NITRATE TMDL DEVELOPMENT: THE MUDDY CREEK/DRY RIVER CASE STUDY

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In 1972, Section 303(d) of the Clean Water Act (CWA) established the regulatory concept of a Total Maximum Daily Load (TMDL) as the maximum loading rate of a pollutant that a receiving water can assimilate without resultant water quality impairments with respect to the applicable water quality standards. The CWA specified that the watershed-level TMDL approach should be used to systematically manage both point and non-point source pollution. However, it was not until the 1990's after a series of legal actions that the TMDL program has been actively pursued at federal and state levels. The TMDL concept has now grown into a comprehensive surface water management approach. A thorough description and guidance for the TMDL program can be found at the U.S. Environmental Protection Agency web page (USEPA, 2001).

While the systems approach of the TMDL program may help to initiate an era of sustainable watershed management, the program presents many challenges for the water resource management community. For instance, computer modeling of watershed hydrology, water quality, and load allocations is typically necessary to address required components of a TMDL, such as spatial and temporal variability. Although the science and tools of watershed modeling are expanding rapidly (e.g., Vieux, 1991; Devantier & Feldman, 1993; Hornberger & Boyer, 1995; Sample et al., 2001), there is still a desperate need for practical tools and approaches to facilitate modeling of the diverse range of watersheds and water quality problems to be addressed by the TMDL program. Not only must the analyses be accurate while coping with typically scarce data, but they must also be completed rapidly. The USEPA expects timely completion of about 40,000 TMDL's for over 20,000 impaired river segments, lakes and estuaries, which includes approximately 475,000 kilometers (300,000 miles) of river and shoreline (USEPA, 2001). The USEPA suggests that states plan to complete the TMDL's with a maximum planning time frame of 13 years (Perciasepe, 1997). Given that there are typically hundreds of impaired waterbodies per state, the effort required to meet these timelines is enormous. Furthermore, in many states, court orders or consent decrees now specify the rate at which TMDL's must be established (USEPA, 2001). In addition, active and effective community involvement is expected in a TMDL project, so modeling analysis should be made intelligible to community members.

There are many opportunities for researchers to contribute to the development of the state-of-the-art for TMDL analyses. In fact, in Virginia, universities have had a direct role in the TMDL program with university representatives serving as the primary technical analysts for ten of the first twenty TMDL's in the state (VADEQ, 2001). As an example, this work briefly presents the Muddy Creek/Dry River nitrate TMDL case study and then discusses the relationship between the University research efforts and the TMDL program. Full details of the nitrate TMDL study can be found in Culver et al. (2000a).

THE MUDDY CREEK/DRY RIVER CASE STUDY

Background

The Muddy Creek/Dry River watershed is located in Rockingham County in northwestern Virginia (Figure 1). Sections of Muddy Creek, Dry River and North River are designated for public drinking water use because they are less than 8 kilometers (5 miles) upstream of the intakes for water treatment plants on the North River (VADEQ, 1998). The U.S. EPA water quality standard for nitrate, also adopted by Virginia, in the portions of Muddy Creek, Dry River, and North River designated for drinking water is 10 mg/l nitrate-nitrogen (VADEQ, 1998). This nitrate standard is intended to be protective of human health, especially for infants who are especially susceptible to high levels of nitrate intake and may develop methemoglobinemia ("blue-baby" disease), a potentially fatal blood disorder (USEPA, 1996; USEPA, 1998b).

An 11.35 kilometers (7.04 mile) reach of Muddy Creek, Dry River and the North River was added to the state 1998 303(d) list after a preliminary modeling study (Yu & Barnes 1998) suggested that violations of the nitrate standard could occur in the listed reach due to a combination of point and non-point sources. The state water monitoring program also found that three of 75 water samples in the listed reach of Muddy Creek collected between September 1993 and October 1999 violated the nitrate water quality standard (Culver et al., 2000a). The highest concentration observed was 13.5 mg/L nitrate-nitrogen (Culver et al., 2000a). These violations of water quality standard within the reach protected for drinking water use were measured at a sampling location on Muddy Creek (Virginia State Water Control Board monitoring station 1BMDD000.4), just above its confluence with the Dry River (Figure 1). No water quality violations were observed on the Dry River or North River (Culver et al., 2000a). In addition to the surface water, three recent studies (Shenandoah Valley Soil and Water Conservation District 1995; Ross 1999; Culver et al., 2000b) have found elevated nitrate levels in the karst aquifer below the Muddy Creek/Dry River watershed. Through these studies, a total of 152 ground water samples were collected from private wells between 1994 and 2000. The average and standard deviation of the nitrate-nitrogen concentration in the samples was 12.01±13.18 mg/L, with 51 percent of the samples over the drinking water standard of 10 mg/L nitrate-nitrogen.

