Methodology for Developing Sediment TDMLs Using WARMF

Technical Report

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REPORT SUMMARY

This report presents a methodology for doing clean sediment total maximum daily loads (TMDLs) using EPRI's Watershed Analysis Risk Management Framework (WARMF). This report will be valuable to industry, agriculture, environmental organizations, and government agencies involved in managing and protecting watershed resources and water quality criteria.

Background

Sediment is one of the more frequently listed contaminants of impaired water bodies. The U.S. Environmental Protection Agency (USEPA) has published a protocol for developing sediment TMDLs. In the protocol, USEPA discusses empirical estimation methods that require little data. These estimation methods often use very conservative assumptions and, hence, result in large margins of safety that can make implementation more costly than necessary or, possibly, infeasible. However, the USEPA protocol recognizes the weaknesses inherent in a situation where little data is available and endorses, under such circumstances, a phased approach. In the first phase, empirical methods are used to provide an initial analysis. This first phase evaluation then becomes the basis for new data collection and further analyses. With more data available, a more sophisticated modeling tool may be used to reduce uncertainties and create a smaller margin of safety.

Objectives

To develop a methodology for sediment TMDLs that reduces uncertainties, margins of safety, and implementation costs.

Approach

Based on prior application of WARMF, the project team examined how to tune USEPA's sediment TMDL methodology to produce smaller margins to safety. The team first reviewed sediment TMDLs and the USEPA protocol. By using a science-based model, collecting more wet weather data, and applying a jackknife-based simulation technique, the team then examined the value of using a phased TMDL approach to reduce uncertainties and margin of safety. The methodology is illustrated with the case study of Muddy Creek watershed in North Carolina.

Results

The report recommends a methodology for sediment TMDLs that complements the existing USEPA protocol. The new methodology uses a phased TMDL approach, a sophisticated science-based model (WARMF), increased wet weather sampling, and a jackknife-based simulation technique. The result is an anticipated reduction in uncertainty, and margin of safety, and increase in implementation efficacy and cost efficiency. The methodology is complementary to the USEPA protocol for developing sediment TMDLs.

EPRI Perspective

TMDLs will strongly influence water resource regulations and policy for at least the next two decades. They also will have major implications for air pollution and land use regulations and policy. In 2002, the states identified over 52,000 impairments of water bodies, each requiring a TMDL. Sediment is one of the more frequently listed impairments. TMDLs affect the electric power industry both through the industry's role as a point source of contaminants directly discharged to water bodies and a nonpoint source via both atmospheric deposition of substances such as nitrogen and mercury and runoff from facilities and rights-of-way. TMDLs also affect the industry by impacting its business and residential customers and, therefore, the demand for electricity.

Keywords

USEPA TMDL protocol
Sediment TMDL
Margin of safety
Wet weather sampling
Jackknife method
WARMF

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Many of the wet weather sampling techniques and laboratory procedures, discussed in this report, were used in the Muddy Creek Watershed Restoration Initiative Project of North Carolina. Drs. Bill Foris and Larry Olmsted of Duke Energy Company have been instrumental in developing and applying the techniques.

We also wish to thank Tim Lohner, American Electric Power, for his encouragement and advice.

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INTRODUCTION

Sediment TMDLs

Sediment is only second to coliform as the leading cause for the 303d listing of quality impaired waters in the United States. By law, it is necessary to determine the total maximum daily load (TMDL) of sediment that can be discharged to a water body without violating the water quality standards for its designated uses. An implementation plan for the TMDL must also be developed through a stakeholder consensus process.

There are two classes of sediment TMDLs. The TMDL for clean sediment deals with excessive suspended sediment that affects the beneficial uses. Fish need water clear enough to see prey. Siltation may bury the larvae of invertebrates and the gravel of fish spawning habitat. The beneficial use of water supply may be impaired by sediment accumulation in water supply reservoir and by higher treatment cost for filtration. Water can become turbid for recreation/aesthetic enjoyment such as swimming and river rafting. For agricultural uses, the sediment-laden water can foul pumps and become unsuitable for livestock to drink. For industrial uses, it may raise the treatment cost for cooling and process waters.

The TMDL for contaminated sediment deals with excessive pollutants adsorbed to suspended sediment and settled to the bottom of rivers, lakes, and estuaries. The pollutants include trace metals, PCBs, pesticides, and mercury. These pollutants are very persistent and toxic to benthic invertebrates and bottom dwelling fishes. These pollutants can also be mobilized and accumulate through the food chain to fish, mammals and birds. The incidence and severity of sediment contamination in surface waters of the United States have been documented in three volumes of EPA reports to the Congress (EPA 1997a, EPA 1997b, and EPA 1997c).

U.S. EPA (1999a) has issued a protocol for developing sediment TMDLs. The protocol provides an overall framework for completing the technical and programmatic steps in the TMDL development. The protocol advocates the use of various methodologies in a phased approach. Initially, one may use a simple method of estimation that requires little data. Eventually, a more sophisticated method can be used with intensive data for a more definitive answer.

The protocol suggests that simple methods may use conservative assumptions and a large margin of safety, which can lead to an infeasible TMDL plan. The more sophisticated methods may have a smaller margin of safety for a more feasible alternative.

For more than 10 years, the Electric Power Research Institute has sponsored the development of Watershed Analysis Risk Management Framework (WARMF) for TMDL analysis (Chen, Herr, and Ziemelis 1998 and Chen, Herr and Weintraub 2001). WARMF has previously been used in the sediment TMDL analysis of Oostanaula Creek, Tennessee (Herr et al. 2002). It has also been used to determine measures to reduce total suspended sediment concentration for 30 kilometers of Muddy Creek (North Carolina) (Chen et al. 2005) and the best management practices (BMPs) needed to meet the water quality standards (nutrients and turbidity) of eight coves in Lake Wylie (North Carolina) that receive storm water runoff from a proposed land development project of Palisades gulf course community (Chen and Loeb 2003).

It appears that WARMF can qualify as the sophisticated tool referred to in the EPA protocol for developing sediment TMDLs.

Scope and Objective

The objective of this research is to describe the methodology of developing sediment TMDLs using WARMF. The scope of work will be limited to the TMDLs of clean sediment, which is addressed by the EPA protocol. It is felt that the current version of WARMF can address the TMDL of clean sediment adequately. The Muddy Creek application in North Carolina can be used as a case study to illustrate the methodology.

Clean sediment will include natural organic matter that can be transported and decayed to create low dissolved oxygen condition in the receiving water. It will also include phosphorous adsorbed to suspended sediment and transported to surface water, where it may stimulate periphyton and phytoplankton growth that supersaturates dissolved oxygen in daytime and depletes dissolved oxygen at night.

While the TMDL of contaminated sediment is important, it is not addressed in this report. It was felt that the subject matter is so complex that it deserves a separate report. Most of the contaminated sediments are subject to the superfund clean up program, which involved dredging, capping, and other treatment techniques beyond the scope of TMDL analysis (Ancheta 1997). Also, WARMF has not been applied to a site for the TMDL of contaminated sediment that can be used to illustrate the methodology.

Given opportunities, WARMF can be applied to address a number of issues for contaminated sediments. WARMF already has the capability to include chemical species such as copper, PCBs, pesticides as simulated parameters. It can simulate the adsorption of contaminants to suspended sediment, the sediment contaminant concentrations of rivers and lakes, and the bioaccumulation of contaminants in zooplankton, benthos, and fish through the food web. The model coefficients are available for PCBs, dioxins, and dibenzofurans (Rice, O'Keefe, and Kubiak 2003), pesticides (Blus 2003), and other pollutants (Pitt 2003). The coefficients can be adjusted for the model predictions to match the wet weather data during the model calibration.

After calibration, WARMF can be used to determine the amount and timing of pesticide applications to meet the water quality standard. WARMF can also be used to simulate the nonpoint load of PCBs from the landfill and the transport and fate of PCBs in the receiving water. WARMF can calculate the time required for the contaminated sediment to recover itself to acceptable level through the natural processes of resuspension and dispersion of contaminated sediment (Thornburg and Garbaciak 1997). Chen, Leva, and Olivieri (1996) have used a similar approach to determine the recovery rate of copper already deposited in the sediment of San Francisco Bay, after the waste minimization program to reduce the illegal copper discharges to the sewerage system by industries.

Technical Approach

The EPA protocol provides a step-by-step process for developing TMDLs of clean sediment. We will show how each of the steps can be carried out using WARMF.

As indicated in the EPA protocol, a sophisticated method requires intensive data. Sediment data is often lacking due to the fact that sediment transport occurs during the storms and water quality samplings are often taken on clear days. Our past experience indicates that WARMF predicted total suspended sediment concentrations during the storms to be higher than those collected in clear days. Without the TSS data for the storms, there is no way to ascertain the accuracy of model predictions.

The margin of safety (MOS) is very important for developing a TMDL implementation plan that is reasonable, implementable, and not delayed by lawsuits. The MOS can be reduced by increasing the accuracy of model predictions. To improve model predictions, it is important to collect field data during storms. Some simple techniques for wet weather sampling will be discussed in this report.

2
EPA PROTOCOL FOR SEDIMENT TMDL

EPA Protocol

The EPA protocol provides technical guidance to help state, interstate, territorial, tribal, and federal agency staff as well as stakeholders develop sediment TMDLs to meet the “fishable and swimmable” goal of the Clean Water Act. The stated purpose of the protocol was to assist with the development of rational, science-based assessments and decisions that would lead to the establishment of an understandable and justifiable TMDL. It was emphasized that the protocol represented a suggested approach, but not the only approach to TMDL development. The responsible agency can adopt approaches that differ from the protocol where appropriate.

Figure 2-1 presents the general framework for TMDL development (EPA 1991, EPA 1997c, EPA 1999b). This framework was adopted for sediment TMDL though it is applicable to all pollutants. The framework shows the tasks to be performed on the left hand side column and the products on the right-hand side column. Each task produces a document for the results of analyses performed. When they are completed, the documentations for all tasks can be assembled into a final TMDL report that comprises all the necessary elements of TMDL.

