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Hoam Faculty House, Seoul, Korea

Ministry Food,Agriculture,
Forestry and Fisheries

kr Clean & Green RRI
Rural Research Institute

Agricultural Nonpoint Source
AgBMP
Best Management Practice

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Session 1.
International Agricultural NPS Management

Importance of mechanistic, Science driven design of Best Management Practices for Watershed quality protection

Rafael Munoz-Carpena

University of Florida, USA

Importanceofmechanistic, Science driven design ofBest ManagementPractices forWatershed quality protection

R. MuÑoz-carpena and Michael D. Dukes
University of Florida, PO Box 110570, Gainesville, FL 32611-0570
E-mail: carpena@ufl.edu

Abstract

The Total Maximum Daily Load (TMDL) program, established by U.S. federal law, drives US water quality policy/management today. A TMDL comprises the sum of loads from point and nonpoint sources plus a margin of safety. For water bodies' not meeting water quality standards a watershed action plan must be implemented on a prioritized schedule. TMDL watershed plans rely on the application of specific best management practices (BMPs) in the landscape. For the success of the plans it is critical that BMPs are properly designed for site-specific conditions to meet their quantitative pollution control objectives. Empirical design approaches are limited in their validity to the particular experimental conditions they were developed for. Instead, mechanistic approaches that consider general physical, chemical and biological principles that control the BMP performance (and their failure) must be chosen to understand the performance under general conditions beyond those of a particular setting. Additionally, once the optimal design is identified an uncertainty analysis must be conducted to identify the level of confidence (margin of safety) that design has against the uncertainties present as a result of the system variability and complexity. An example of TMDL program in the USA is shown for the State of Florida where the institutional and individual stakeholder roles are outlined and the five-phase cycle of implementation is discussed. An illustration of BMP mechanistic design and uncertainty evaluation is presented for vegetative filter trips (VFS) using the numerical model VFSMOD. The results show how VFS can be optimized for particular site conditions to meet a TMDL standard and how margins of safety can be objectively obtained. Although BMPs can be effective tools for watershed protection, until easy-to-use, generally applicable and tested BMP design aid tools are developed we will never get beyond the current "one size fits all" approach used for many best management practices.

Surface water pollution control and policy in the USA

Water pollution derives from point (direct and identifiable pollution discharges) and nonpoint (pollution from diffuse sources caused by rainfall or snowmelt moving over and through the ground) sources. In the USA, a Total Maximum Daily Load (TMDL) is defined by the U.S. Environmental Protection Agency (US-EPA) as the calculated maximum amount of a pollutant that a waterbody can receive and still meet applicable water quality standards, and an allocation of that amount to the pollutant's sources. A TMDL comprises the sum of loads from point and nonpoint sources plus a margin of safety.

U.S. Congress mandated the TMDL program in Section 303(d) of the original Clean Water Act of 1972, and charged the US-EPA and the states to develop the program. The Clean

Water Act (CWA) is the cornerstone of surface water quality protection in the United States. Most of the early efforts by US-EPA and states (1972-1990s) focused on controlling point sources through National Pollutant Discharge Elimination System (NPDES) permits. Starting in the late 1980s, efforts to address polluted runoff have increased significantly. For "nonpoint" runoff, voluntary programs, including cost-sharing with landowners are the key tool. For "wet weather point sources" like urban storm sewer systems and construction sites, a regulatory approach is being employed. Evolution of Clean Water Act programs over the last decade has also included something of a shift from a program-by-program, source-by-source, pollutant-by-pollutant approach to more holistic watershed-based strategies (NRC, 2001; US-EPA, 2008). Under the watershed approach equal emphasis is placed on protecting healthy waters and restoring impaired ones. A full array of issues are addressed, not just those subject to Clean Water Act regulatory authority.Involvement of stakeholder groups in the development and implementation of strategies for achieving and maintaining state water quality and other environmental goals is another hallmark of this approach.

The US-EPA did not publish any guidelines for state implementation of Section 303(d) until 1991 (US-EPA, 1991 and others) despite the fact that Section 208 of the 1972 Act had acknowledged the need. Active litigation from the states has brought the TMDL program to the public light making it the center of the US water quality policy today. The validity of the TMDL process was reaffirmed in 2001 after U.S. Congress requested a committee to assess the scientific basis to reduce water pollution.

In 2006 close to 60,000 types of impairments were reported by the US-EPA (2006) as violating different water quality standards such as drinking, swimming, fishing, etc. The top 10 causes of waterbody impairments encompass nearly 80% of the 303(d) listed waterbody segments and include pathogens (14.6% of total segments listed), heavy metals (mercury 14.3% and others 8.3%), nutrients (8.8%), sediment (8.2%), oxygen depletion (6.7%), and biological impairments (habitat alteration 4.4%, temperature 4.6%, pH 4.6%, and unknown causes 4.8%). These are responsible for close to 36,000 impaired waters listed so far, for which close to 20,000 TMDLs have been approved. The number of impaired waters, however, is expected to increase substantially as additional monitoring is performed and new and revised water quality standards are adopted. The average annual cost of the TMDL program to states and US EPA over the period 2000-2015 is estimated to be between US$900 to US$3200 million/year, nationwide, of which US$63-69 million/year would be invested in developing TMDLs, US$17 million/year in monitoring to support the TMDLs and the rest in implementation (US-EPA, 2001).