TMDL development in the Muddy Creek has laid important groundwork for future TMDL development in Virginia. Virginia's first and second TMDL's (VADEQ, 2001) to be approved by the USEPA were the Muddy Creek fecal coliform TMDL (MCTEW, 1999) and the Muddy Creek/Dry River nitrate TMDL (Culver et al., 2000a), respectively. Furthermore, the Muddy Creek/Dry River nitrate TMDL was Virginia's first TMDL to be approved with significant contributions from both point and non-point sources. All other approved TMDL's in Virginia have focused on fecal coliform impairments.

<u>Muddy Creek/Dry River Nitrate TMDL</u>

Muddy Creek generally flows south to its confluence with Dry River, which joins the North River approximately 3.63 kilometers (2.25 miles) farther to the south (Figure 1). The North River discharges to the South Fork of the Shenandoah River, a tributary of the Potomac River that eventually flows into the Chesapeake Bay. The land area of the Muddy Creek watershed is approximately 8,106 hectares (20,030 acres), with forest (34 percent) and agriculture (61 percent) as the primary land uses (Culver et al., 2000a). The Upper Dry River watershed is approximately 18,960 hectares (46,850 acres), with over 99 percent of the land forested, while the Lower Dry River watershed is approximately 4,120 hectares (10,180 acres) with 30 percent forested and 62 percent agricultural lands (Culver et al., 2000a). The intensive agriculture of this watershed helps to give Rockingham County the highest poultry and dairy production levels in Virginia (VADEQ, 1997). To date fecal coliform TMDL's have been developed for both the Muddy Creek (Muddy Creek TMDL Establishment Workgroup (MCTEW) 1999), and Dry River watersheds (Virginia Tech, 2000), and a nitrate TMDL was developed for the Muddy Creek/Dry River area (Culver et al., 2000a). All three TMDL's have been approved by the USEPA (VADEQ, 2001).

The Muddy Creek/Dry River watershed was subdivided into eleven subwatersheds. The Muddy Creek and Dry River watersheds contained eight and three subwatersheds, respectively (Figure 2). The study area was divided to allow for spatial variation of nitrogen loading throughout the watershed and to allow the relative contribution of sources to each stream segment to be determined. Subwatershed delineation was based on a topographic analysis of the region and past work completed by the Virginia Department of Conservation and Recreation. In addition, nitrogen non-point source loads differed between the Muddy Creek and Dry River watersheds due to variations in farm management practices. No subdivisions were imposed on the Upper Dry River watershed due to its homogeneity; it is almost completely forested.

The water quality/quantity model, Hydrologic Simulation Program-FORTRAN (HSPF) version 11.0 (Bicknell et al., 1997), was used to predict stream flow, in-stream water quality and the significance of nitrogen sources. HSPF was selected because of its ability to simulate both nonpoint and point source loads, as well as the flow and transport of pollutants in each stream reach. In addition, HSPF is able to assess in-stream water quality response to changes in flow, season, and load (Bicknell et al., 1997). While HSPF is a component of the USEPA watershed model, Better Assessment Science Integrating Point and Nonpoint Sources, or BASINS (USEPA, 1998), the nitrogen chemical cycle is not supported within the BASINS modeling framework. Thus HSPF was used outside of the BASINS modeling system for the nitrate TMDL.

