

## Review

# Approaches to TMDL planning and implementation and policy tools for implementation to achieve water quality standards

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## Abstract

This review is based primarily on information gathered in the TMDL Knowledgebase Clearinghouse developed by the Center for Total Maximum Daily Load (TMDL) and Watershed Studies at Virginia Tech. The TMDL programme has received renewed attention since the US Environmental Protection Agency (EPA) published revised guidelines in 1991. Under the TMDL programme, pollutant-specific TMDLs are developed for impaired waters. A TMDL specifies the pollutant load reductions needed to achieve water quality standards. The magnitude and distribution of the load reductions among pollution sources can have implications for watershed stakeholders. Implementing the TMDL load reductions is the responsibility of the individual US states. Adaptive implementation occurs when limited corrective actions designed to improve water quality are implemented using available information and data; and as information and data availability improve implementation adjustments are made, i.e. 'learn while doing'. While several policy tools are available to ensure that corrective actions are implemented, economic incentives are most often used, particularly for non-point source pollution sources. Typically, successful TMDL implementation depends on careful planning and stakeholder engagement. However, meaningful stakeholder engagement requires that stakeholders be empowered to make decisions about outcomes relevant to their goals, which may be problematic given the narrow way the TMDL process is currently enacted. Planning using watershed-scale models to assess plausible load reduction scenarios is most likely to produce credible TMDL pollutant load estimates. Models should be coupled with adaptive implementation so that pollutant load estimates can be revised as better information becomes available. TMDL implementation plans should consider both barriers to and opportunities for implementation.

**Keywords:** Standards, Policy, Uncertainty, Load Allocations, Adaptive Implementation, Stakeholders

**Review Methodology:** This review relied heavily on the contents of the TMDL Knowledgebase Clearinghouse [1] developed by the Center for Total Maximum Daily Load (TMDL) and Watershed Studies at Virginia Tech in cooperation with US Environmental Protection Agency (EPA). The searchable Clearinghouse contains summaries of the 50 US states' TMDL programmes, available TMDL development and TMDL implementation planning guidance documents, and topical synopses of TMDL-related scientific and trade literature. The Clearinghouse can be searched in a variety of ways (e.g. by cause of impairment, TMDL development method or approach, or waterbody type). In developing the Clearinghouse, TMDL-related literature was gathered using AGRICOLA, CAB Direct and Cambridge Scientific Abstracts (CSA) Illumina databases current through 1 May 2007. Additional information was collected via state TMDL Web sites, individual TMDL reports and from email and personal interviews with state agency personnel responsible for the TMDL programme and other TMDL experts. TMDL development is still in its infancy and TMDL implementation has an even shorter history. As a result, the review presented here relies heavily on non-peer reviewed citations.

## Introduction

Although the US Congress mandated the Total Maximum Daily Load (TMDL) programme in Section 303(d) of the

Clean Water Act (CWA) of 1972, Environmental Protection Agency (EPA) first published guidelines for Section 303(d) in 1991 [2]. A portion of the TMDL development and implementation that has occurred to date has been

**Table 1** Frequency that selected TMDL development methods are used for common stream/river impairments [1]

Method	Impairment				
	Pathogens	Nutrients	Metals	Sediment	Oxygen demand (DO)
Single value targeting (mass balance)	27% (10/37) <sup>a</sup>	28% (5/18)	63% (12/19)	40% (8/20)	10% (2/21)
Statistical method (load duration curves)	54% (20/37)	11% (2/18)	21% (4/19)	10% (2/20)	5% (1/21)
Spreadsheet model	n/a	n/a	5% (1/19)	10% (2/20)	43% (9/21)
Water quality modelling software	19% (7/37)	61% (11/18)	16% (3/19)	45% (9/20)	57% (12/21)

<sup>a</sup>Numerator is equal to the states reporting method for the impairment in the Clearinghouse Database, denominator is equal to the total number of states reporting TMDLs for that impairment in the Clearinghouse Database.

Note: Some states use two methods for setting TMDLs for a given impairment. Approach methods categorized based on each state's dominant approaches used in their most recent approved TMDL reports.