The protocol only provides guidance for the technical aspects of the TMDL development. The subject of public participation was excluded even thought EPA recognized the importance of public participation in TMDL development.

Analytical Approaches

EPA recognized that the development of sediment TMDL is a problem solving process to which no “cookbook” approach can be applied. A combination of monitoring and modeling may be needed.

Availability of data will influence the analyses to be performed and models to be used. For that reason, EPA will accept a phased approach. Initially, screening level approaches based on limited data may be used. The analyses may provide qualitative assessment and result in a monitoring and evaluation plan. When new data are collected, detailed investigations with rigorous modeling techniques may be undertaken for a more definitive answer. But, the protocol did not provide any guidance on data collection.

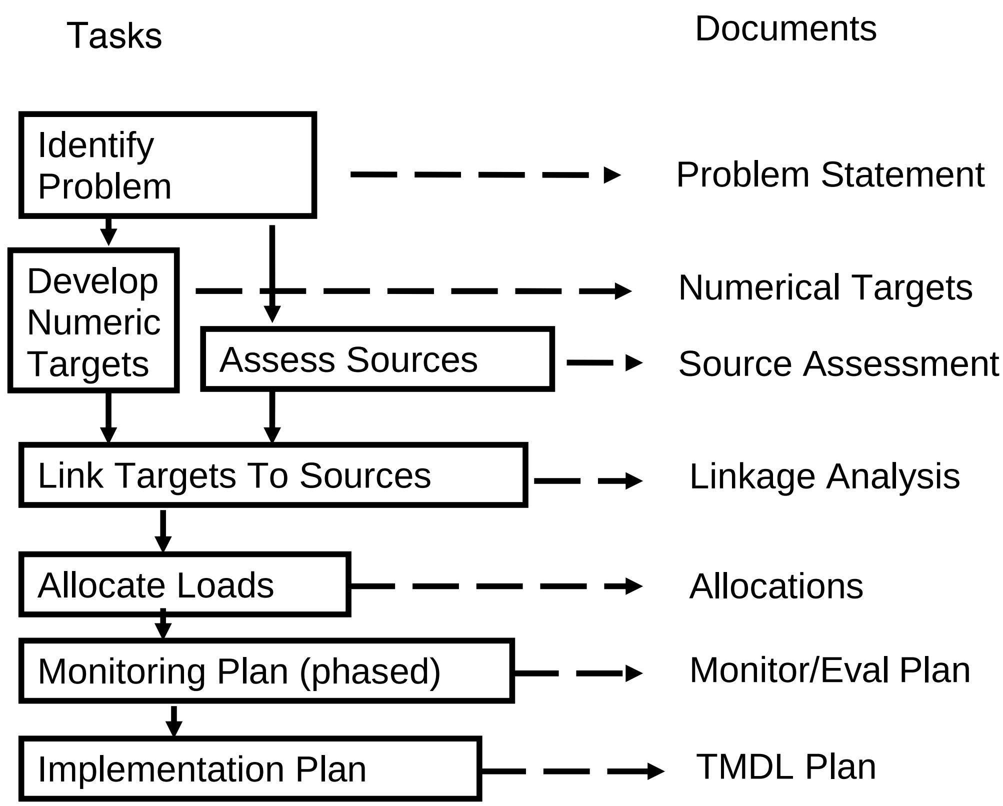

Figure 2-1
General Framework for TMDL Development

The protocol used nine case studies to illustrate a wide range of analytical techniques for developing sediment TMDLs. Most of the case studies used simple approaches for screening level analyses. None of them used rigorous modeling techniques.

The advantages of simple approaches are 1) limited data requirements, 2) easy to understand, 3) low cost, and 4) incorporation of local experts' opinions. The disadvantages are: 1) low predictive accuracy, 2) inability to make predictions at fine geographic and time scales, 3) uncertainty in predicted improvements, 4) high margin of safety, 5) high cost of TMDL plan that cannot be implemented, and 6) may be subjected to more law suits.

The time scale issue is very important, because most methods of estimation can provide only annual loads. The average annual loads cannot be linked to high sediment concentrations which occur during storms. Also, sediment problems are very site specific, which was acknowledged in the EPA protocol. Due to lack of data, simple approaches may rely on information from outside of the study area. These assumptions can readily be challenged by lawsuits.

The advantages of detailed approaches using rigorous models are: 1) higher predictive accuracy and greater spatial and temporal resolution, 2) a good match of the model predictions to the observed data can translate to greater stakeholder "buy-in", 3) smaller margin of safety, 4) more management alternatives to evaluate, 5) more definitive answer on predicted improvement, and 6) lower cost TMDL alternative that can be implemented. The rigorous approaches do not exclude the input of local expert opinions. The results are no less understandable to stakeholders, provided that the results are explained in a rational and logical manner. The disadvantages of detailed approaches are the cost and time required to complete the TMDL development.

As a practical matter, the stakeholders may need to make trade-offs between simple and rigorous approaches. The rigorous approach requires a front end investment of money and time for the study that may result in a better implementation plan at a lower cost. The less precise analysis has a lower front end cost but a higher margin of safety and a higher cost of implementation at the end.

TMDL Elements

The EPA protocol for TMDL development covers several elements. The elements include problem identification, development of numerical targets, source assessment, linkage of targets and sources, allocation of loads among sources, development of monitoring and review plans, development of an implementation plan, and assembly of a TMDL document.

The guidance document provides good information on how to identify sediment problems, how and where to gather published or unpublished information, key questions to consider in formulating the problem, and the content of a problem identification document. It even includes an example of how an error occurred in the problem definition in a TMDL project.

The section on the identification of water quality indicators and target values also provides good information about key questions to consider and how to obtain information to address them. A variety of factors can be used as end points for TMDL calculations, including the water column TSS or turbidity, the sediment yield from watershed land, the streambed fine sediment, and biological and habitat indicators. The biological and habitat indicators are quantitative in terms of numerical values, however, they are difficult to use as the end points for a TMDL. The protocol discusses the need for integrated assessment to relate biological and habitat indicators to physical and chemical parameters, which can be used as end points for a TMDL. The predicted physical and chemical indicators of habitat can then be used to estimate the expected improvement in biological and habitat indicators.

The section on source assessment provides good information about the tools to use. They include analyzing existing monitoring information, aerial photography analysis, simple calculations, and spreadsheet analysis using empirical models. Some erosion process models were suggested for application to determine the magnitude of landscape erosion. Many of the mentioned models cannot handle the fate and transport of sediment in the river after delivery from the landscape. The protocol cautioned that such models worked well for sheet flow erosion from relatively low-sloped lands. They may not be applicable to the landslide dominated erosion in steep-sloped lands. The protocol also discussed the problems of using direct measurement methods and rating curves and other statistical extrapolation methods. The motto is that source loading of sediment is very complex and the protocol only provides cursory evaluations, which should only be the starting point for further evaluation.

The protocol lists a large number of models (e.g. USLE/RUSLE, AGNPS, BASINS-NPSM, WATSED, BOISED, WEPP, HSPF, and SWAT) that can be used for source assessment. Many of them are research models developed by U.S. Department of Interior for agricultural watersheds. They are not necessarily designed for practical applications. Many features of those research models have been incorporated into SWAT, which stands for soil water assessment tool (Arnold et al. 1998 and Srinivasan et al. 1998). SWAT is now a model in EPA BASINS for TMDL development. BASINS stands for Better Assessment Science Integrating Point and Nonpoint Sources (USEPA 2001). The other model in BASINS is HSPF, which stands for Hydrologic Simulation Program Fortran (Bicknell et al. 1993). HSPF has a lineage with Stanford Watershed Model (Crawford and Linsley 1966).

WARMF stands for Watershed Analysis Risk Management Framework developed by the Electric Power Research Institute (Chen, Herr, and Weintraub 2001). WARMF has a lineage with SWMM (Chen and Shubinski 1971) and ILWAS (Chen, et al. 1983 and Gherini et al. 1985). WARMF is currently under revision for release as a public domain model to be included in BASINS. So, there are three watershed models for source assessment discussed in the protocol.

The section on linkage between water quality targets and sources provides information about various techniques for linkage analysis, including process modeling, empirical correlation, inference from index, and multiple indicators and multiple source assessment. The process modeling by far is the best, particularly if the model can be shown to match the monitoring data. The process models can not only predict how the current source of pollution relates to existing water quality conditions, but also how a proposed implementation plan may help improve the water quality to meet the criterion for designated uses of the water body.

The protocol provides a section for waste load allocations. It does not provide a section for the development of an implementation plan. In principal, the waste load allocations determine what waste load reductions are needed in order to meet the sediment criteria. The implementation plans determine what best management practices to use in order to reduce the waste loads to the allocated amounts. For waste load allocations, a margin of safety is very important. For implementation plans, the scientific assurance of success and political acceptance of stakeholders are very important. The protocol did not provide specific guidance on how to reduce the margin of safety nor how to engage stakeholders in the participatory decision making process.

The section on follow-up monitoring evaluation provides guidance on how to conduct monitoring to validate and evaluate the adequacy of the TMDL plan. A monitoring program includes 1) the specification of the locations and times of sampling; 2) field and laboratory techniques and personnel; 3) quality assurance protocols, 4) a data management plan, and 5) a data interpretation plan. The data can be used 1) to determine the improvement made on sediment quality; 2) to check whether all BMPs are installed; and 3) to assess whether the source controls had achieved the desired effect.

The section on assembling the TMDL provides guidance on the format and content of the TMDL document. This will ensure that all information is provided to EPA for their approval of the TMDL plan.

Summary

The EPA protocol provides guidance for developing a rational and science-based TMDL of clean sediment. It does not address the TMDL of contaminated sediments. It covers only the technical issues, not the political issues of stakeholder involvement.

The example case studies used simple analytical tools based on limited existing data. The approaches may not provide predictions with spatial and temporal resolution needed. The assumptions made can be subject to court challenges by lawsuits. The conservative assumptions and large margin of safety may lead to a high cost implementation plan. No guidance was provided on how to collect supplemental new data that might improve the TMDL analysis and reduce the margin of safety.