The basis for the hydrological calibration was the coliform bacteria TMDL for Muddy Creek (MCTEW, 1999). In the coliform bacteria study, BASINS (USEPA, 1998) was calibrated to the continuously recording U.S. Geological Survey (USGS) gage (01621050) for the period of 4/13/93-9/30/96. The USGS gage is located in Mount Clinton along the main branch of Muddy Creek in the Muddy 2 subwatershed (Figure 2). Weather data was obtained from the Dale Enterprises climatological station located along the eastern boundary of the Muddy Creek watershed. The nitrate study simulated the period between 4/13/93-12/31/97. The nitrate TMDL study verified that the hydrological parameter values determined during the coliform TMDL provided an excellent flow calibration for the location on lower Muddy Creek (VASWCB station 1BMDD000.4) where the nitrate violations had been observed (Figure 3). Calibration of flows for the Dry River watershed began by using the hydrological parameter values as developed for the Muddy Creek watershed. Given the unusual hydrogeology in the Dry River watershed, there was good reason to believe that the infiltration rates (both surface and deep infiltration) varied between the Muddy Creek watershed and the Dry River watershed. Thus, parameter values for Dry River watershed were adjusted to calibrate flows to monthly measurements taken on the Dry River near its confluence with the North River (VASWCB station 1BDUR000.02).

Consistent with the observed data, the calibrated model accurately identifies the fall as the period with the highest nitrate concentrations (Figure 4). The simulated periods of violation in Muddy Creek are consistent with the observed violations, and the concentration ranges are similar (Figure 4). No violations of the nitrate standard were predicted in the Dry River or North River reaches (not shown).

For the nitrate TMDL, the current nitrogen loads from point sources and non-point sources loads were estimated, and the impacts of these loads on the surface water quality were modeled. A poultry processing facility that discharge into Muddy Creek was the only significant point source in the watershed. The discharge point for the poultry processing facility is along the main branch of Muddy Creek at the northern edge of the Muddy 1 subwatershed, just below where War Brach joins Muddy Creek (Figure 2). The nitrogen loading from the point source was based on monitoring records for its discharge permit, although the load from the plant was highly variable in both flow and concentration and the monitoring record was sparse compared to the modeling requirements. The point sources, septic tanks and cattle in the stream were modeled as direct discharges along each stream reach. Although the septic tank load was assumed constant, the point source load and the loads from cattle in the stream varied over time.

Non-point sources of nitrogen in the Muddy Creek/Dry River watershed originated from agricultural, residential, forest, and atmospheric sources. Agricultural sources included animal waste (primarily cattle manure and poultry litter), runoff from concentrated animal operations, and nitrogen-based fertilizers. Livestock inventories, combined with published data on waste production rates per animal and the typical daily routines of the livestock, were used to estimate livestock loading rates. Residential sources included properly functioning septic tanks and fertilizer. Atmospheric sources of nitrogen included both dry and wet deposition. Deposition rates were measured at regional weather stations. Nitrogen released from decomposing wildlife waste and decaying organic matter constituted the nitrogen load from the large forested area. Published values were used to determine the forest loading rates. Nonpoint source loads varied monthly depending on numbers of animals grazing in pasture and the amount of manure, litter, and fertilizer applied to the land.

The goal of the nitrate TMDL was to bring nitrate concentrations down to the standard with a five percent margin of safety with no exceedances within the reach designated for drinking water quality (Culver et al., 2000a). Thus the objective was to maintain surface water concentrations at or below 9.5mg/L nitrate-nitrogen at all times within the listed reach. Based on the results of the calibrated model (Figures 3 and 4), the TMDL study determined a set of feasible nitrogen load allocations in which the load reductions required to meet the 9.5 mg/L nitrate-nitrogen goal, at all times, were specified. Since no nitrate violations were measured or simulated below the Muddy Creek watershed, no nitrogen load reductions were required in the Dry River watershed. Load reductions were applied to the major nitrogen loads in the Muddy Creek watershed. Major loads, contributing more than five percent of the total load, were the point sources, croplands, haylands and improved pastures (hay), unimproved pastures, overgrazed pasture, high density animal enclosures (loafing lots), and cows-in-stream. All load reductions were with respect to the total nitrogen loads from each source, and the percent load reductions for the nonpoint sources were applied equally to the eight subwatersheds in the Muddy Creek watershed. Although the water quality goal was to reduce nitrate levels, total nitrogen was managed due to transformations of nitrogen forms that commonly occur in the environment.

The first step in developing the nitrogen load allocations was to consider possible impact on nitrate concentrations due to the coliform load allocations (MCTEW, 1999). The coliform bacteria load allocations require removal of the direct manure load caused by cows in the stream. For consistency, this management approach was also assumed in all nitrate load allocations. For the coliform study, the most limiting conditions occurred in summer when large numbers of cattle were frequenting the stream; thus removing cattle from the stream was an important management strategy for the coliform bacteria levels. However, during the period with the highest nitrate peaks, there are either no cattle or extremely few cattle in the creek. Thus peak nitrate levels and load allocations are not sensitive to reductions in the number of cows in the stream, and removing cows from Muddy Creek reduces the daily average nitrate level by only 0.15 mg/L NO_3-N. Until a management plan is in place for the Muddy Creek coliform TMDL, it cannot be determined whether the other required coliform load reductions will also reduce the nitrate loads. For the nitrate load allocations, no other load reductions were presumed due to coliform management.