**Table 2** Frequency that selected TMDL development methods are used for common lake and estuary impairments [1]

Method	Impairment				
	Pathogens	Nutrients	Metals	Sediment	Oxygen demand (DO)
Single value targeting (mass balance)	33% (2/6)	18% (5/28)	67% (4/6)	17% (1/6)	n/a
Statistical method (load duration curves)	n/a	n/a	n/a	n/a	n/a
Spreadsheet model	n/a	18% (5/28)	n/a	33% (2/6)	n/a
Water quality modelling software	67% (4/6)	68% (19/28)	33% (2/6)	50% (3/6)	100% (7/7)

brought about by litigation intended to motivate EPA to execute Section 303(d). This paper reviews the current approaches used for developing TMDLs and briefly discusses TMDL implementation for the purpose of attaining ambient water quality standards.

Sections 303(d) and 305(b) of the CWA require that waterbodies in the USA be evaluated in the context of applicable water quality standards developed by the states and assigned to specific waterbodies. Under the CWA, pollutant-specific TMDLs are established for waterbodies that are not meeting water quality standards (impaired waters). Of the waters assessed to date, 40% have been found to be impaired: representing approximately 60 000 impairments [3]. Pathogens, heavy metals, nutrients, sediment, dissolved oxygen (excessive oxygen depletion) and loss of in-stream aquatic life amount and diversity (resulting from habitat alteration, temperature, pH and other undetermined causes) are the most common impairments. Approximately 24 000 TMDLs have been completed to date [3].

TMDLs have been developed using various approaches including mass balance/conservation of mass (e.g. determining pollutant loads to achieve a numeric water quality criteria), statistical methods (e.g. load duration, regression models) and computer-based water quality modelling (e.g. using simulation models to establish pollutant load allocations). Although each of these methods has been used, some are more common than others, especially for certain types of impairments. Acknowledging that there may

be others, the following section focuses on these three broad TMDL development approaches. Data available in the TMDL Clearinghouse [1] was used to determine the number of reporting states that used the TMDL development approaches mentioned above. The frequency of US states reporting that these approaches have been used to address pathogen, nutrient, metal, sediment and dissolved oxygen impairments is presented in Table 1 for streams and rivers and in Table 2 for lakes, reservoirs and estuaries.

### Establishing Causes of Impairments and Identifying Maximum Loads

#### Mass Balance Approach

The mass-balance approach for TMDL development utilizes observed water-quality data and an average flow condition or volume to determine pollutant loads. Jarrell [4] suggests developing TMDLs using a 'conservative' mass balance approach that focuses on targeting a single value of the offending pollutant. This 'single-value' is a function of the applicable water quality criteria and some physical condition of the impaired waterbody (e.g. a particular design flow).

The mass balance approach is used most often for heavy metal impairments (Table 1). According to an EPA case study [5], mass balance is an acceptable method to be

used for heavy metal impairments from acid mine drainage, since ambient monitoring indicates that the most critical point for the metals contamination from the sites occurs close to the point of discharge and the metal concentrations tend to attenuate downstream from the source. Developers of a pathogen impairment TMDL in Mississippi used this approach and concluded that the approach was best suited to situations where data limitations preclude the use of more complex methods [6]. Bonta and Cleland [7] criticize the use of the mass balance approach because information on how frequently or how long a single 'conservative' value actually occurs is typically not available. Thus a TMDL developed using this approach is often either not restrictive enough to be protective of water quality standards or so strict so as to be unattainable. Stiles [8] concludes that a single-value mass balance approach has limited utility when dealing with impairments caused by non-point source (NPS) pollution because this kind of approach may not take into account water quality violations associated with larger storm events, where NPS pollution becomes the dominant factor influencing water quality.

### **Statistical Approach**

The load-duration curve method is one form of a statistical approach that is commonly used to develop TMDLs. Flow-duration curves illustrate the percent of time that a particular flow rate is exceeded. A load-duration curve extends this concept by combining flow data with observed pollutant concentration data and comparing the resulting observed loads with allowable loads based on the combination of the flow data and the applicable water quality criteria. The load-duration curve compares the applicable water quality criteria (typically concentration based) with observed water quality and the range of flows seen at a specific monitoring location to determine needed pollutant reductions [8]. The flow conditions under which observed loads exceed the allowable loads indicate the potential pollutant sources and are used to develop pollutant load allocations.