It is advisable to follow the general approach outlined in the EPA protocol. However, additional methodologies are needed to address the issues not covered in the EPA protocol.

3
METHOD FOR REDUCING MARGIN OF SAFETY

Margin of Safety

A sediment TMDL is defined as the total daily waste loads of sediments that can be discharged into the upstream of a water quality limited section before violating its sediment criteria. The law requires that a margin of safety must be provided to account for uncertainty about the relationship between pollutant loads and receiving water quality. The mathematical equation for TMDL is:

$$TMDL = \sum WLA + \sum LA + MOS$$ **Equation 3-1**

Where TMDL = mass of pollutant per day; WLA = wasteload allocation to existing and future point sources; LA = allocation to nonpoint sources of pollution; and MOS = margin of safety. The margin of safety can be expressed explicitly as a factor of the allocated loads:

$$MOS = \alpha \sum WLA + \beta \sum LA$$ **Equation 3-2**

Where α and β = safety factors. Substituting Equation 3-2 into Equation 3-1 results in:

$$TMDL = (1+\alpha)\sum WLA + (1+\beta)\sum LA$$ **Equation 3-3**

The larger the uncertainty of the relationship between pollution loads and receiving water quality, the larger the safety factors must be used. Larger safety factors result in smaller WLA and LA, higher load reduction needed to meet the water quality criteria, and higher cost of TMDL implementation plan.

For sediment TMDL, the sediment loads are mostly from nonpoint sources. The TMDL may be reduced to the equation below:

$$TMDL = (1+\beta)\sum LA$$ **Equation 3-4**

Method to Reduce MOS

The values of safety factors (α and β) depend on method used to describe the load and water quality relationship. As indicated in the EPA protocol, empirical methods of estimation use conservative assumptions, which result in a smaller TMDL to begin with. Empirical methods are thought to be less reliable, larger safety factors may be needed. The compound effect leads to a very large load reduction requirement.

If a rigorous science-based model is used for the load and water quality relationship, the model simulates the necessary physical and chemical processes to account for multiple factors interacting to affect water quality. There is no place for conservative assumptions in the model. Since the model predicts the water quality condition that can be compared to the observed data, the accuracy of the relationship can be ascertained. If the model predictions can be shown to match the observed values, the stakeholders are more willing to accept the model results. If an uncertainty analysis of the model is performed, a much smaller safety factor may be accepted by the regulatory agency and the stakeholders.

Thus, there are three key ingredients for a smaller margin of safety and reasonable TMDL. They are the use of a science based model, accurate prediction of observed data, and rigorous uncertainty analysis of the model.

Science Based Simulation Model

In this report, the plan is to use WARMF as the science-based simulation model. WARMF includes a GIS-based dynamic watershed model. The size of the river basin is flexible. WARMF has been applied to the 3,260 $mile^2$ Truckee River Basin (California and Nevada), the 320 $mile^2$ Dillon Reservoir Watershed (Colorado), the 5,000 $mile^2$ Catawba River Basin (North and South Carolinas), the 4,000 $mile^2$ Western Lake Superior Basin (Minnesota), the 20,000 $mile^2$ San Juan River Basin (New Mexico, Colorado, Arizona, Utah), and the 10 $mile^2$ Mica Creek Watershed (Idaho).

The model delineates a river basin into land catchments, river segments, and lake layers. The spatial resolution of the delineation can be as fine as needed. Land catchments can have various land uses on the surface and up to five soil layers below the ground. The soil layers and river segments form a series of control volumes, which are modeled as continuously stirred tank reactors (CSTR) to facilitate the mass balance calculations for water and pollutants, similar to the WASP5 model of USEPA.

WARMF simulates snow hydrology, soil hydrology, and river hydrology. The water is routed from the surface soil layer to the bottom soil layers and as lateral flow to downstream river segments. The model calculates soil moistures of each soil layer during every time step. The soil moisture controls the infiltration rate. When the soil layers become saturated, surface runoff occurs. The river segments accept surface runoff and groundwater lateral flow from land catchments. The river flow is routed from upstream segment to downstream segment. The river flow can be routed to lake layers of same the temperature (density). Lake stratification is simulated, and lake outflows are routed to their downstream river segments.

WARMF simulates sediment transport processes to calculate the total suspended sediment concentrations of sand, silt and clay fractions. Surface runoff is used to calculate soil erosion from land surface. The sand fraction moves as a bed load, and can be re-deposited to the land surface depending on flow velocity. Silt and clay are transported to the stream segments. If a buffer strip is present along the flow path, the model simulates the settling process to remove some of the sediment and its adsorbed ions before emptying the remainder to the river segments. River bank erosion, settling to riverbed and bed erosion are also simulated.

Clearly, WARMF can simulate the physical processes of sediment transport. The outputs can be used to judge whether the total suspended sediment concentration in water column meets the sediment criteria, whether the settling flux leads to clogging of gravel in the riverbed, whether scouring of the river bed is harmful to fish spawning ground, and whether sediment yield from watershed fills up the water supply reservoir too fast.

The strength of WARMF is that it has a strong scientific basis. Many of its formulations are taken from the best algorithms used in well known models (e.g. SWMM, WASP5, QUAL2, ILWAS, ANSWERS, etc.). The WARMF model formulations and users' manual have been documented (Chen, Herr, and Weintraub 2002; Herr, Weintraub, and Chen 2002) and peer reviewed for TMDL analysis under the USEPA guidelines (Keller 2000, Keller 2001, Driscoll et al. 2004). Papers for site specific applications have been published (Herr et al.2001, Chen et al. 2005).

Accurate Prediction of Observed Data

The output of WARMF can directly be compared to observed data so that the accuracy of the model predictions can be ascertained. The "weight of evidence" approach is used for more instructive model to data comparisons. This approach utilizes various qualitative and quantitative techniques to analyze the comparisons from different angles.

WARMF provides time series plots to qualitatively determine whether the model predictions are capturing the magnitudes, trends, and patterns seen in the observed values. WARMF provides three statistics (mean relative error, root mean square error, and correlation coefficient) to quantitatively compare the data pairs (model predictions vs. observed values) of the time series at each station. The frequency distributions of observed and simulated values of a station are plotted by WARMF to determine whether model predictions are in the same range of the observed values, irrespective of their timing.

A number of simulations are run to tune the model predictions to the observations. These measures minimize the difference between predictions and observations.

Uncertainty Analysis with Jackknife Simulation

WARMF is a dynamic watershed model with multiple parameters. It is not suitable for the Monte Carlo simulations without a major modification of the computer code. A Jackknife simulation technique has successfully been adapted for the uncertainty analysis of WARMF.

The Jackknife technique has been described in the WARMF document (Chen, Herr, and Weintraub 2002). The procedure specific to sediment TMDLs is as follows. The model is first calibrated by adjusting model coefficients to minimize the difference between model predictions and observed data as described above. After the calibration, a sensitivity analysis is performed by adjusting various model coefficients (e.g. erosivity of soil, critical shear stress for scouring, settling velocity, bed load carrying capacity of sand) up and down 20%, one parameter at a time. The percent change of output variables (e.g. total suspended sediment concentration, sediment yield) with respect to the change of model coefficients are ranked to select 3 to 5 most sensitive parameters. A Jackknife table is prepared for possible simulation cases; each represents a permutation of the parameter values (average-20%, average, average +20%). WARMF performs the simulation for one case at a time. The results are analyzed for the statistical spread of predicted values.

Supplemental Wet Weather Sampling Program

To reduce the margin of safety, it is necessary to demonstrate that the model predicts the observed. This cannot be demonstrated without observed data. Yet, observed data for total suspended sediments are often lacking because the sediment transport occurs during storms but most samples are taken in dry days. For that reason, WARMF often predicts high total suspended sediment concentrations for the raining days, not comparable to the data collected on dry days.

Sediment data can be collected inexpensively by a supplemental wet weather sampling program. Such a program can be carried out during the TMDL study. The short term intensive sampling of storm events can meet the needs of WARMF, unlike the empirical methods that rely on annual data, which take several years to collect.

The wet weather sampling program must first determine the number of monitoring stations and their locations. In general, the monitoring stations must be set up upstream and downstream of water quality limited sections for sediment TMDL analysis. Professional judgment may be required to select the stations that can meet the technical requirement and the budget constraint.

The data to be collected include stream flow and total suspended sediment concentration for each station. The flow stage, cross sectional area and current velocity are measured to establish the rating curve. The flow stage can be measured by the back pressure of nitrogen bubble introduced to the river. The current velocity can be measured with modern Acoustic Doppler Profiler (ADP) or Acoustic Doppler Velocimeter (ADV). The instruments for continuous recording of flow stage and current velocity are available at a reasonable price from many vendors. A local U.S. Geological Survey office should be contacted for information about how to set up and calibrate those instruments.

Water samples taken during storm events can be collected with a single stage sampler shown in Figure 3-1. This sampler for suspended sediment was designed by the Inter-Agency Committee on Water Resources (1961).

The single stage sampler can be home made with milk bottle, copper tubing, and rubber stoppers. Two copper tubes are bent into a gooseneck shape and are secured to the sample bottle through two holes of the rubber stopper, as shown in Figure 3-1. The sampler is mounted on a post hammered into the riverbed. As the river stage rises above the top of the lower gooseneck, a siphon is created to fill the sample bottle with the river water. The air escapes through the other tube. When the water in the sample bottle reaches the lower opening of the second tube, the air cannot escape, which stops the water filling operation. By adjusting the relative elevation of the two tubes inside the sample bottle, one can control when to start and when to stop the water filling operation.