Forests were also determined to be a major nitrogen source in the Muddy Creek watershed. However, the total forest contribution of nitrogen is only significant on the watershed-scale due to the large acreage of forest, which covers over a third of the Muddy Creek watershed. Forests have the lowest nitrogen contribution per acre of any land use in the watershed. Thus, the load allocation scenarios focused on reductions in the other significant nitrogen sources (row crops, haylands, pastures, loafing lots and point sources).

Given the complexity of this system and the interaction between sources, a variety of load allocation scenarios resulted in similar impacts on the peak nitrate levels. The selection of the best combination of source reductions is a subjective decision. Several allocation scenarios that met the TMDL target of 9.5 mg/L nitrate-nitrogen were developed through trial-and-error reductions in loads. These feasible allocation scenarios (Table 1) were presented to the community and reported to the USEPA. The allocations (both load and waste load allocations) are described in terms of reductions from the estimated loads over the modeling period of 1993 to 1997. Point source reductions were applied year round, while the agricultural reductions generally occurred between September and December, unless otherwise indicated. Significant trade-offs exist between the sources. For instance, scenario 7 (Table 1) shows that a 50 percent reduction at the point source allows nonpoint source reduction to be 25 percent (fall only for each land use), while in scenario 1 (Table 1) a 20 percent reduction to the point source results in required nonpoint source loading reductions of 40 percent for most land uses and 50 percent for the loafing lots (fall only).

The community was asked to select a scenario from the matrix of options shown in Table 1. Scenario 4 was the load allocation scenario selected by the community and submitted to the USEPA. However, the state and the community reserved the right to implement any of the feasible scenarios presented in Table 1. This flexibility was requested since the best allocation scenario would become more evident during development of the implementation plan. Until management plans are in place, costs are unknown. Another reason for flexibility in scenario selection for this watershed was the realization that load reductions for fecal coliform bacteria could also impact nitrate levels, given that most of the sources contribute to both coliform and nitrate impairments. The TMDL annual load reductions for coliform bacteria for the agricultural sources are as follows: 13 percent croplands, 80 percent loafing lots, 41 percent haylands, 42 percent unimproved pasture and 42 percent overgrazed pasture. For comparison, Table 2 shows the total nitrogen load reductions in terms of the annual load reductions. In addition, the fecal coliform TMDL required exclusion of cattle from the streams. Unfortunately, until an implementation plan is developed one cannot determine how coliform management will impact the nitrate levels. Some management techniques, such as storage, may be effective for decreasing fecal coliform levels (Walker et al., 1990), but may not provide a corresponding reduction in nitrogen levels (Kirchmann & Lundvall, 1998). Furthermore, Meals (1996) found that agricultural best management practices were more effective on a watershed-scale for coliform management than for nutrient management.

Table 1: Summary of feasible allocation scenarios that meet surface water quality goals. Numbers for each load are percent nitrogen load reductions from current levels. Agricultural percent reductions are the reductions in load during September through December, unless otherwise indicated.

Scen-ario	Point Source	Crop	Hay	Unimproved Pasture	Overgrazed Pasture	Loafing Lots	Peak NO_3-N (mg/L)
1	20	40	40	40	40	50[a]	9.47
2	20	46	40	0	40	50[a]	9.50
3	30	40	40	0	40	40	9.50
4	35	25	30	20	20	50[a]	9.46
5	35	27	30	0	20	50[a]	9.49
6	45	25	25	0	30	50	9.45
7	50	25	25	25	25	25	9.50
8	50	30	25	0	25	25	9.50

[a]Load reduction occurs year-round

Table 2: Summary of feasible allocation scenarios that meet water quality goals. Numbers for each load are percent annual load reductions from current levels. All agricultural load reductions occur between September and December, otherwise indicated.