In 2007 a collection of articles focused on a critical evaluation of current water quality technology for TMDL development and application was presented (Muñoz-Carpena et al., 2006). This compilation was the result of the collective effort of a large multidisciplinary group of experts from academic, regulatory, and consulting organization. The outcome of this review indicates that the status of tools for assessment and implementation of TMDLs for four of the most common stream impairments is inconsistent. In spite of their limitations, nutrient, sediment, and pathogen transport models are considered suitable for current modeling efforts, although efforts to update them should continue to address their existing limitations (Benham et al., 2006; Borah et al., 2006). In addition, it is essential that users be better trained to improve the application of these models for specific combinations of pollutants and watershed conditions. Despite advancements, many DO assessment tools are still not capable of simulating some of the most complex drivers of DO dynamics, partly because the scientific community does not yet fully understand these processes, and the models continue to require user-estimated inputs for these processes. Further research is needed to understand and quantify DO processes and gather data sets for calibration and validation (Vellidis et al., 2006). Meanwhile, an explicit quantification of uncertainty through the margin of safety in the TMDL is strongly recommended. While biological indicators are widely used to detect stream impairments, models do not currently exist that link the biology with specific pollutants. The fact that each of the biological communities responds differently to increases in a given pollutant complicates the interpretation and modeling of the biological indexes, but this also provides more information about the source of an impairment and could be key to understanding the pathways between individual pollutants and biological responses (Yagow et al., 2006). Research is needed to link pollutant loadings and biological responses so that useful diagnosis and quantification tools can be developed. Quantification of modeling uncertainty (Shirmohammadi et al., 2006), communication to end users, and economic optimization of the results (Bosch et al., 2006) are suggested as indispensable components to improve the success of the TMDL program.

Development and implementation of TMDLs at the state level.

Following the evaluation of the major water bodies in the USA with respect to their intended use (water supply, agricultural, power generation, fishing, recreational etc.) TMDL watershed action plans are required under the Clean Water Act on water bodies' not meeting water quality standards and must be implemented on a prioritized schedule. The states are responsible for the development of the TMDL plans subject to US-EPA supervision and approval. However, the complexity of the process is enormous and each state is allowed to organize their TMDL program.

After the TMDL evaluation, impaired watersheds require an implementation plan to reduce the impairment factor to the regulatory levels. The plan consists of a combination of accepted best management practices (BMPs) optimized and distributed in the landscape to achieve the maximum efficiency. BMPs are practical, cost effective actions that reduce pollutants such as excess nutrients, pesticides, and animal waste from entering water resources while maintaining or enhancing agricultural production. BMPs are typically a suite of generally accepted practices such as buffers (riparian areas and vegetative filter strips), grass waterways, infiltration basins, erosion control practices, drip and deficit irrigation, stream channel management, stream restoration, animal waste management, etc.

An example of a state TMDL program is presented for the State of Florida. The Florida Department of Environmental Protection (FLDEP) carries primary responsibility for the TMDL program in the state. Chapter 99-233, Laws of Florida (Fla. Stat. § 99-223) also known as the "Florida Watershed Restoration Act of 1999" defines the process by which the impaired waters list is refined, adoption of TMDLs, allocation of pollutant loading to sources, and implementation of pollution reduction strategies. The Florida Watershed Restoration Act identified methods that FLDEP must use to implement the TMDL program. FLDEP is primarily responsible for point source and urban nonpoint source pollution (NPS) while the Florida Department of Agriculture and Consumer Services (FLDACS) is responsible for agricultural NPS. Currently 7 watersheds with TMDLs are listed in Florida by FDEP (FLDEP, 2011a). A map of these locations can be seen in Figure 1.

TMDL development is based on a five phase cycle (FLDEP, 2011c) that rotates throughout the state every five years with phases as follows: initial basin assessment, coordinated monitoring, data analysis and TMDL development, basin management plan development, begin implementation of basin management plan.

a) *Initial basin assessment.* This phase is aimed at determining the general ecological health of the basin, identifying water bodies requiring TMDL development, develop a monitoring plan, and develop consensus-based water resource protection and restoration goals.
b) *Coordinated monitoring.* In this phase, a monitoring plan is implemented to collect data for evaluation of a water body, determine effectiveness of pollution abatement, and to collect further data for TMDL development. This phase is intended to determine if goals of a TMDL are being met after the initiation of the first round of these phases.
c) *Data analysis and TMDL development.* Water quality data collected in the second phase are analyzed to provide a detailed assessment of pollutant sources including NPS pollution estimation. A major function of this phase is to quantify pollutant contribution sources.
d) *Basin management action plan (BMAP) development.* Once a body has been determined as impaired and the pollution contribution sources have been determined (in the case of point sources such as wastewater treatment plants) or estimated (in the case of nonpoint sources, a plan is developed to reduce pollutants by implementation of BMPs, restoration activities, environmental infrastructure improvements, and issuance of permits.
e) *Implementation of BMAP.* The plan developed in the previous phase is now implemented to do such things as carry out development and implementation of BMPs.

