solution Concentration	2	Estimated
Adsorption		
Cation Exchange Capacity (CEC)	2	Data / estimated
Initial Adsorbed Concentration	2	Data / estimated
Mineral Composition		
(Mineral Composition)	2	Data / estimated

Parameter	Sensitivity	Source of parameter values
TIC (Total Inorganic Carbon)		
Option	1	Atmospheric equilibrium is normal option
Factor	3	
Mining		
Bottom layer is deep mine…	1	Data
Bottom layer is surface mine…	1	Data
Area	1 or 3	Data
Thickness	2-3	Data / estimated
Initial Moisture	2-3	Data / estimated
Field Capacity	2-3	Data / estimated
Saturation Moisture	2-3	Data / estimated
Horizontal Conductivity	2-3	Data / estimated
Vertical Conductivity	3	Data / estimated

Parameter	Sensitivity	Source of parameter values
Physical Data		
Upstream Bed Elevation	2	DEM data
Downstream Bed Elevation	2	DEM data
Length	2	DEM data
Initial Depth	3	Estimated
Manning’s N	2	Literature / Hydrology Text Books
Stage-Width Curve		
(Stage-width Curve)	2	Data / estimated
Diversions		
Diversions From	2	Data
Diversions To	2	Data
Point Sources		
(Point Source Files)	2	Data
Water Source	2	Data
Unspecified Constituents	2	Data
NPDES Permit	3	Data
Reactions		
Aeration Factor	2	
SOD	2	
Organic Carbon Decay Rate	2	
Nitrification Rate	2	
Sulfur Reduction	3	
Coliform Decay	2	Thomann & Mueller
Convective Heat Factor	2	

Parameter	Sensitivity	Source of parameter values
Sediment Transport		
Detachment Velocity Multiplier	2	Estimated / literature
Detachment Velocity Exponent	2	Estimated / literature
Initial Sediment Depth	2	Data / estimated
Primary Clay	3	Data / estimated
Primary Silt	3	Data / estimated
Primary Sand	3	Data / estimated
Initial Concentrations		
(Initial Concentrations)	3	Data / estimated

Reservoir Coefficients apply to lakes/reservoirs and also affect simulations results in downstream rivers and lakes.

Parameter	Sensitivity	Source of parameter values
Physical Data		
Initial Water Surface Elevation	1	Data
Minimum Surface Elevation	1	Data
Maximum Surface Elevation	1	Data
Outlets	1	Data
Outlet Elevation	2	Data
Outlet Width	2	Data
Outlet Type	1 or 3	Data
Outflow File	1	Data
Meteorology		
Meteorological File	1	Data
Precipitation Weighting	1	Estimate / calibrated
Average Temperature Lapse	2	Estimate / calibrated
Radiation Fraction Absorbed	2	
Depth of Radiation Fraction	2	
Secchi Disk Depth	2-3	
Diffusion		
Inflow Entrainment	3	Estimated
Min. Negative Density Gradient	2	WQRRS manual / literature
Wind Mixing Diffusion Coefficients		
Minimum Diffusion Coefficient	2	WQRRS manual / literature
A1	2	WQRRS manual
A2	2	WQRRS manual
Maximum Diffusion Coefficient	2	WQRRS manual

Parameter	Sensitivity	Source of parameter values
Density Gradient Diffusion Coefficients		
Critical Density Gradient	2	WQRRS manual
Maximum Diffusion Coefficient	2	WQRRS manual
Diffusion Attenuation Exponent	2	WQRRS manual
Stage-Flow Curve		
(Stage-flow Curve)	1	Data
Stage-Area Curve		
(Stage-area Curve)	1	Data
Point Sources		
(Point Source Files)	2	Data
Water Source	2	Data
Unspecified Constituents	2	
Outlet Elevation	2	Data
Outlet Width	2	Data
NPDES Permit	3	Data
Initial Temperature		
(Initial Temperature Profile)	2	Data / estimated
Reactions / Sediment		
Nitrification	2	Literature
Denitrification	3	
Organic Carbon Decay	2	
Sulfur Reduction	3	
Fecal Coliform Decay	2	
SOD	2	
Thickness	3	
Bulk Density	3	
Percent Organic	3	
Porosity	3	
Diffusion	3	
Detritus Decay	3	
DOC Decay	3	
Initial Concentrations		
(Initial Concentrations)	2	Data / estimated