Scen-ario	Point Source	Crop	Hay	Unimproved Pasture	Overgrazed Pasture	Loafing Lots	Peak NO_3-N (mg/L)
1	20	10.6	12.6	13.0	13.0	50.0	9.47
2	20	11.6	12.6	0.0	13.0	50.0	9.50
3	30	10.2	12.6	0.0	13.0	13.2	9.50
4	35	6.0	9.5	6.5	6.5	50.0	9.46
5	35	6.9	9.5	0.0	6.5	50.0	9.49
6	45	6.4	8.0	0.0	9.8	16.5	9.45
7	50	6.0	8.0	8.2	8.2	8.3	9.50
8	50	7.7	8.0	0.0	8.2	8.3	9.50

UNIVERSITY CONTRIBUTIONS

The University of Virginia's participation in this project was successful on a variety of fronts. Not only did it have immediate impact on the successful completion of the Muddy Creek/Dry River nitrate TMDL and impact TMDL process in general in Virginia, but it also has provided opportunities for student training and environmental management research. Clearly the most important outcome is the successful completion of the TMDL study. The State of Virginia was highly pleased with this work for several reasons. First, by request of the VADEQ, we submitted the final report one month earlier than originally agreed upon. Another TMDL project was behind schedule, so we were asked to accelerate the submission of our final report so that the State could meet its completion schedule as specified by a legal Record of Agreement. By doing so, we helped avoid possible legal action against the State. Secondly, state representatives have indicated that the quality of our work and our willingness to work closely with the community and various state agencies significantly contributed to helping to manage what could have become a highly contentious and litigious process. To date, no legal challenges to the nitrate TMDL have been made. Finally, the nitrate TMDL development has already built momentum in the watershed for improving water quality management. The point source contributors have indicated that they will voluntarily reduce the nitrate load in their effluent by 30 percent. This step is being taken years before an implementation plan for nitrate reduction is in place. In addition, the agricultural community also realizes that they need to actively pursue effective nutrient management. The community, including the point source contributors, believes that if some nutrient management actions are taken now in conjunction with the coliform management plan, then the nitrate concentrations in Muddy Creek can be significantly reduced. It is hoped that with these actions, water quality improvements may allow the stream to be de-listed; that is the stream would no longer be legally considered impaired. At the encouragement of the community, the VADEQ included the potential for de-listing in the TMDL report (Culver et al., 2000a).

Several aspects of the nitrate TMDL study may have impacts beyond the Muddy Creek/Dry River watershed. For instance, the practice of presenting the community with a range of feasible options, when appropriate, and asking for USEPA approval of this range of options for flexibility is being encouraged (Lazarus, 2001). In addition, the State hopes to replicate our successful community interactions. With supplemental funding from the Virginia Environmental Endowment, we observed and analyzed the TMDL process from the community's perspective. Since the Muddy Creek community was participating in their second TMDL development project, community members were able to discuss and compare their experiences in the two projects and had excellent insights into what did or did not work for them. As a value-added product for the State, we provided a recommended community outreach protocol (Culver et al., 2000b), which has been disseminated by the State and stimulated extensive discussions at the State level. The most important conclusion emerging from our work in the area of community outreach is this: effective outreach is as much a matter of building relationships and trust as it is of providing pertinent, accurate information. The community members, most of who will never understand the details of the technical analysis, must come to trust the technical judgment of the analysts. This conclusion is not particularly surprising, but it does have significant implications, especially if we consider the TMDL process on a national scale. A perfunctory approach to community outreach will not work. On numerous occasions throughout this project, we found that establishing relationships meant adapting to the schedules, customs, and rhythms of the community. It involves flexibility and the willingness to operate within a give-and-take relationship—features not typically associated with bureaucratic efficiency. In addition, the importance of professional fundamentals, such as maintaining an unbiased analysis and attention to detail, in all communications cannot be underestimated. Presentations and reports, which may be the only products that the community has to evaluate the watershed analysis, must be painstakingly clear and intelligible. Presentations or reports with small, even typographical, errors that a non-technical observer can catch will leave the community members wondering what technical errors lurk inside the analysis.