Responsibility for development and implementation of agricultural BMPs in Florida lies with the Office of Agricultural Water Policy in FLDACS. The BMP process for a particular commodity or agricultural operation is developed through a consensus process closely with industry, extension professionals and scientists. Individual growers are solicited to sign up for the BMP program. When they sign up, they agree to use certain BMPs from an appropriate manual or rule that fits their operation best. By enrolling, they sign a "Notice of Intent". The program is voluntary; however, in watersheds where there is a BMAP, agricultural operations must enroll in the BMP program or conduct water quality monitoring to prove that there is no impact to the receiving water body. Enrolling in the BMP program benefits agricultural producers with a "presumption of compliance" with state water quality standards. Thus, as long as an agricultural operation is duly enrolled in the program, they are not subject to enforcement action by the state should there be no improvement in water quality of receiving bodies for example.

Although in past years there was some research on BMPs, more recently the focus has been on development of BMP manuals. There are currently 14 BMP manuals adopted for many agricultural operations/crops (citrus, container nurseries, vegetable and agronomic crops, sod, cow/calf operations, silviculture and aquaculture) (FLDACS, 2011). Figure 2 shows the regional application of the BMP manuals.

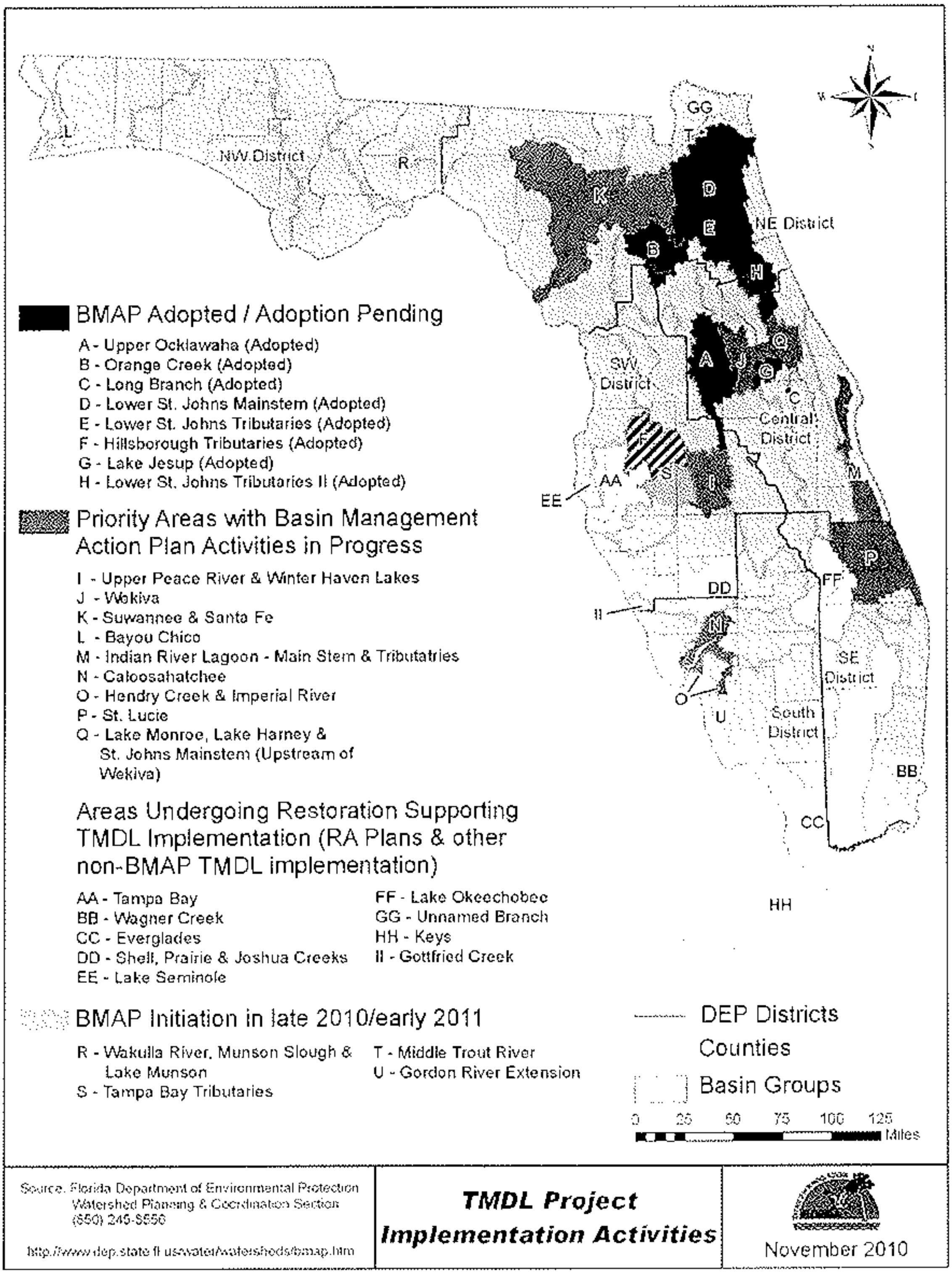

Figure 1. Total Maximum Daily Load program implementation activities in Florida (FLDEP, 2011a).