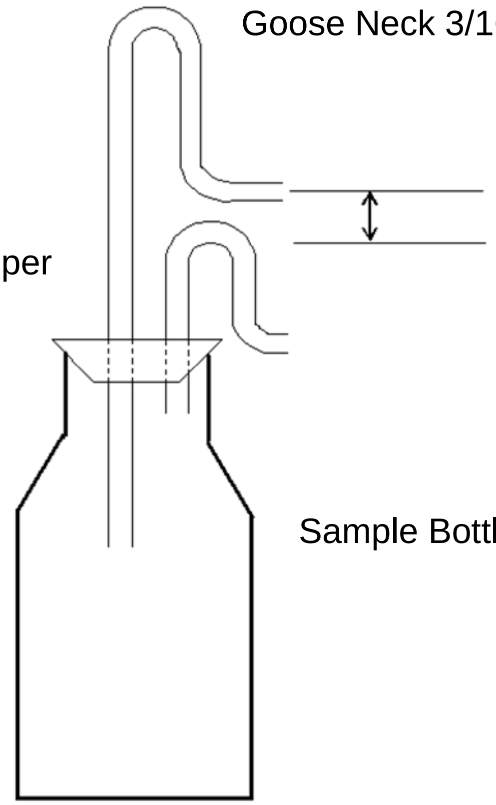

Figure 3-1
Single Stage Sediment Sampler

The single stage sampler collects water in the rising limb of the hydrograph. It does not collect water during the hydrograph recession. During the study for the Muddy Creek Watershed Restoration Initiative of North Carolina, Dr. Bill Foris and Mr. Dave Braatz of Duke Energy Company mounted multiple single stage samplers at different elevations on a post, shown in Figure 3-2. This enabled them to collect samples for multiple stages with the single stage samplers. The water samples were collected one day after the storm event. There is no record of the exact time, when the bottles were filled.

The water samples are retrieved for the laboratory analysis of total suspended sediment (TSS) concentration. The conventional laboratory procedure is to filter the sample, dry and weigh the solids retained on the filters. Because of the high TSS concentrations in the water samples collected during the storm events, it is not possible to filter the water sample in full strength. Dilution of sub-sample for filtration is commonly practiced in the laboratory analysis. Such practice must be performed carefully to ensure the soil particles are in suspension during the sub-sampling process. Foris, Rodriquez, and Davis (2002) found that sub-sampling represented a source of errors due to the difficulty in retaining large size particles in suspension during sub-sampling.

Figure 3-2
Multiple Single Stage Samplers Mounted on a Post for Sediment Sampling

TSS is expressed in concentration units of mg/l. Some water quality targets for sediment TMDLs, however, are in Nephelopmeters turbidity unit (NTU). The NTU measures the light scattering property of the soil particles. WARMF is a mass balance model, which predicts TSS in mg/l. In order to use NTU as the end point for TMDL, it is necessary to develop the relationship between NTU and TSS.

The NTU and TSS are not tightly correlated for waters of different rivers (Davies-Colley and Smith 2001). Different rivers contain TSS with different particle size distributions. However, Foris, Rodriquez, and Davis (2002) have shown a reasonable correlation of TSS and NTU in diluting samples. Diluting the samples and measuring their NTU and TSS simultaneously may help establish the relationship ship between TSS and NTU, which may be used to translate the target end point in NTU to the target end point in mg/l of TSS.

4
TMDL OF CLEAN SEDIMENT

Introduction

The framework for developing the TMDL of clean sediment includes seven elements shown in Figure 3-1. This chapter describes the procedure to develop those elements using WARMF as a tool.

As it will become evident later, the procedure of WARMF includes engaging the stakeholders early on and in every step of the TMDL process. This is in contrast to the EPA protocol, which addresses the technical issues by analysts first and engages the stakeholders in public hearings later.

Some preparation work is needed prior to using WARMF as the analytical tool for TMDL development. The model must be adapted to the specific river basin. The DEM (digital elevation model) data of the river basin must be imported to WARMF. The river basin is delineated into land catchments, river segments, and lake layers. The site-specific data of land use, soil, meteorology, point source discharges, pictures and others must also be imported to WARMF. The GIS map of the river basin can then be displayed by WARMF on the computer screen (see Figure 4-1).

It is assumed that the readers are somewhat familiar with Windows and WARMF. Some simple explanations of their operations are provided in the text. For more detailed discussions, the readers are referred to the documentation report and user manual (Chen, Herr, and Weintraub 2001, and Herr, Weintraub, and Chen 2002).

Problem Identification

The objective of this task is to identify background information and establish a general framework for the development of sediment TMDL. The background information includes the locations of the sediment impairments, their pollution sources, and possible control techniques. The framework for TMDL development includes data needs and the model to use. For this report, the model to use is WARMF.

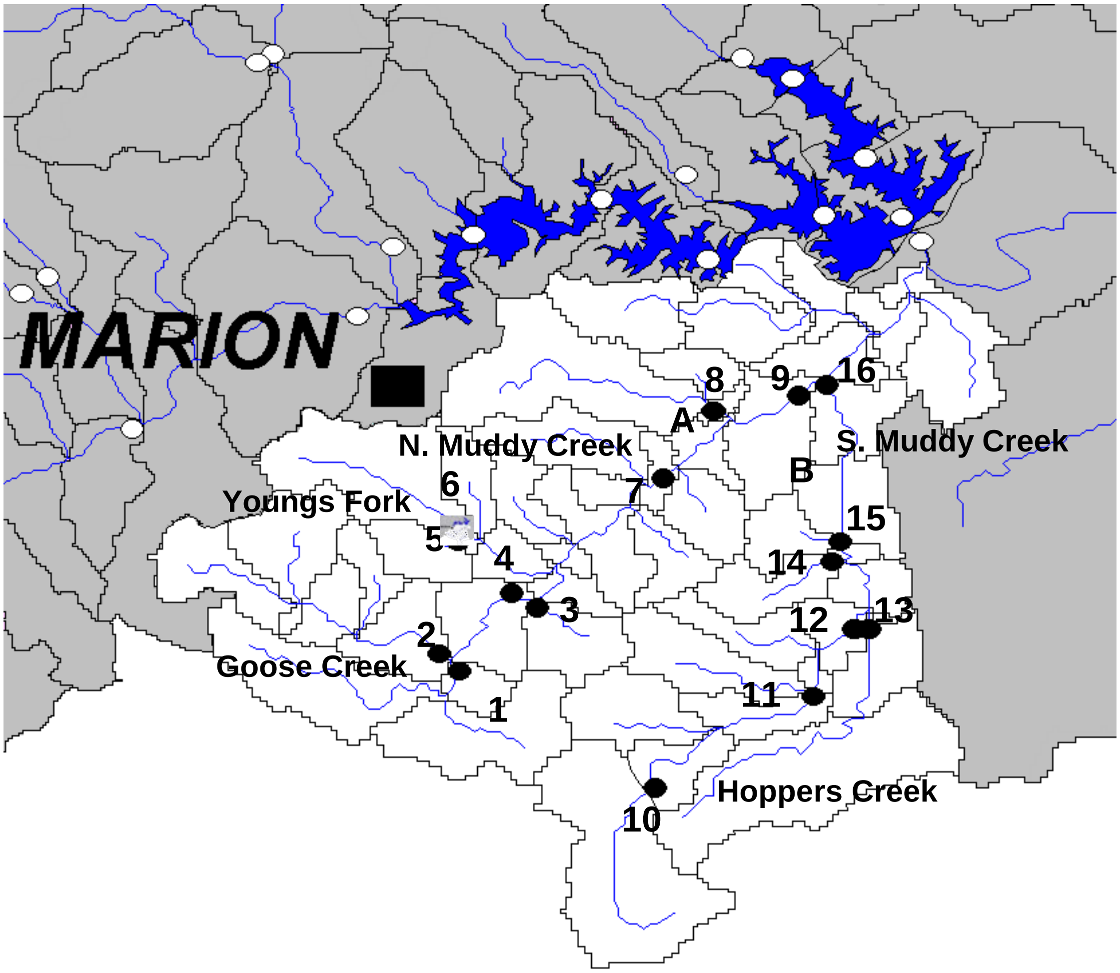

Figure 4-1
Basin Map of Muddy Creek Watershed, North Carolina (Numbers are Supplemental Monitoring Stations for Total Suspended Sediment)

"Problem identification" is equivalent to "water quality issues", according to the terminology of WARMF, in step 3 of the consensus roadmap shown in Figure 4-2. According to the roadmap, the first step is to compile a list of stakeholders and organize them into committees. The second step is to develop a work plan with a mission statement and tasks. By pointing and clicking on the buttons of those steps, WARMF provides dialogs for the stakeholders to follow.

For the sediment TMDL project, it is assumed that the mission is to develop a sediment TMDL plan that will achieve the designated uses of the water body and can be implemented. To help identify the water quality issues, it is further assumed that one of the tasks is for the stakeholders to conduct a watershed tour, take pictures, and identify the locations of land slides and bank erosion in the river basin. For example, Figures 4-3 and 4-4 are pictures taken at locations with severe bank erosion in the Muddy Creek watershed of North Carolina. These pictures among others are entered into WARMF, which can be used in a slide show to educate the stakeholders about where landslides and bank erosion occurs and what the watershed landscape or a buffer strip looks like.