Specifically for the Muddy Creek/Dry River community, the most important step to adapt outreach to the community was a willingness to interact in small groups. The Mennonite-dominated community preferred meetings with community leaders to the mandatory large public meeting format. In fact, we expect, in general, that an outreach program based solely on large public meetings is unlikely to establish effective communication. In this study, we repeatedly met with a group of community leaders. We opened up all of our analysis methods and results to public scrutiny. Immediately before all large public meetings, we previewed the presentation to the small group of community leaders. Their feedback not only improved the official presentations, but our willingness to incorporate their suggestions demonstrated our respect for their concerns and made them feel a partner in the TMDL development process. Community suggestions included revising the presentation format to emphasize the impact on the community over the technical details, warning the analysts about omissions in information of concern to the community, such as the rates of residential fertilization, and timing public meetings around the agricultural schedule of the community. Our willingness to repeatedly meet with and listen to community representatives unquestionably was the key factor in building trust in the community.

Beyond the impacts on the local and state-wide TMDL process, the Muddy Creek/Dry River TMDL has been the basis for a variety of research efforts. Two master's theses and one doctoral dissertation have been completed that utilized the nitrate TMDL as their primary case study. One of these projects (Naperala, 2000) used the Nitrate Leaching and Economic Analysis Package, NLEAP, (USDA, 1997) to explore the potential impacts of the feasible nitrate TMDL load reductions on the mass of nitrogen leaching into the subsurface of the Muddy Creek watershed. For different load scenarios, the average annual mass of nitrogen leaching below the root zone, given 18 years of weather input, was calculated. For the different feasible load allocation scenarios, the average reduction in leaching mass, relative to current conditions, was around 10 percent. However, the total reduction in mass leached varied significantly between feasible TMDL allocation scenarios. That is, while the feasible scenarios all result in similar peak nitrate concentrations in the surface waters, they do not perform equally well when impact on nitrogen leaching is considered. Interestingly, the load allocation selected by the community had the lowest reduction in leaching load of any of the feasible scenarios analyzed with NLEAP. Other feasible scenarios could have nearly doubled the reduction in nitrogen leached. If the community had been aware of the differences in leaching (which were not available at the time of scenario selection), they may have chosen a different preferred alternative. This is especially likely given that the community seemed more concerned about contamination of ground water, their sole drinking water source, than the surface water contamination. Unfortunately, given the rush to satisfy Virginia's TMDL completion goal, there was insufficient time to consider water quality management more holistically within the TMDL analysis of the watershed. A complete description of the leaching study can be found in Culver et al. (2001).

A second study (Potts, 2000; Culver & Potts, 2001) evaluated the sensitivity of the performance of the allocation scenario to the hydrological calibration. There is no widely accepted definition of what it means to have the "best" dynamic hydrological calibration. HSPEXP (Lumb et al., 1994), a decision support software for the hydrological calibration of HSPF, recommends evaluating the difference between the observed and simulated values of a variety of hydrological measures, including seasonal and annual water balances, flow recessions, storm peaks, low flows and the entire time series. Unfortunately, one can rarely find a parameter set that simultaneously improves the performance of all potential measures of fit. Furthermore, hydrological calibration is typically considered a prerequisite for water quality simulation. Yet the literature on hydrological calibration gives little to no consideration as to what are the key characteristics of a hydrological calibration to most reliably reproduce stream water concentrations for systems governed by both point and nonpoint source pollution, and ultimately in a TMDL analysis it is the water quality simulation that drives the allocations. Since we were given a hydrologic calibration for the Muddy Creek watershed, with no statistical justification of the quality of the calibration, the question of the quality of the hydrological calibration arose during the nitrate TMDL study. Three alternative hydrological calibrations, which are arguably equivalent, were developed based on measures of the daily and monthly root mean square error, the daily and monthly mean relative errors, annual and total flow balances, and for low flow conditions, the mean square error, the daily root mean square error and flow balance. Note that the root mean square error uses an absolute measure of error, and therefore tends to bias fits towards peak flows. For each new hydrological calibration, the water quality calibration was adjusted to reasonably reproduce the observed in-stream concentrations. In-stream nitrate concentrations were then predicted using each new calibration and a feasible load allocation from the TMDL study (Scenario 5 in Table 1). In all cases, the simulated peak nitrate-nitrogen concentration fell below the water quality standard of 10 mg/L nitrate-nitrogen. For the three new calibrations, peak nitrate-nitrogen concentrations ranged from 9.44 mg/L to 9.87 mg/L. This calibration study validates the need to incorporate a margin of safety into the analysis, and suggests that the 5 percent margin of safety used in this TMDL was reasonable.