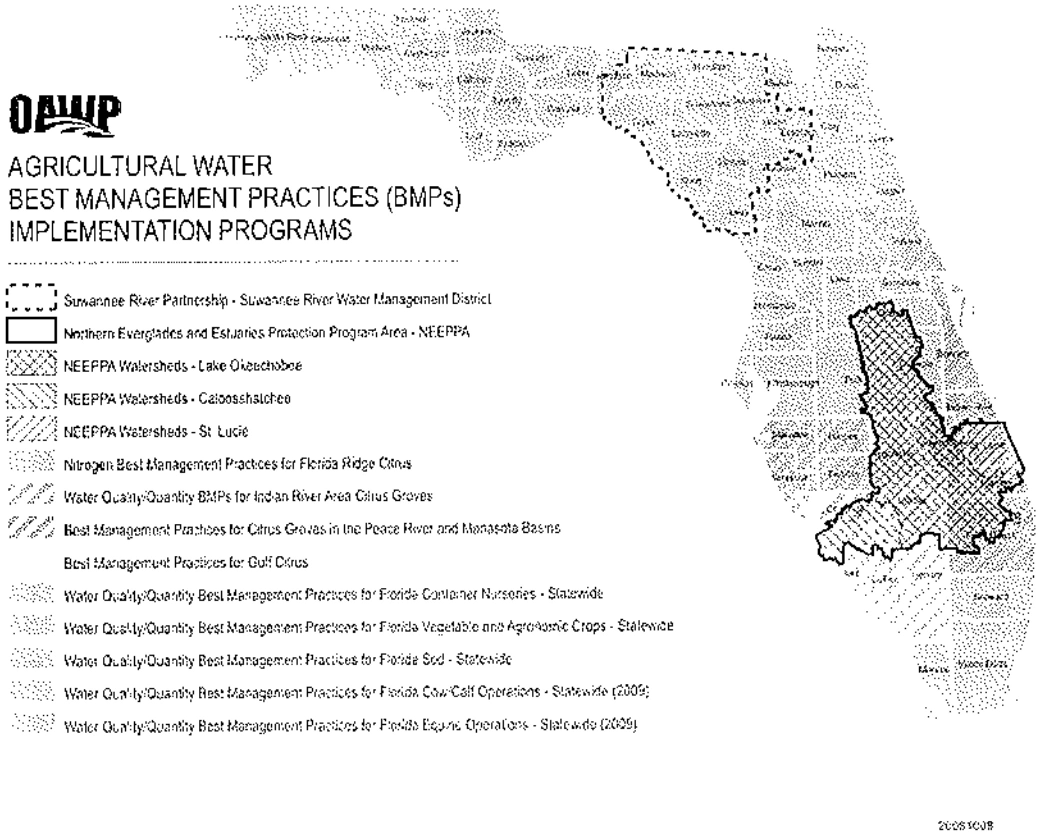

Figure 2. Agricultural water BMPs implementation plans in Florida (FLDACS, 2011)

Currently, according to FLDACS statistics, there are over 3 million Ha enrolled in BMPs in Florida (41% of agricultural land in Florida), yet there is virtually no monitoring to determine effectiveness of these programs.Monitoring is performed as part of the TMDL implementation; however, this monitoring is not targeted toward evaluation of field BMPs.

Science behind the BMPs. Mechanistic design of BMP to achieve environmental goals.

TMDL watershed implementation plans rely on the application of specific BMPs in the landscape. For the success of the plans it is critical that BMPs are properly designed to meet their quantitative pollution control objectives. However, many practices are based on common sense, empirical knowledge that is more qualitative than quantitative in nature. Although BMPs are subject to extensive research and experimentation, often the approach is to quantify their effectiveness empirically for specific scenarios. As with all empirical approaches, the validity of the findings is typically limited to the particular experimental conditions.Instead, mechanistic approaches that consider physical, chemical and biological principles involved in their performance must be taken to understand the performance of BMPs (and in particular their failure) under general conditions beyond those of a particular setting.

The challenges of mechanistic approaches to study BMP performance are many. In addition to the natural complexity steaming from the bio-physico-chemical interactions under the intrinsically variable conditions of the landscape, often socio-economic drivers condition the BMP performance and the success of the TMDL process (NRC, 2001). To understand the success and limitations of BMP implementation during the last 50 years in real watershed settings, the US Department of Agriculture launched an ambitious project – the Conservation Effects Assessment Project (CEAP) to provide the agricultural community, the public and others involved in environmental policy issues an accounting of the benefits obtained from conservation program costs (Mausbach and Dedrick, 2004). It is expected that tracking progress of conservation programs will allow policy makers and program managers to improve the effectiveness of existing programs and design new programs to increase the conservation of natural resources.