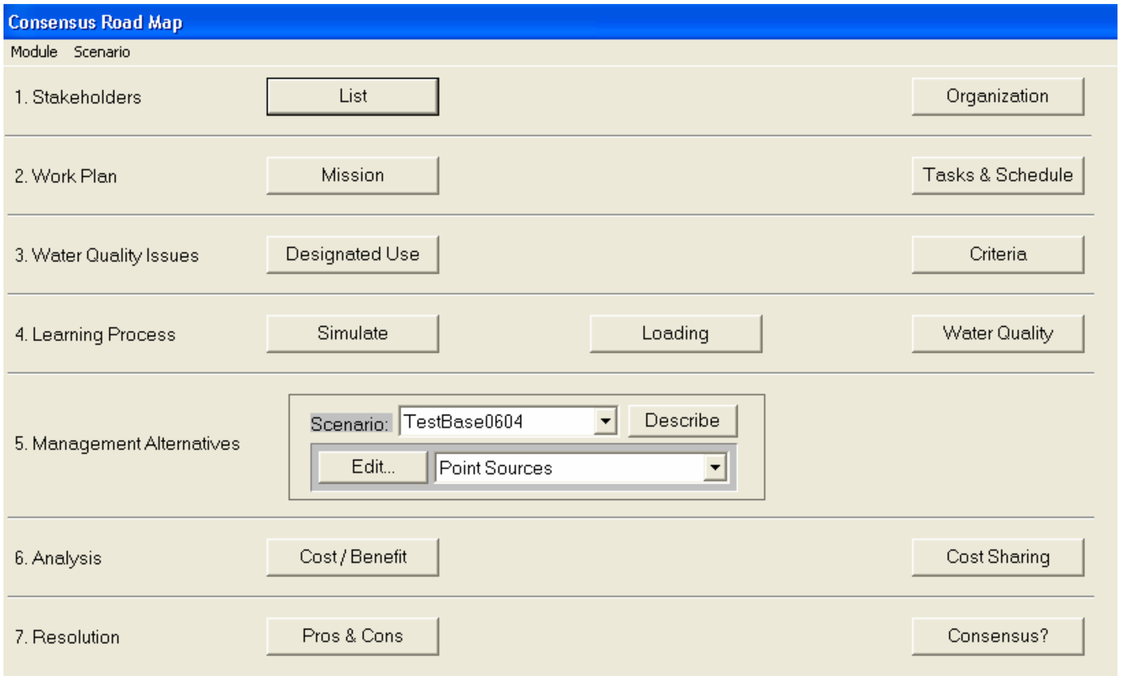

Figure 4-2
Consensus Roadmap

Continuing with the identification of water quality issues (problem identification) in WARMF, one can click on the "designated use" button of the Consensus Module. WARMF will display a dialog box showing a list of potential uses, i.e. cold water fish, warm water fish, aesthetic, public water supply, swimming etc. Select one of the uses (e.g. "warm water fish"), hold down the ***shift key***, move the mouse to click on the water sections of the basin map where the designated use applies. To undo the selection, one can click on the "designated use" button of the Consensus Module, select "warm water fish" from the dialog of potential uses, hold down the ***shift key***, and move mouse to click on the river sections to be unselected.

WARMF identifies the water quality issues from the standpoint of designated uses. There are water quality criteria for each designated use. For example, the "warm water fish" habitat could have criteria established for temperature, dissolved oxygen, and total suspended sediment. Through this connection, the sediment impaired river sections are identified. WARMF can then be used to generate the tributary areas that contribute total suspended sediments to the impaired sections.

Figure 4-3
Picture of a Bank Erosion Site in Muddy Creek, North Carolina

Figure 4-4
A Picture of Measuring Mass Loss of River Bank Erosion in Muddy Creek, North Carolina

The output of this task is a document for problem identification. The document can be prepared by using GIS maps generated by WARMF to show the sediment impaired sections and tributary areas where sediment come from. The pictures of landslides, buffer strips, and river bank erosions provide information about the problem areas and potential remedial measures to consider. The data needs may include a supplemental wet weather sampling program.

Develop Numerical Targets

The objective of this task is to develop numerical targets for the sediment TMDL to meet. The criteria for sediment are usually set for fish to see prey, for fish to spawn on clean gravel, for the invertebrate larvae not to be buried by fine silt and clay, and for people to be able to use the water for swimming and aesthetic enjoyment. The numerical criteria can be expressed in terms of the water column total suspended sediment concentration (mg/l), water column turbidity (NTU), settling flux of silt and clay to the river bed, biological integrity index, invertebrate community index, and index of well-being.

According to the EPA protocol, the development of numerical targets is the responsibility of the state regulators. In principle, the targets must be site-specific. A target established elsewhere to protect a certain fish (or organism) may not be applicable, simply because the said fish (or organism) does not exist in the water body. The regulators must consult local fishery biologists to establish the criteria, which can be problematic due to the lack of scientific data.

Any water quality criteria can be entered into WARMF. Default sediment criteria are 25 mg/l TSS for cold water fishery and 80 mg/l TSS for warm water fishery. These default values were derived from Newcombe (1999) and Newcombe and Jensen (1996). Because of the large fluctuation in TSS concentrations, the criteria are evaluated using a four day geometric mean at 90% compliance level.

To view or change the criteria, point and click at the “criteria” button of the Consensus module. A criteria dialog, as shown in Figure 4-5, appears. Push the down arrow button of the Designated Use box to display a list of potential uses and select “warm water fish”. Push the down arrow button of Criterion # box and select number 2 for total suspended sediment. The criterion #1 is for temperature. The metrics of the water quality objective are displayed for review. Any of the metrics can be easily changed, if the site specific numerical criteria developed by the state regulators are modified.

WARMF is a mass balance model that simulates TSS in the concentration units of mg/l. It cannot calculate NTU, which is not unit based on mass. The relationship between NTU and TSS for the river must be determined in the wet weather monitoring program.

WARMF, like many other available models, cannot calculate the biological indices directly. Those indices have correlations with physical and chemical habitat descriptors, simulated by WARMF. The correlations can be used to predict changes in biological indices by the post processing of WARMF outputs, using spreadsheet models.

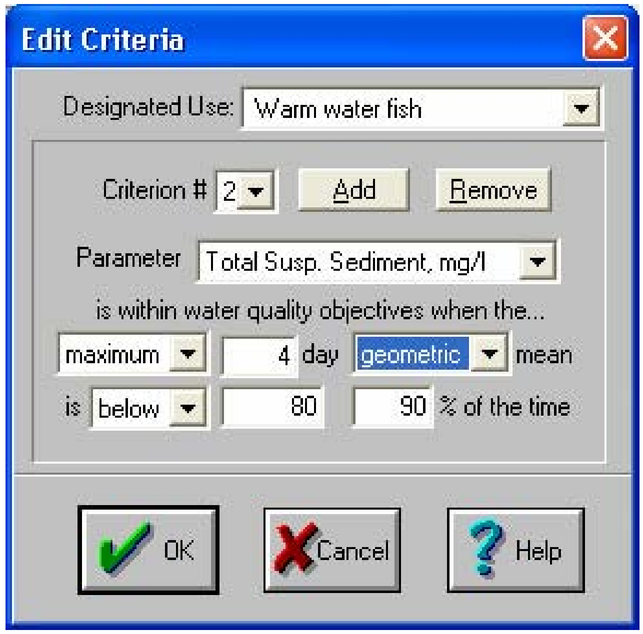

Figure 4-5
Default Criteria of Total Suspended Sediment for Warm Water Fish

Source Assessment

The objective of this task is to characterize the sources of sediment discharged to the water body. The sediment loading from various sub regions of the river basin must be quantitatively determined.

Source assessment with WARMF is very straightforward. One can simply run WARMF and output the regional nonpoint loading of sediment. Figure 4-6 shows the regional loading of sediment in Muddy Creek Watershed, North Carolina. WARMF displays regional loading in bar chart. The bar chart has two parts. The green bar in the lower segment represents nonpoint point load. The magenta in the upper segment represents point load. For this example, the upper portion does not show, because all sediment loads are from nonpoint sources.

The height of the bar represents the relative magnitude of the sediment load. North Fork Muddy Creek is shown to produce the highest sediment load. South Fork Muddy Creek produces the medium sediment load and the downstream region produces the lowest sediment load. To generate a more detailed breakdown of regional sediment loads, one can simply point and click at the tributary stream segment to establish additional subwatershed breakpoints. WARMF will change the color of the watershed region tributary to the new breakpoint and display a bar chart for its regional sediment load. By this procedure, one can trace the sediment load to its primary source.

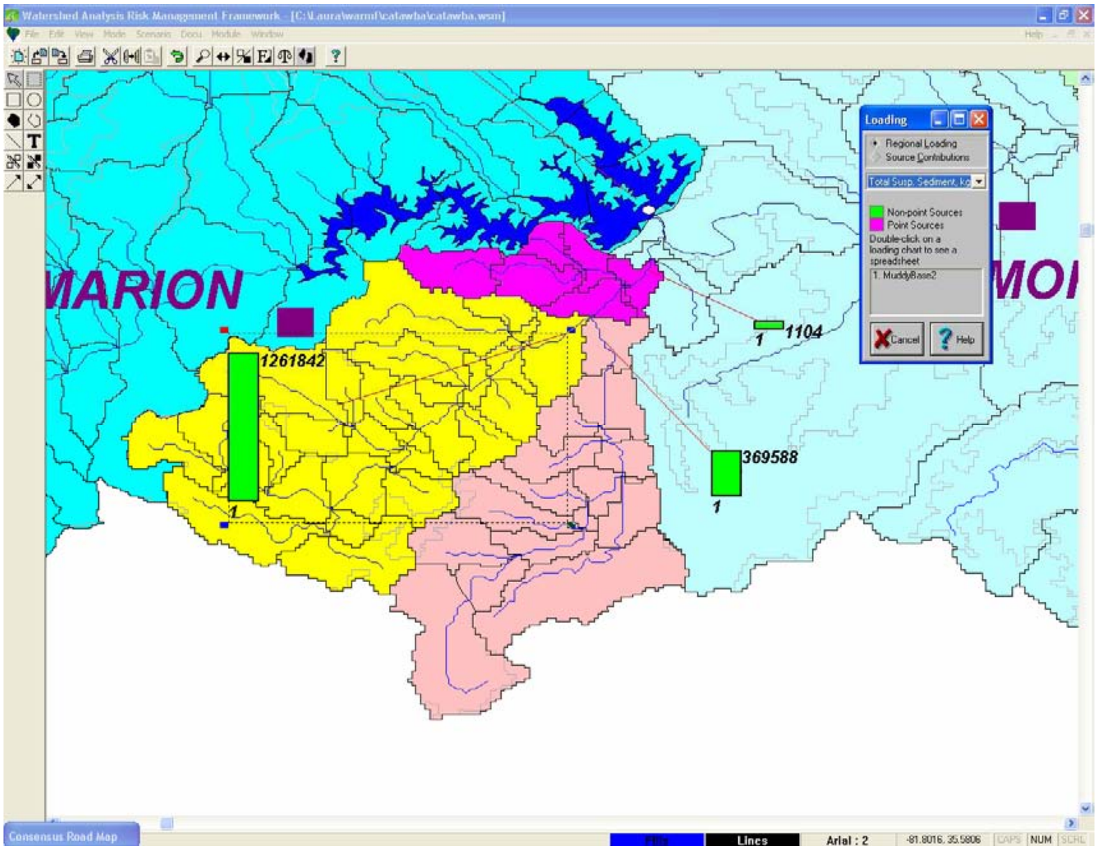

Figure 4-6
Regional Loading of Sediment in Muddy Creek, North Carolina

To obtain the numerical values of sediment loads, one can point and click at a bar chart. WARMF will display a spreadsheet with detailed accounting of the sediment loading. The spreadsheet provides information about the numerical values of point and nonpoint loads, and the distribution of the loadings among the various land uses of the sub region.