The load duration curve approach was developed by the Kansas Department of Health and the Environment (KDHE) to meet its 1998 TMDL consent decree obligations [9]. Twenty-two states report using the load-duration curve approach to develop TMDLs for one or more impairments [1]. Three states have developed load-duration curve TMDL development guidance documents [10–12]. While the load-duration method has been primarily used to address pathogen impairments for flowing waterbodies (Table 1), it has also been used to develop TMDLs for metals, nutrients, sediments and chlorides. The load-duration curve method provides a representation of overall water quality and accounts for watershed processes. However, intra-watershed pollutant contributions must be determined through supplemental sampling

or through subsequent modelling that relates land use and hydrologic response to pollutant loads [13].

The Nevada load-duration curve guidance document [12] outlines benefits of this approach including the ability to identify flow conditions under which most violations occur. Bonta and Cleland further discuss how load-duration curves can be used to quantify changes in flow, pollutant loading rates and concentrations over time due to implementation of best management practices (BMPs) by looking at how frequently allowable loads are exceeded [7, 14, 15]. Both Bonta and Cleland [7] and the Nevada guidance document [12] discuss how load-duration curves maximize the use of limited data, can potentially overcome problems of communicating complex watershed phenomena to lay persons, and can assist in quantifying the variability and uncertainty associated with the TMDL.

### **Computer-based Modelling Approach**

Use of computer-based models to develop TMDLs can be further divided into the use of spreadsheet-based models (i.e. situations where spreadsheet software is used rather than a pre-existing, dedicated modelling software package) and more sophisticated water quality simulation software (e.g. Hydrological Simulation Program Fortran HSPF; Generalized Watershed Loading Function model, GWLF). TMDLs addressing lake or reservoir impairments are sometimes developed using spreadsheet-based modelling. Havens and Walter [16] discuss using spreadsheet-based modelling in conjunction with empirical lake loading relationships in their case study of phosphorus load reduction goals for Lake Okeechobee, Florida. Based on data collected for the TMDL Clearinghouse, the use of water quality simulation software to develop TMDLs is the most common method across all impairments and waterbody types (Tables 1 and 2).

Water quality simulation software can be used to estimate watershed loads for existing conditions and evaluate the effectiveness of proposed control alternatives in reducing pollutant loads to meet ambient water quality standards [17]. The particular water quality simulation software (model) used for TMDL development varies with the impairment, the offending pollutant and complexity of the system. Comparisons of the approach, assumptions and capabilities of existing water-quality simulation models have been published [18–20] including a special series published in *Transactions of the ASABE* (Volume 49, Number 4). This series of papers represents the efforts of a multidisciplinary panel of experts who assessed the current status of modelling as it relates to TMDL development for various types of impairments [13, 21–24].

A 1991 EPA TMDL guidance document [2] identified three guidelines for model selection for TMDL development. The model should: (1) be applicable to the specific

situation, (2) provide appropriate level of analysis and (3) incorporate practical constraints into the selection criteria. DePinto *et al.* [17] further discussed the principles of model selection and good modelling practice for use in TMDLs. The steps they outline for good modelling practice include: problem definition and setting management objectives; data synthesis for use in model selection; model calibration and, if possible, validation; model application; iterative modelling and a modelling post audit. Muñoz-Carpena *et al.* [23] also concluded that although model selection should be objective-dependent, it should also be part of an adaptive management process and subject to revision.

Several case studies discussing the application of water quality simulation models for TMDL development for various impairments have been published including bacteria for both fresh water [25–27] and saltwater [28, 29], nutrients [25, 30–35], dissolved oxygen [36–38], metals [39, 40], sediment [25, 41] and pesticides [42]. Many of these case studies outline the methods used to characterize the watershed and the pollutant sources, model calibration and validation, and the methodology used to develop the pollutant reduction/allocation scenarios.

Muñoz-Carpena *et al.* [23] express concerns that the role and power of models are often overstated by users and developers. The water quality simulation modelling that occurs as part of TMDL development is only one component in a complex process. Model developers need to better clarify the proper use and limitations of their models to prevent misuse or abuse of available modelling tools. Muñoz-Carpena *et al.* [23] also state that models may be better suited for assessing relative, rather than absolute changes in pollutant loads. The pitfalls and related opportunities of water quality modelling and the TMDL decision process are further discussed by Chapra [19] who focuses on six particular areas: (1) model complexity, (2) data and monitoring, (3) reliability, (4) uncertainty, (5) decision support and (6) future investment. Whittemore and Beebe [43] are critical of EPA's BASINS for use in TMDL development because the packaged software includes NPS models and data sets, which gives rise to technical and philosophical concerns related to default data usage. They further note that more rigorous peer-review is needed to address glitches in the programme.