Although BMPs can be effective tools for watershed protection, until easy-to-use, generally applicable and tested design aid tools are developed we can never get beyond the current "one size fits all" approach used for many practices. Design aids are needed to help municipalities, property owners, and others take the "guesswork" out of determining adequate buffer widths for the purpose of water resource quality protection (Slawski, 2010). An illustrative example of mechanistic BMP design is presented for vegetative filter trips (VFS). Vegetative filter strips or buffers, defined as dense areas of vegetation planted between the disturbed soil and the receiving water body, are widely used BMP to remove surface runoff pollutants. VFS combine the benefits of their relative low cost with potentially high pollutant removal efficiency for particle (sediments, colloids) and particle-bonded (phosphorus, pesticides, some pathogens) runoff pollutants.

While complex mathematical models can be used to estimate sediment and nutrient removal efficiencies in VFS, these are not easily applied by the people who need them including homeowners, farmers, businesses and developers. To fill this gap, design aid tools can be developed using factors such as slope, soils, field length, incoming pollutant concentrations, and vegetation to allow the user to identify and test realistic buffer widths with respect to the desired percent pollutant load reduction and storm characteristics (Figure 3).

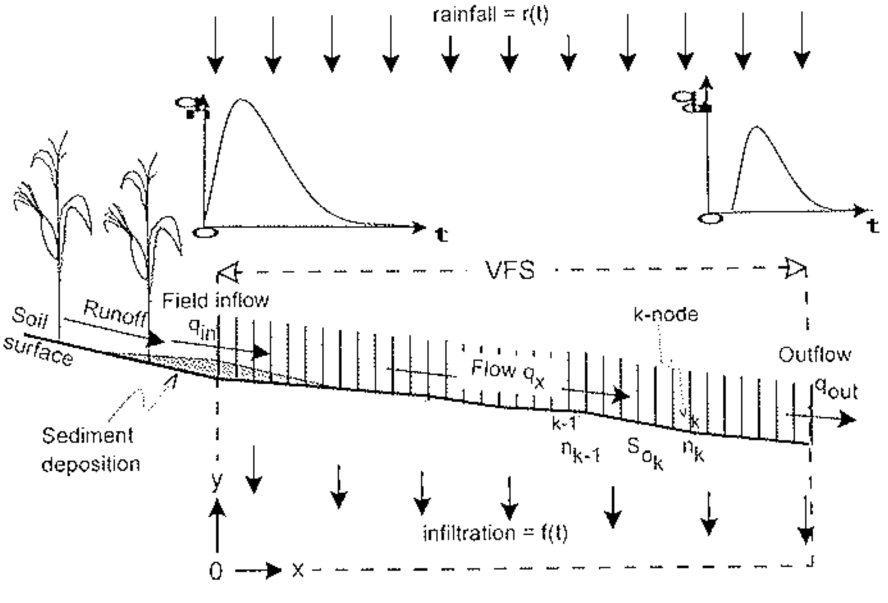

Figure 3. System components controlling efficiency of vegetative filter strips to remove surface runoff pollutants.

By developing a set of relationships among factors that determine buffer effectiveness, the width of buffer needed to meet specific goals can be identified. The design objective is to find optimal constructive characteristics (length, slope, vegetation) of a VFS to reduce the outflow of sediment from a given disturbed area (soil, crop, area, management practices) to achieve a certain reduction in % sediment (i.e. that for TMDLs). Proposed target outputs for analysis will be the sediment delivery ratio (SDR) and runoff delivery ratio (RDR) computed as:

SDR = (Mass of Sediment Exiting the Filter)/(Mass of Sediment Entering the Filter)
RDR = (Runoff Exiting the Filter)/(Runoff Entering the Filter)

From a design perspective, we require the VFS to accommodate storms with return periods of at least 1 and 2 years and probably 5 years. Notice that return periods of 10 years (or larger) are not considered since they will likely overburden the buffer by sediment inundation and stopping their function. This means that as part of their required maintenance plan the filter area will need to be periodically re-graded and re-established when sediment deposition at the filter strip-field interface jeopardizes its function.

The BMP design procedure uses the vegetative filter strip modeling design system, VFSMOD (http://abe.ufl.edu/carpena/vfsmod; Muñoz-Carpena et al., 1999; Muñoz-Carpena and Parsons, 2004). VFSMOD is a field-scale, mechanistic/ numerical, storm-based model developed to route the incoming hydrograph and sedigraph from an adjacent field through a VFS and to calculate the resulting outflow, infiltration, and trapping efficiency of sediment, and dissolved and sediment-bonded pollutants (pesticides, colloids, phosphorous, etc.) (Figure 4).