A source assessment report must be prepared for this task. All the above mentioned outputs can be copied and pasted into the said report.

Linkage Analysis

The objective of this task is to provide the linkage between the sediment loads and total suspended sediment concentrations in the receiving water. This is implicit in WARMF, which combines the point and nonpoint loads of sediment, stream hydrology, and in-stream physical processes to calculate the sediment concentration.

An important aspect of the linkage analysis is to prove that the model simulates the observed. For the Muddy Creek study, Figures 4-7 and 4-8 were used to show that WARMF simulated the general pattern of observed TSS at two monitoring stations. Figures 4-9 and 4-10 were used to show that the range and frequency distribution of simulated and observed TSS were similar. Since no flow measurement was performed for the Muddy Creek, it was not possible to compare the simulated and observed flows. Figure 4-11 was used to show that WARMF was reasonably accurate in simulating the stream flow of a nearby stream, the Linville River. All of these comparisons provide the "weight of evidence" for the validity of WARMF.

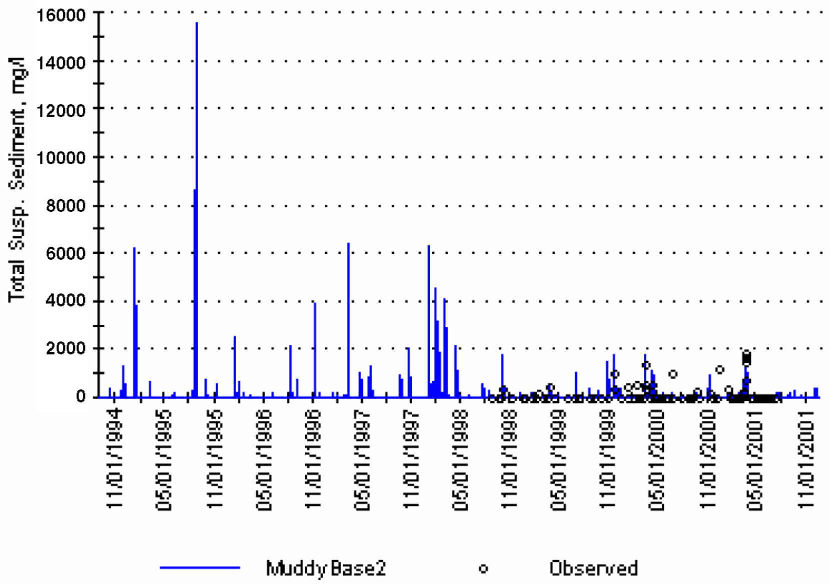

Figure 4-7
Simulated and Observed Total Suspended Sediment for North Muddy Creek at Glenwood Bridge (Station 4)

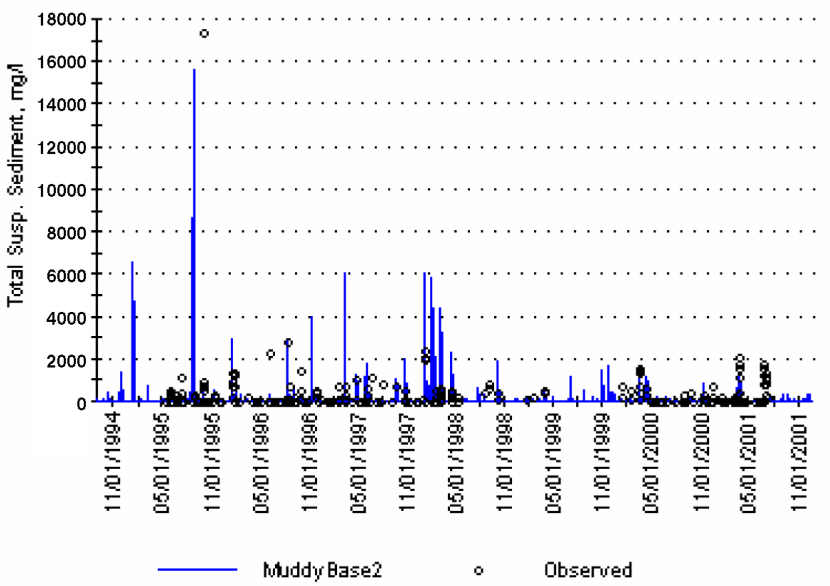

Figure 4-8
Simulated and Observed Total Suspended Sediment for South Muddy Creek at Main Station (Station 15)

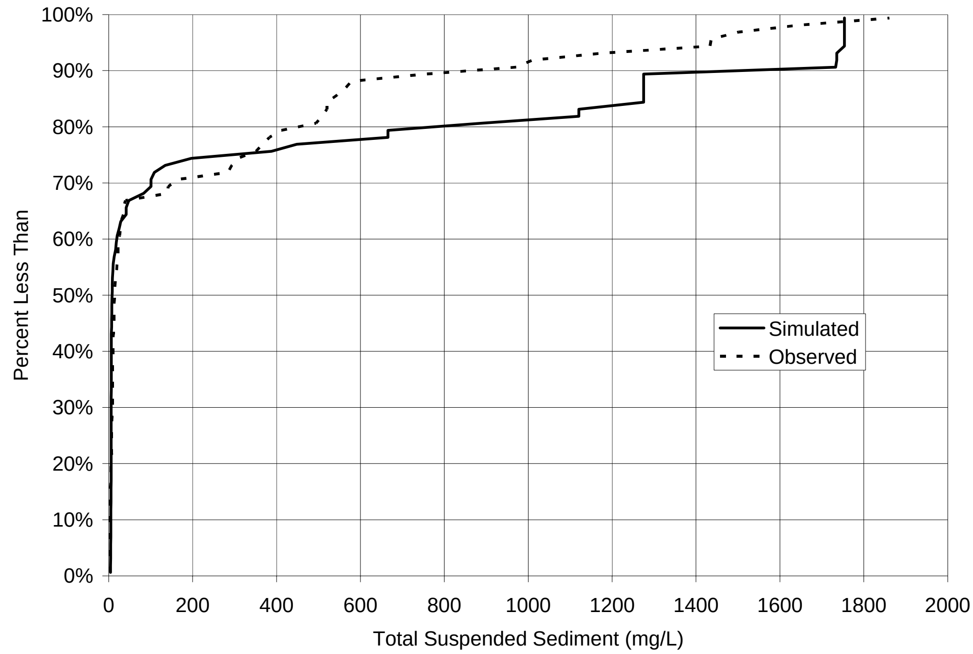

Figure 4-9
Frequency Distribution of Simulated and Observed TSS for North Muddy Creek at Glenwood Bridge (Station 4)

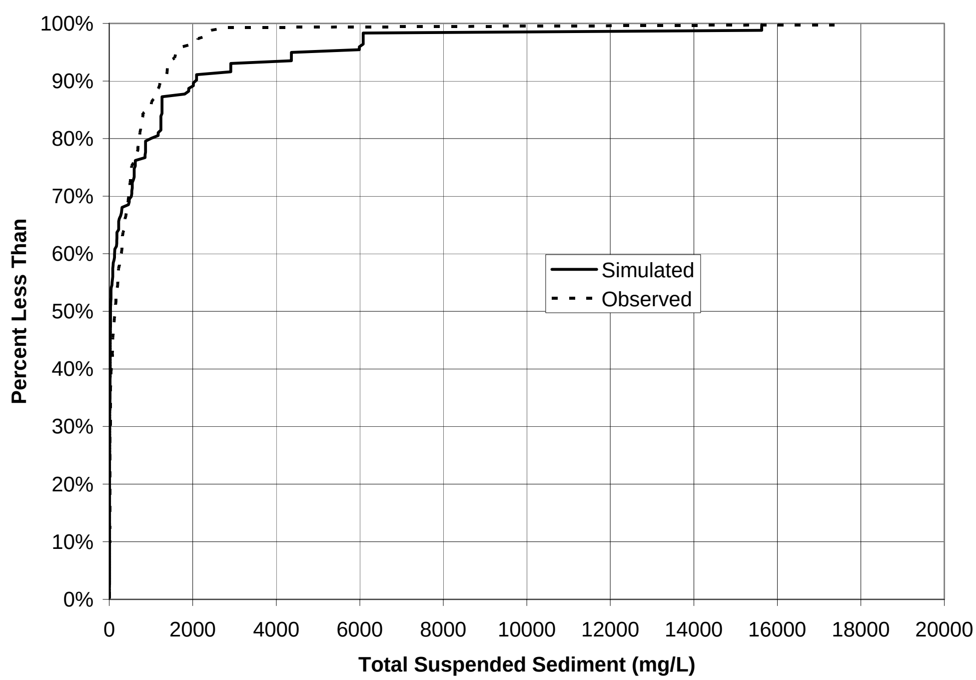

Figure 4-10
Frequency Distribution of Simulated and Observed TSS for South Muddy Creek at Main Station (Station 15)

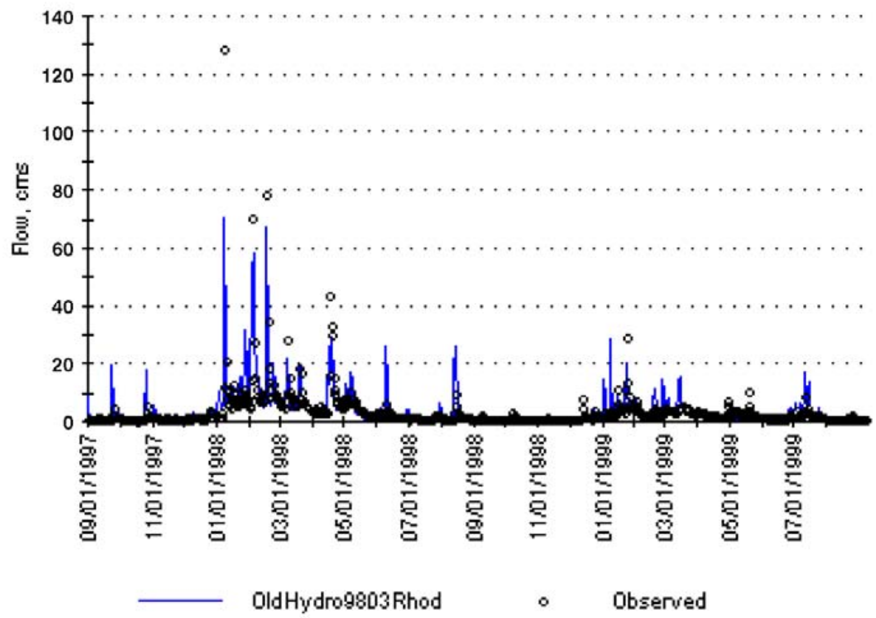

Figure 4-11
Comparison of Simulated and Measured Flow for Linville River, Tributary to Lake James, North Carolina

Allocations

The objective of this task is to calculate the TMDL to meet the water quality criteria of the designated use. WARMF is used to perform the analysis as follows.