Muñoz-Carpena *et al.* [23] suggest that when selecting a TMDL development method several factors must be considered: the type of impairment, the source of the offending pollutant (point source or NPS), data availability and resource constraints (e.g. time, money and expertise) among others. No matter which method is used, Benham *et al.* [44] suggest that the more detailed the watershed characterization that is performed during the TMDL study, the more likely it is that TMDL implementation will result in water quality improvement. A detailed watershed characterization is also essential for defining watershed

management needs as addressed in the EPA watershed handbook [45].

### Developing Pollutant Load Allocation Scenarios

There is little literature describing how load reduction allocations among pollutant sources are actually made. Conceptually, approaches include (1) making allocations among NPSs after deciding how much load reduction can be obtained from permitted sources; (2) making allocations based on uniform percentage reductions among all sources and (3) making allocations to source(s) with lowest costs of control (L. Shabman, personal communication, 2007). The statutory and regulatory structure of the CWA would tend to create a bias for the first approach. The CWA authorizes EPA or a designated state the authority to impose effluent limitations on a specific subset of dischargers called point sources. Technology-based effluent limits for these sources are established within a permit system. Other sources, often called NPSs, face no federal statutory requirement to limit discharge. Agency permit staff are instructed to issue permits that are consistent with water quality standards. In the load allocation process, the goal is often to assign the lowest possible load (wasteload allocation) to the sources where regulatory agencies have permitting authority (e.g. point sources). The remaining load reductions that cannot be achieved through the application of stringent point source controls are then allocated to NPSs (load allocation) (for example, see Christina River, Delaware [46]). The perceived imperative to maximize point source reductions may be one possible reason watershed managers generally regard stakeholder involvement in developing load allocations as unhelpful [47].

Other approaches, however, are sometimes used to allocate loads. The second approach of assigning a proportional load reduction has been used to set pollutant load reduction goals for point source and NPS in the Neuse River Basin in North Carolina and Toms Brook watershed in Virginia [48, 49]. The third approach could be accomplished by using cost minimization models [50], however, it is perhaps the least often practiced (L. Shabman, personal communication, 2007).

### Uncertainty in TMDLs

All TMDLs account for uncertainties associated with TMDL development. This is often accomplished by including an either explicit or implicit margin of safety (MOS). An implicit MOS is most often associated with the use of conservative assumptions during modelling and establishing pollutant load calculations [2]. An explicit MOS is expressed as an unallocated assimilative capacity, i.e. some, typically arbitrarily determined, fraction of the allowable pollutant load that is not allocated to point

source or NPSs within the watershed [2]. Uncertainty associated with TMDL development can include both knowledge uncertainty that results from an incomplete understanding of the system(s) being studied and stochastic uncertainty that comes from the inherent variability in the system(s) (e.g. climate variability, variability in soils).

Typically, uncertainty analysis in TMDL calculations is not addressed in a rigorous manner, and the approaches currently used vary widely [51, 52]. Reckow [53] discusses the issue of uncertainty as it relates to using water quality simulation models to develop TMDLs and the need to assess uncertainty in a context of adaptive management to improve the chances of achieving compliance with water quality standards. Shirmohammadi *et al.* [54] reviewed several methods for determining uncertainty when using water quality simulation models to develop TMDLs, and conclude that the best method to account for uncertainty in modelling would be to develop uncertainty probability distribution functions and incorporate uncertainties into TMDL load allocation through the MOS, the magnitude of which, at the present time, is arbitrarily set. Bonta [7] and Cleland [13] discuss using load-duration curves to aid in identifying and quantifying uncertainty. Shabman *et al.* [55] also identify sources of uncertainty in TMDLs and the need to address them to allow for cost-effective attainment of water quality standards. They also outline steps to identify sources of uncertainty.