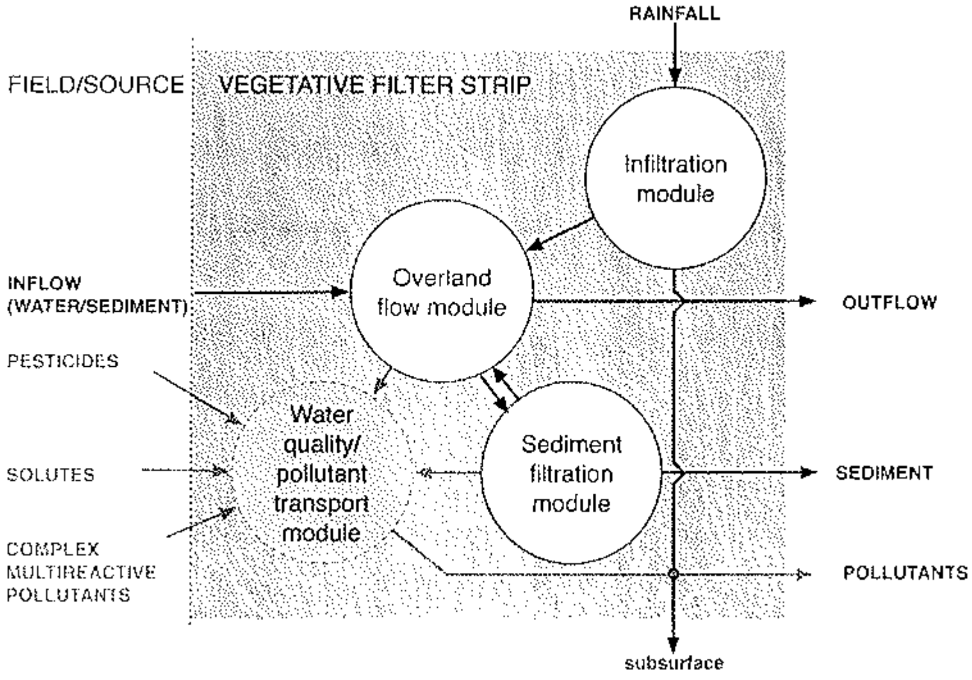

Figure 4. Conceptual diagram of the mechanistic design tool for vegetative filter strips (VFSMOD)

The first step in the analysis is to generate inputs into the VFS from the soils and crops present in the source study area, for each of the design storms and soils selected for the analysis. To do this, the precipitation depths of selected return periods for the area, along with the area, runoff and erosion inputs are processed through an input preparation utility (UH) that represents the field/source conditions to create formatted inputs for VFSMOD that represents the vegetative filter strip: hyetograph, incoming sedimentograph and hydrograph (Figures 3,4).

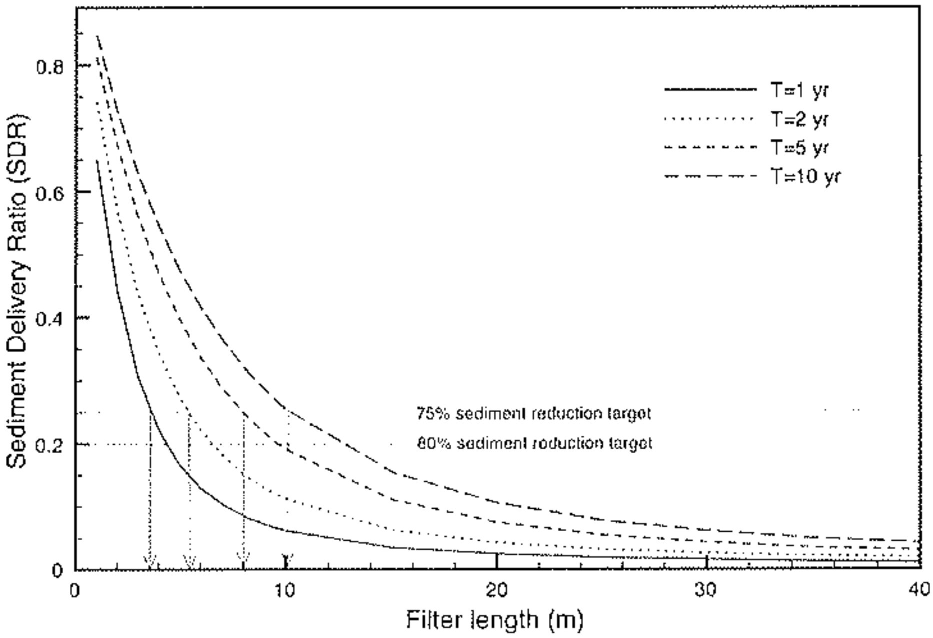

Figure 5. Generalized design graph depicting the optimal buffer width to achieve a 75% sediment reduction for a range of soil and slope, vegetation, and storm conditions characteristic of North Carolina.

With these inputs, the VFSMOD model routes the incoming runoff and sediment, and calculates water and sediment retained at the filter, outflow, and filter performance. For this, we must describe the actual vegetative filter strip characteristics to analyze for each design runoff event. Usually the most relevant VFS characteristics to consider from a design perspective are: soil type, filter length, uniformity and slope, and vegetation characteristics. For each combination of inputs the model executed and SDR and RDR obtained. Response curves (i.e. SDR or RDR versus filter length) are then constructed that allow the user to obtain the optimal filter characteristics for each return period and soil type when overlaying the pre-defined sediment (or other pollutant) TMDL expressed in terms of a desired reduction for a particular watershed action plan, over the response curves. Figure. 5 depicts the optimal filter lengths to achieve a 75% sediment reduction (SDR=0.25) in a North Carolina typical Piedmont site (Muñoz-Carpena and Parsons, 2004). A 0.5 Ha agricultural field is upslope from the planned VFS. The agricultural production is a row crop (with a curve number of 85) and the soil type is clay. The slope of the source area is 2%. Design storms with 6-hour duration for 1-yr to 10-yr (54-103 mm) return periods were selected for evaluation. The VFS parameters were selected to represent a good stand of grass such as fescue. The design assumes homogeneous sheet flow across the filter in all cases. Filter lengths from 2-10 m are needed to accommodate storm events ranging from the common and small events (associated to 1 year return periods) to more severe ones (5-10 yrs).