In the final study (Zhang, 2001), a critical flow-storm approach was developed for management of nonpoint source pollution. The objective of the critical flow-storm approach is to provide a simpler, alternative approach to continuous simulation of a multi-year period. For systems dominated by point sources, water quality management has typically been based on critical conditions defined in terms of a low-flow event with a specified return period. The critical flow-storm approach demonstrates that for systems with significant nonpoint source pollution, the hydrological critical conditions can be defined by a combination of initial in-stream flows and precipitation events. Very small storms produce little runoff, while large precipitation events may act as a source of dilution. Thus, a medium-sized storm may be the most problematic for nonpoint source pollution. Zhang (2001) used the Muddy Creek case study to demonstrate that the critical flow-storm could be used to define the limiting conditions for water quality in terms of a return period. By using event simulation, a TMDL allocation could be determined that is similar to the one developed by continuous simulation in the Muddy Creek/Dry River nitrate TMDL (Culver et al., 2000a).

CONLUSIONS

The State of Virginia has extensive university participation in Total Maximum Daily Load (TMDL) development. This approach can have significant advantages for both the state and the research-oriented university team. An excellent example of this approach is the Muddy Creek Nitrate TMDL, which was developed by the University of Virginia. Several additional studies were built around the TMDL project and completed while simultaneously developing and gaining approval for the TMDL. Our team, which included a social scientist, studied the community-outreach process, demonstrated successful community interactions, and developed outreach guidelines that have been disseminated by the state. Furthermore, we were able to study the impact of model calibration on management plan effectiveness, expand the study of ground water contamination in the area, and develop and test alternatives to continuous simulation for TMDL development. For the researcher, not only were students trained and environmental management research completed, but insight was also gained into areas that require further study.

This case study demonstrates that it is possible to both participate in and contribute to the TMDL development process, while furthering one's research agenda. Participation is not without risks, given the significant potential for litigation and the poorly defined time demands. Nevertheless, the TMDL program offers extensive opportunities with an estimated 40,000 TMDL's to be completed and much to improve in the analysis process. Unquestionably, as a researcher interested in effective watershed management, active participation in the TMDL program is a very effective way to stimulate and evaluate new research avenues.

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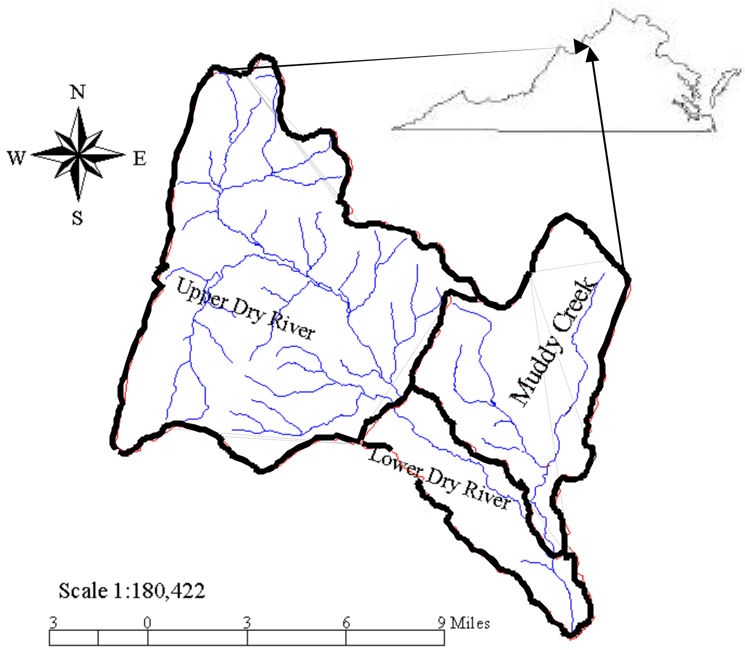

Figure 1. Map and location of the Muddy Creek and Dry River Watersheds.