## TMDL Implementation

The ultimate measure of success of the TMDL programme is the attainment of ambient water quality standards through the control of both point source and NPS pollution [51]. While the CWA has no specific provisions for TMDL implementation planning or execution, there is recognition of the need for both to achieve TMDL programme goals. Support for implementation planning is evident in federal guidance [2, 56, 57]. The 'Guidance for Water Quality-Based Decisions: The TMDL Process' [2] published in 1999 recommends the following minimum elements for a TMDL Implementation Plan (IP):

- a description of the implementation actions and management measures;
- a time line for implementing these measures;
- a description of available legal or regulatory controls;
- the time required to attain water quality standards; and
- a monitoring plan and milestones for attaining water quality standards.

While most state recommendations and requirements for TMDL implementation closely track these minimum elements, states exercise flexibility in how they approach their TMDL implementation responsibilities [58]. More

than a dozen states have passed laws and/or established regulatory guidance related to TMDL implementation planning, and TMDL IPs are being implemented across the country using a variety of approaches, with varying levels of detail, stakeholder participation and success [44]. An examination of TMDL implementation case studies conducted by Benham *et al.* [44] indicates that there is no one-size-fits-all approach to TMDL implementation. Every watershed is unique: not just in terms of environmental features, but also in its regulatory landscape, socio-economic factors, and many other location-specific characteristics, problems, risks and resources.

The minimum IP elements listed above describe standard implementation whereby a plan is developed initially and followed until standards are achieved [55]. In contrast to standard implementation, adaptive implementation is frequently presented as a flexible means of responding to the dynamic complexities of most watersheds [44, 55, 59–61]. Adaptive implementation can facilitate effective planning and execution efforts if watershed managers have the ability and willingness to adjust the implementation plan based on what is learned from monitoring. An adaptive approach to TMDL implementation allows for adjustments to what the Maryland Department of Environment refers to as, 'the realities on the ground, such as the willingness of particular property owners to participate, the availability of particular funding, or physical constraints' [58]. In an adaptive implementation process, interim implementation goals and milestones help to reduce uncertainty by utilizing information obtained as the plan is implemented. Shabman *et al.* [55] advocate using an adaptive implementation process which takes into account uncertainty in the TMDL process through waterbody-specific and carefully-targeted monitoring, ongoing research and experimentation. They further describe approaches for utilizing adaptive implementation within and outside the TMDL programme as part of a watershed management effort.

Freedman *et al.* [61] noted that with adaptive implementation, initial successes can be achieved, while additional information is collected and incorporated into the IP. The results of such an approach, over time, can include improved monitoring and modelling, and reassessed water quality targets and control actions: all contributing to increased TMDL implementation effectiveness [61]. Shabman *et al.* [55] also conclude: 'adaptive implementation will succeed only if there is a commitment of resources to the learning process'.

Monitoring is a key element in adaptively managing a watershed. Davenport and Kirschner [62] conclude that the most defensible measure of the management effort's performance 'is a well-designed and implemented monitoring effort that statistically examines the relationship between the project's activities and changes in water quality'. They recommend adaptive implementation with an evaluation framework that consists of a mixture of

administrative, social and environmental measures. A comprehensive approach is also outlined in California guidance [59] where multiple types and levels of tracking and monitoring are recommended.

Various state guidance documents also suggest an adaptive approach to TMDL implementation [58–60, 63]. However, other elements may conflict with adaptive implementation. For example, the emphasis on ‘reasonable assurances’ may lead to emphasis on a MOS to insure that TMDL load reductions are met. While commitment of time and money to upgrading implementation plans over time within the framework of adaptive implementation could also be viewed as a reasonable assurance, it is less likely to be viewed as such by EPA compared with a MOS. Some states require specific elements in IPs, while others simply offer suggestions for what information an IP should contain.