Based on this information, decision-makers have the option of fitting a desired level of sediment removal into the context of their specific conditions. Additionally, once the optimal design parameters are selected an uncertainty analysis must be conducted (Shirmohammadi et al., 2006). The objective of this analysis is to identify the level of confidence (margin of safety) that the adopted design has against the uncertainties present when selecting the model inputs (Parsons and Muñoz-Carpena, 2001, 2002). Details on the uncertainty estimation procedure are provided in the next section.

Uncertainty in BMP effectiveness, a critical component for environmental management

The complexity and variability of the drivers of in-situ BMP effectiveness translate in uncertainty in their value within the TMDL implementation plan. However, when mechanistic approaches and tools (models) have been developed for a particular practice it is possible to assess the expected level of uncertainty in the BMP efficiency. An extensive review of uncertainty analysis methods applied to environmental management tools can be found in Morgan and Henrion (1992), Haan (2002), and Shirmohammadi et al. (2006). The best method to quantify model uncertainty is based on constructing probability distribution functions (PDFs) of the model outputs (Haan, 2002; Rechhow, 1994; Shirmohammadi et al., 2006). A general approach is the technique of Monte Carlo simulations (MCS), which is performed by randomly sampling the multivariate input distribution, running model simulations with the sampled values to produce estimates of model output values, and combining these to produce a PDF. The procedure is typically computationally expensive since the process must be repeated many times to obtain a smooth PDF. More efficient sampling methods have been proposed and widely used based on stratified sampling of the input PDF, such as replicated Latin hypercube sampling (r-LHS) (McKay et al., 1979; McKay, 1995). An advantage of the MCS method is that it does not require a priori knowledge on the linearity of the model, and it does not introduce assumptions about the form of the output PDF distribution, although it relies on the correct determination of the input parameter distributions. The output PDFs can be used for decision-making by placing confidence levels on the outputs, usually in the form of a margin of safety (MOS) component, or by calculating a probability of exceedance of a threshold value (Morgan and Henrion, 1992). However, MOS is often arbitrarily selected as a fixed percent range around the model output (Sexton et al., 2005) rather than based on the output PDF.

A case study presented in Shirmohammadi et al. (2006) demonstrates how uncertainty analysis is also a critical factor to consider in the design of BMPs in the TMDL context. Parsons and Muñoz-Carpena (2001) proposed integrating sensitivity and uncertainty analyses in the modeling and design process vegetative filter strips (VFS) using VFSMOD-W. As presented in the previous section a set of design response curves, i.e., sediment and runoff reduction vs. filter construction characteristics, can be developed from VFSMOD-W outputs for a given design scenario (Muñoz- Carpena and Parsons, 2004). The response curves can be evaluated with respect to the TMDL plan design goal, i.e. a required sediment reduction expressed in terms of sediment delivery ratio (SDR= sediment out from filter/sediment into the filter), or runoff reduction expressed in terms of runoff delivery ratio (RDR= runoff out from filter/runoff into the filter). The procedure to evaluate the uncertainty for a given design case is based on the following steps (Parsons and Muñoz-Carpena, 2001): 1) identify and rank the input parameters of UH and VFSMOD relative to their sensitivity on sediment trapping, 2) develop probability density functions for the most sensitive input parameters, 3) use Monte Carlo Simulation to sample the input parameters and develop a probability density function for sediment trapping. This procedure allows the estimation of confidence intervals or exceedance probabilities for the BMP effectiveness to meet a TMDL requirement. In this way, the user can use a priori knowledge of local variability and obtain better (or more certain) predictions.

The analysis is illustrated with the typical application in the Piedmont region of North Carolina presented in the design example above and in this case the VFS is designed to meet a required TMDL sediment reduction of 80% (SDR=20%). Based on previous design results (Figure 5), the VFS length was fixed at 5 m for the 1-yr storm and 10 m for the 5-yr storm. A sensitivity analysis allowed selecting the sensitive parameters of the model to use in the uncertainty analysis (Muñoz-Carpena et al, 2007). A total of 3300 simulations (1800 and 1500 for the 1-yr and 5-yr storms, respectively) were run in the MCS procedure. The resulting cumulative probability density functions for SDR and RDR compared with those for the 1-year return period storm with a 5 m buffer length are shown in Figure 6.