WARMF uses the GIS map to show the status of the water quality condition, as shown in Figure 4-12. There are two main branches of Muddy Creek. The South Fork Muddy Creek flows from south to north on the eastern part of the river basin. The North Fork Muddy Creek flows from southwest to northeast on the western part of the river basin. The two branches merge into the mainstem of Muddy Creek which flows into Catawba River, below Lake James.

The designated use of South Fork, North Fork, and main stem of Muddy Creek is warm water fishery. The designated use for Catawba River below Lake James is cold water fishery, because the Bridgewater Dam releases cold water to the Catawba River from Lake James.

There is a water quality criterion of warm water fishery for total suspended sediment concentration. The GIS map (Figure 4-12) uses a color scheme to depict the water quality condition. The river sections meeting the sediment criterion are shown in green and the sections not meeting the criterion are shown in red. As shown, the green covers the upstream sections of both South Fork and North Fork Muddy Creek. The red covers the downstream sections of both forks. The red sections are the sediment impaired waters that require the TMDL calculations. The calculation of the TMDL is performed using the TMDL module of WARMF (Figure 4-13).

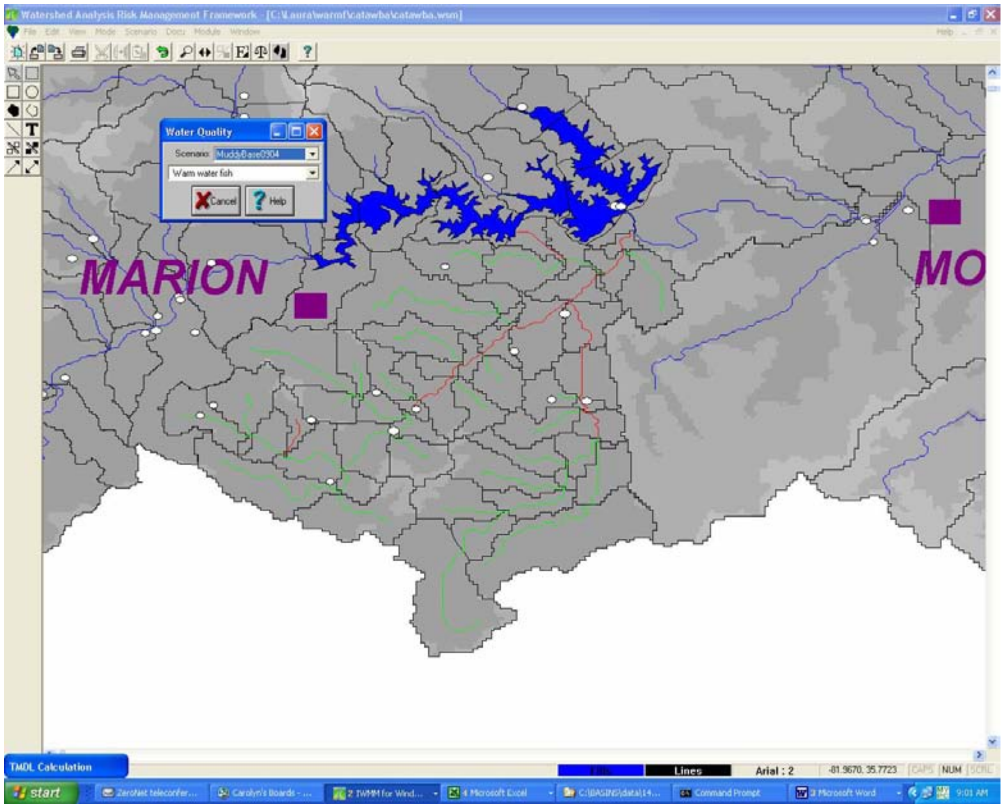

Figure 4-12
Base Water Quality Condition of Muddy Creek, North Carolina

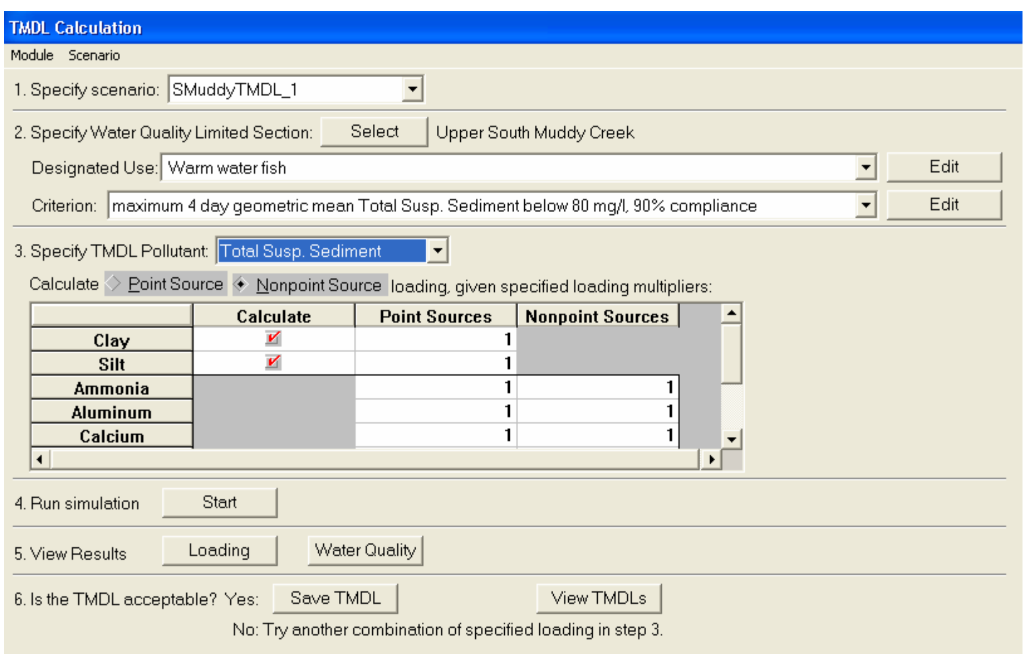

Figure 4-13
TMDL Module of WARMF

There are six steps to follow. Step 1 is simply to specify a scenario name. Step 2 is to specify the water quality limited section. To do that, click on the “Select” button in the TMDL module. WARMF will display the GIS map, from which the sediment impaired river segment can be selected. WARMF will display the name of the river segment (Upper South Muddy Creek) that has been selected for TMDL calculation. Click the down arrow of the designated use box and select “warm water fishery”. Click the down arrow of the criterion box and select the sediment criterion (maximum 4 day geometric mean below 80 mg/l 90 percent compliance).

In step 3, click the down arrow of the specify TMDL pollutant box and select total suspended sediment. Select “nonpoint” for the Calculate box, meaning that the TMDL is to be calculated for the nonpoint load under a specified multiplier for the point source load. This is the case for sediment TMDL, because all pollution loads for sediment are derived for nonpoint sources. For other pollutants, it is possible to calculate TMDL of nonpoint load under a specified multiplier (load reduction) for point source load. By this procedure, one can find various combinations of TMDLs for point and nonpoint loads to meet the water quality criterion.

In step 4, click on the “Start” button for WARMF to calculate the TMDL by performing an iterative set of simulations which reduce the load until the water quality criterion is met. In step 4, click on the “loading” button to see the loading chart and click on “water quality” button to see if the color of the sediment impaired section turns from red to green. Step 6 is for saving the results of TMDLs, which can be recalled by stakeholders during their deliberations for the implementation plan.

As shown in the roadmap, WARMF sometimes cannot find the TMDL for the specified condition. In that case, one can try it again with a smaller multiplier for the point source load. This cannot happen for sediment TMDL, because the point source load of sediment is already zero.

The TMDL calculations are performed for one water quality impaired section at a time. The procedure is to calculate the most upstream section first. WARMF will save the answer for the first section. When WARMF performs TMDL calculations for the next impaired section, the result of the upstream allocation will not be adjusted.

For illustration purposes, sediment TMDLs were calculated for the Upper South Fork Muddy Creek and the Lower South Fork Muddy Creek. Figure 4-14 shows the results, which display the loading charts for base case (left bar) and TMDL case (right bar). For the Upper South Fork Muddy Creek, the sediment load for the TMDL case is only slightly lower than the base case. For the Lower South Fork Muddy Creek, the sediment load for the TMDL case is substantially lower than the base case.

To obtain the numerical values of the bar chart, click on the bar. WARMF will display the detailed loading results in a spreadsheet. These values are summarized in Table 4-1. For the Upper South Fork Muddy Creek, the sediment loads were reduced from 194,800 kg/d to 176,900 kg/d. This represents a required TMDL multiplier of 0.907 (9.3% reduction). For the Lower South Fork Muddy Creek, the base case sediment load of 174,500 kg/d was reduced to 20,600 kg/d, representing a TMDL multiplier of 0.118 (88.2% reduction).