Often CWA Section 319 grants are used to support TMDL implementation activities [64]. The *Supplemental Guidelines for the Award of Section 319 Nonpoint Source Grants to States and Territories in FY 2002 and Subsequent Years* [56] contains specific information related to potential funding of TMDL implementation projects. The following nine elements must be included in a project to receive 319 monies:

1. Identify the causes and sources or groups of similar sources that will need to be controlled to achieve the load reductions estimated in the watershed-based plan.
2. Estimate the load reductions expected from NPS management measures.
3. Describe the NPS management measures that will need to be implemented to achieve the identified load reductions.
4. Estimate the amounts of technical and financial assistance needed, associated costs, and/or the sources and authorities that will be relied upon to implement the watershed-based plan.
5. Provide an information/education component that will be used to enhance public understanding of the project and encourage the public’s participation in selecting, designing and implementing NPS management measures.
6. Provide a schedule for implementing the NPS management measures identified in the watershed-based plan.
7. Describe interim, measurable milestones for determining whether NPS management measures or other control actions are being implemented.
8. Identify a set of criteria for determining if loading reductions are being achieved and progress is being made towards attaining water quality standards, and if not, the criteria for determining if the watershed-based plan needs to be revised.
9. Establish a monitoring component to evaluate the effectiveness of the implementation efforts.

The nine elements required for CWA Section 319 grants [56] are also frequently referenced in state TMDL IP development guidance documents [58].

The fifth mandatory element for Section 319 funding, ‘encourage the public’s participation’, highlights a concept that is also reflected in state guidance documents and relevant literature. In an assessment of TMDL implementation, active involvement of stakeholders was found to have facilitated TMDL implementation actions and water quality improvement [44]. Developing a TMDL IP is usually a resource-intensive undertaking, requiring significant investments of time, money and technology. Without stakeholder engagement, the return on such investments can be disappointing. Muench and Streeter [65] identified stakeholder involvement as an essential element in successful TMDL implementation.

Stakeholders more readily accept the problem with the waterway, and are more willing to spend resources on cleanup, if TMDL details have been explained well. Establishing stakeholder support is often easier when interested parties are engaged early in the TMDL process. Benham *et al.* [44] suggest that stakeholder engagement is crucial, for example, in NPS dominated watersheds comprised primarily of privately owned lands [44]. Similarly, Fowler and Duvall [66] observed how stakeholder involvement can be vital for TMDL implementation in rural areas where, ‘locally-lead involvement and participation in the process is the only way to ensure success’. Even when there are similarities among watersheds, underlying variables may justify greater attention to stakeholder needs and interests, and how they might effect implementation planning. McClellan *et al.* [67], for example, noticed that cultural differences among stakeholders can play an important role in defining the approach taken during implementation.

While stakeholders from all levels can play a role in TMDL implementation, interest and involvement from government agencies can be especially important. Boman and Thomas [68] highlighted successes in Florida, for example, where the Florida Department of Environmental Protection allocated more than \$1.6 million of CWA Section 319 grant funding to a large educational outreach and BMP demonstration effort. Citrus growers and their employees were the target audience of this stakeholder involvement effort. Thousands were trained to prevent pollution and use BMPs in their operations. The result was more than 95% compliance with the BMP programme.

Others have noted that the TMDL regulatory process may be too narrowly defined to meaningfully address stakeholder concerns with equity, cost effectiveness and tradeoffs between costs and benefits of water quality regulation to be adequately addressed [69]. These barriers may arise before actual TMDL implementation. For example, Maguire notes that technical models may be inaccessible or unresponsive to stakeholder input. Other issues may arise with lack of stakeholder input in evaluating the validity or specific measurement of the water

quality standard (designated use and/or water quality criteria). As a result, the opportunities for effective stakeholder involvement are limited [47], which may undercut political support for TMDL implementation. Adaptive implementation of TMDLs with flexible load allocations would allow stakeholder concerns to be addressed and increase stakeholder support for TMDL implementation [55].

Government involvement can also be important during TMDL implementation, such as in tracking information that is essential to gauging water quality improvement. In addition, land use planning can help anticipate the effects of land use changes on pollutant loads [58]. Chen and Herr [70] suggested the use of a decision-support system (DSS) to facilitate stakeholder involvement in TMDL implementation, 'one that can calculate various combinations of point and nonpoint loads that can meet the water quality criteria, and ultimately support a decision making process that requires negotiation and compromise among stakeholders'. They describe a DSS that features TMDL and consensus modules, the latter of which allows stakeholders to formulate, evaluate, modify and vote for alternatives.

### Policy Tools for TMDL Implementation

Policy tools to induce adoption of corrective actions as part of TMDL implementation can be broadly categorized as (1) effluent standards (technology or water-quality-based effluent limitations), (2) subsidy programmes, (3) education, (4) research and development and (5) effluent trading [71, 72]. Policies may be implemented in combinations. For example, regulations on point sources may be combined with cost-share subsidies to assist in adopting the required technologies to meet the effluent limits.