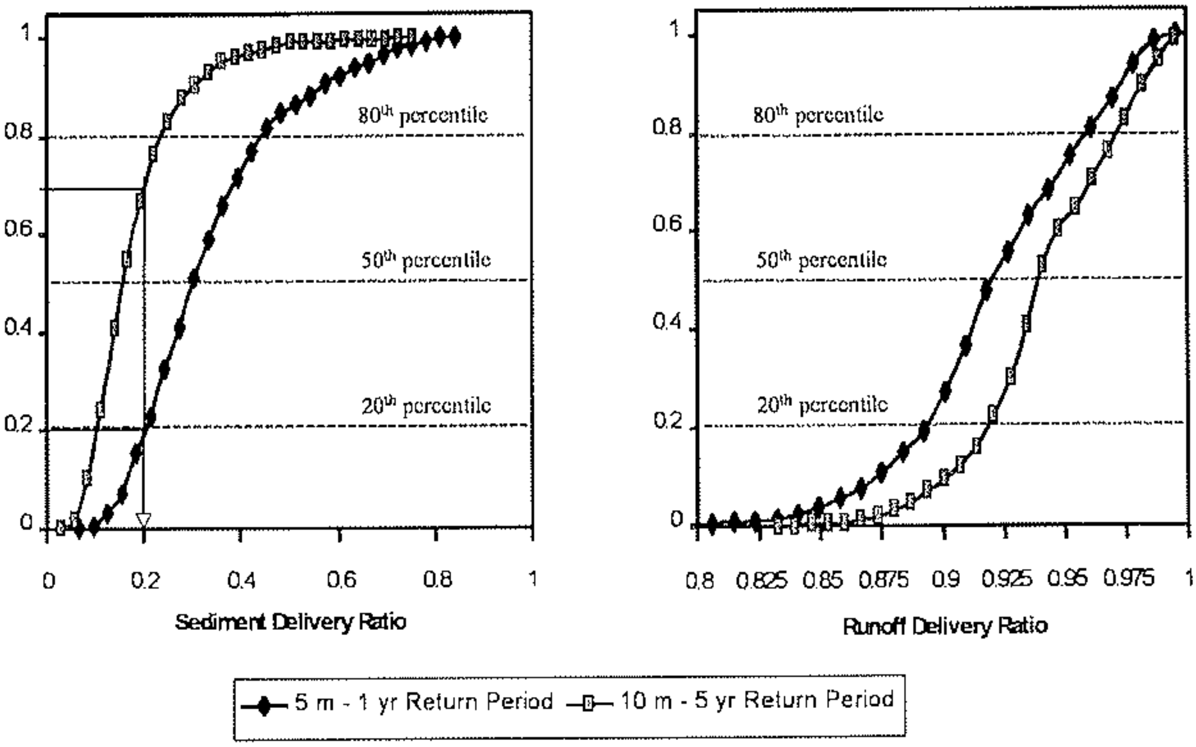

Figure 6. Comparison of simulated probability density functions for sediment and runoff delivery ratios obtained in the uncertainty analysis.

The SDR probability density function is shifted left for the 5-yr/10 m combination, as compared to the 1-yr/5 m. The results show that the probability of achieving the required SDR of 0.2 or less is 70% for the 5-yr scenario, while the probability of meeting this requirement is only 20% for the 1-yr scenario. Conversely, Figure 8 shows that if the same probability of 70% were desired for the 1-yr. design, the TMDL objective would not be met, since only a sediment reduction of 60% (SDR=0.4), a substantial 25% loss of efficiency for this BMP, would be achieved.

The response curves can be evaluated with respect to the TMDL plan design goal, i.e., a required sediment reduction expressed in terms of sediment delivery ratio (SDR = sediment out from filter/sediment into the filter), or runoff reduction expressed in terms of runoff delivery ratio (RDR = runoff out from filter/runoff into the filter).

Conclusions

Today watershed protection in the USA is based on the systematic application of the Total Maximum Daily Load program, the cornerstone of the Clean Water Act. For waterbodies that do not meet the required standards based on their intended use, a watershed action plan must be implemented consisting of best management practices (BMPs) optimized and distributed in the landscape. An example for the State of Florida shows the complexity of the program, as well as its participative nature through stakeholder involvement.

However, on-going evaluation of 50 years of pollution control practices in the USA (CEAP) show that BMPs did not achieve the expected efficiency under field conditions. It is argued that one of the critical limitations of the TMDL program today is the lack of knowledge/understanding of the factors controlling the BMP efficiency under a wide range of conditions. There is an urgent need of design approaches that are based on mechanistic, process-based and fundamental description of the BMP in-field performance. An illustrative design example of vegetative filter strips to achieve TMDL sediment targets is presented based on the application of the numerical/physical model VFSMOD. The flexibility and generality of the approach allows for the objective identification of the VFS performance for a wide range of environmental conditions as well as the assignment of the margin of safety to include the effect of the uncertainty in the design values obtained.

Design aids are needed to help municipalities, property owners, and others take the "guesswork" out of determining adequate buffer widths for the purpose of water resource quality protection. Although BMPs can be effective tools for watershed protection, until easy-to-use, generally applicable and tested design aid tools are developed we will not get beyond the current "one size fits all" approach used for many practices.

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