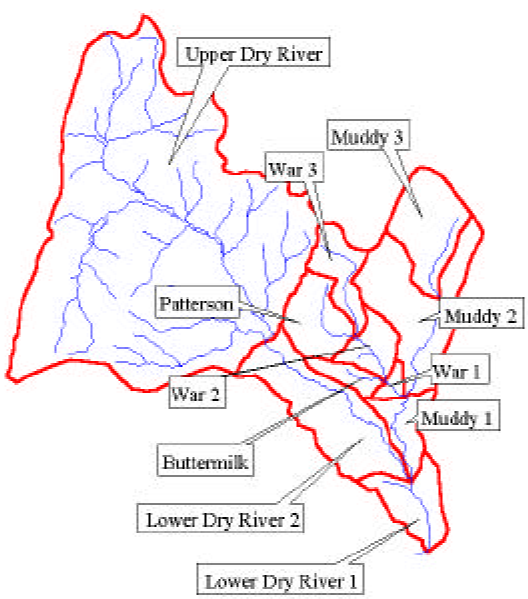

Figure 2. Map of subwatersheds in the Muddy Creek/Dry River System.

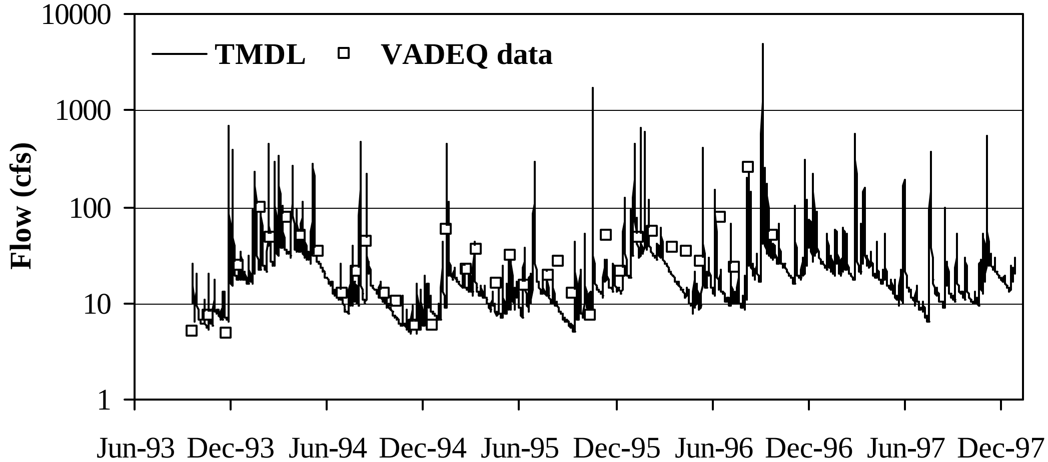

Figure 3. Simulated and observed flow in lower Muddy Creek watershed.

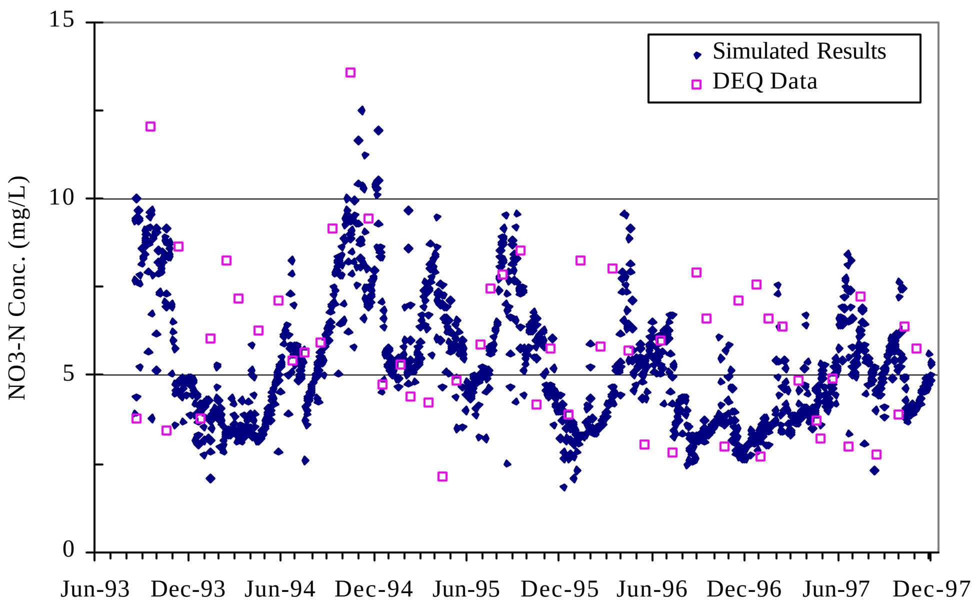

Figure 4. Simulated and observed nitrate-nitrogen levels in lower Muddy Creek