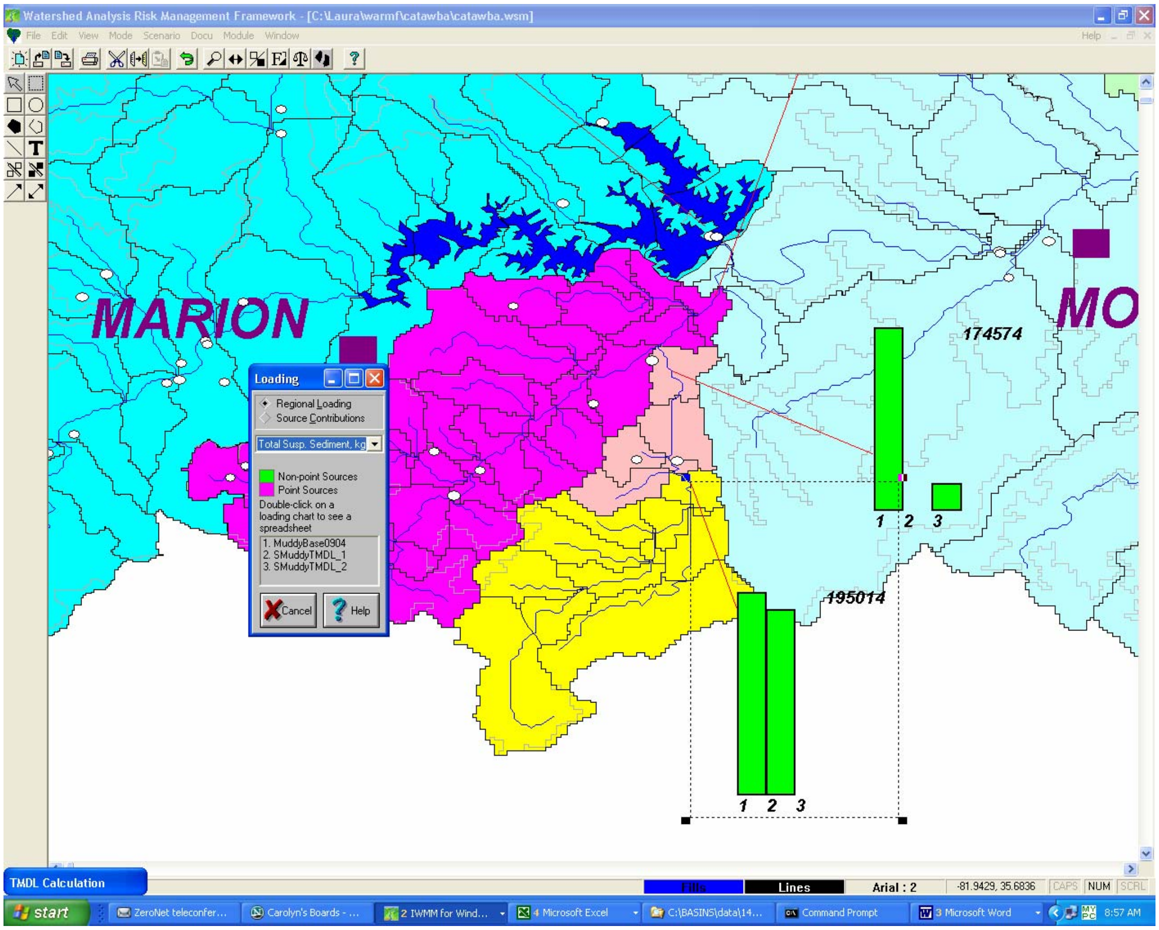

Figure 4-14
Sediment Loads for Base Case and TMDL Case, Muddy Creek, North Carolina

Table 4-1
Sediment Loads for Base Case and TMDL Case, Muddy Creek, North Carolina

	Base Case Loading (kg/d)			TMDL Loading (kg/d)			TMDL Multiplier
	Clay	Silt	Total	Clay	Silt	Total	Total
Upper South Muddy Creek	104,000	90,800	194,800	94,600	82,300	176,900	0.907
Lower South Muddy Creek	87,200	87,300	174,500	10,300	10,300	20,600	0.118

The allocated load must be discounted for the margin of safety. Jackknife simulations can be performed with WARMF to evaluate the uncertainty of model prediction. With the supplemental wet weather data, the uncertainty can usually be reduced to 20%. The allocated loads must therefore be discounted by 10%, since the model has an equal chance of over prediction and under prediction.

Implementation Plan

The Muddy Creek Watershed Restoration Initiative (MCWRI) was established to develop and implement a sediment control plan rather than to conduct a sediment TMDL study. For the MCWRI study, WARMF was used to evaluate the implementation plan that can reduce the sediment load to Muddy Creek. For the TMDL study, WARMF would have been used to evaluate the implementation plant that can reduce the sediment load to the TMDL values.

The first step is to identify the major sources of sediment loads for Muddy Creek. The model calculated that the sources of sediment loads for the whole Muddy Creek Watershed were 135,000 kg/d from surface erosion and 1,300,000 kg/d from bank erosion. With a ratio of 10 to 1, the top priority for sediment control is clearly the reduction of bank erosion.

In North Carolina today, sediment control generally involves buffer strips. WARMF was used to evaluate the effectiveness of buffer strips on the sediment of Muddy Creek. WARMF predicts that increasing the stream buffer from the current 50 to 80% to the ultimate 100% will reduce the sediment load of surface erosion by 48%, with little change to suspended sediment concentration in the river. However, by setting bank erosion to zero, the sediment load was greatly reduced by 90% with a big drop in the total suspended sediment concentration.

The stakeholders accepted the results of the model analysis and proceeded to initiate two stream channel stabilization projects at Site A (North Muddy Creek at Higgins) and Site B (South Muddy Creek at Muddy Creek Rd). More sites will be restored when the funding becomes available.

If the study were for the TMDL development, WARMF would have to be applied to evaluate management options section by section. For the Upper South Fork Muddy Creek, the management option may be leaned toward buffer strips. For the Lower South Fork Muddy Creek, river bank stabilization may be more appropriate. Likewise, buffer strips may be installed in the Upper North Fork Muddy Creek and bank stabilization may be used in the Lower North Fork Muddy Creek.

After the alternatives are proposed and determined to be scientifically feasible, the cost of each alternative must be estimated. The scientific and cost information are entered into WARMF for stakeholders to negotiate a final plan through a consensus process. The Consensus module of WARMF provides a roadmap for stakeholders to follow.

Follow-Up Monitoring and Evaluation

This task will define the monitoring and evaluation plan to validate whether the TMDL plan was implemented and whether the TMDL plan is effective. This TMDL element is the same, whether the TMDL is developed using WARMF or other methods.

For this TMDL element, the EPA protocol is to be followed. The basic concept is to check whether the buffer strips are installed and whether the bank stabilization project is completed.

The follow-up monitoring will probably continue to monitor the total suspended sediment concentrations at the monitoring stations shown in Figure 4-1. The laboratory procedure for TSS may be improved to ensure good data. The flow measurements may be added. The results may be compared to the existing data to detect the improvements made by the implementation of TMDL plan.

Assembling the TMDL

This task is to prepare the TMDL plan according to the EPA format. Conforming to the EPA format is important because they receive a large volume of submittals that must be evaluated systematically for approval.

The EPA protocol suggests a table of contents for nine chapters of the TMDL reports. They are submittal letter, problem statement, applicable water quality standards and their numerical targets, source assessment, linkage analysis, TMDL allocations, follow-up monitoring plan, public participation, and implementation plan.

The preparation of the TMDL report may require numerous maps and graphics. WARMF provides many of those outputs that can be cut and paste into the TMDL report.

5
SUMMARY AND CONCLUSIONS

Summary of Work

The EPA protocol for developing sediment TMDLs was carefully reviewed. The protocol suggested the use of an estimation method with limited data to perform initial analysis. The use of a sophisticated model with detail data can then be used to obtain a final definitive answer.

A methodology was developed to develop a sediment TMDL using WARMF. The methodology included a supplemental wet weather sampling program to collect data during storms to support the model application. The methodology was illustrated with a case study of Muddy Creek watershed, North Carolina.

Conclusions

The following conclusions are made:

1. The EPA protocol provides an overall framework for completing the technical and programmatic steps in the TMDL development. It covers only the methodologies for technical analyses. No guidance is given on the methodology of stakeholder involvement. The example case studies used simple analytical tools based on limited existing data. The approaches may not provide predictions with spatial and temporal resolution needed. The assumptions made can be subject to court challenges by lawsuits. The conservative assumptions and large margin of safety may lead to a high cost implementation plan.
2. The protocol recognized that the development of a sediment TMDL is a problem solving process to which no "cookbook" approach can be applied. A combination of monitoring and modeling may be needed. No guidance was provided on how to collect supplemental new data that might improve the TMDL analysis and reduce the margin of safety.
3. The protocol accepts a phased approach. Initially, screening level approaches based on limited data may be used. The analyses may provide qualitative assessment and result in a monitoring and evaluation plan. When new data are collected, detailed investigations with rigorous modeling techniques may be undertaken for a more definitive answer.
4. EPA (regional offices) and state, territorial, tribal decision makers for the TMDL development have the discretion to adopt approaches that differ from the protocol, on a case-by-case basis.
5. The methodology for developing sediment TMDL using WARMF has been developed to complement the EPA protocol. It includes a method for a wet weather monitoring program to collect data for the model application. It uses WARMF as the sophisticated analytical tool

that includes a GIS-based dynamic watershed model capable of simulating soil erosion from land, redeposition of eroded soil particles back to the land, settling of suspended sediment to riverbed, scouring of sediment from the riverbed, and river bank erosion. Jackknife simulation techniques can be used to perform uncertainty analysis. The model accuracy can be ascertained by the comparisons of model predictions to observed data. The methodology also engages stakeholders in the TMDL process from the very beginning and in every step of the way, using the Consensus and TMDL modules of WARMF.

6
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