As described above, effluent standards for municipal and industrial point source dischargers are the historical focus of the CWA. However, traditional point source dischargers are not the primary cause of impairment in the majority of cases [3]. Because there are no provisions in the CWA for imposing regulations on NPSs, the scope for using regulations to implement TMDLs is limited to point sources. Over time, broadening the definition of point sources to include former NPSs also increases the scope for regulations. For example, the municipal separate storm sewer systems (MS4) programme grew out of the 1987 amendments to the CWA which essentially reclassified urban stormwater from a NPS to a point source [73]. Furthermore, state and local governments have can impose their own regulatory authorities on NPSs outside the scope of federal law [74].

Perhaps the most commonly used policy instruments for TMDL implementation fall in the category of incentives, specifically subsidies to encourage adoption of specific pollution control practices or technologies. Dedicated cost-share programmes such as the USEPA 319

programme and CWA Cooperative Agreements as well as other state and federal programmes are frequently used for TMDL implementation. State grant and low-interest loan programmes subsidize the installation of capital upgrades at municipal wastewater treatment plants [75]. These programmes are frequently used to encourage adoption of BMPs to reduce point source and NPS pollution from agriculture, residential development and other sources. Traditional USDA cost-share programmes (such as the Environmental Quality Incentives Program (EQIP)) could be used to encourage adoption of Best Management Practices. However, these programmes are not targeted for TMDL implementation and are used to a lesser extent [47]. State and federal agencies also provide individuals with in-kind assistance, such as free technical advice to assist with adoption of conservation practices. States may target selected subwatersheds for priority assistance to insure that limited funds are allocated where the greatest pollution reduction is achieved per dollar of expenditure [64].

Public education is an important part of TMDL implementation. Education falls under two broad categories: (1) education to make stakeholders aware of the importance and value of watershed protection and (2) education about ways that stakeholders can reduce pollution such as adoption of BMPs [64]. Education may be provided through printed materials, demonstration projects and oral presentations.

Because TMDL implementation plans are watershed specific and have relatively short timelines, research and development play a limited role in implementation. Research and development projects often have high costs, long time lags and uncertain success rates. However, in some cases applied research projects may be used to further TMDL implementation plans. For example, applied research may be conducted to validate TMDL goals with respect to pollution reduction and thus enhance continued cooperation of stakeholders [64].

Trading is increasingly being encouraged as a way to enhance TMDL implementation [76, 77]. Trading can be implemented in a variety of forms, but there are of two major types [78]. One type of trading programme is a response to the regulatory issue encountered in the load allocation process. As described above, regulators may require permitted point sources to maximize effluent control technologies in order to meet necessary TMDL load reductions. Growth in wastewater flows or imposition of zero discharge limits may make compliance difficult or impossible. In such cases regulatory agencies can allow or require the regulated point source to sponsor effluent load reductions from unregulated effluent sources. Such trading programmes might be described as another regulatory compliance mechanism because more expensive point source controls cannot be avoided through a 'trade'. Such programmes are not motivated by cost-effectiveness issues. A second type of trading programme establishes transferable discharge allowances based on the aggregate

allowable load identified under a TMDL. Regulated sources have the discretion to decide how to meet wasteload allocations, including trading allowances with other sources [79]. Unlike regulator-directed compliance programmes described above, these trading programmes are designed on market-like principles and are mechanisms to reallocate loads based on lowering costs. While less common than regulator directed trades, market-like trading programmes have been implemented in some locations [79].

## Conclusions/Summary

The TMDL programme, which was mandated in Section 303(d) of the 1972 CWA, has received renewed attention since EPA guidelines for Section 303(d) were published in 1991. The most common methods used to develop TMDLs are mass balance, statistical or modelling approaches. The approach used depends on the type of impairment, the source of the offending pollutant (point source or NPS), data availability and resource constraints. The allocation of reductions in loads to stakeholders has important implications for stakeholder costs and for stakeholder support in implementation. Numerous procedures (approaches) are available to assist in making load allocations to pollution sources in order to achieve defined objectives, but there is less published evidence on what approach is followed. Developing a TMDL allocation scenario includes inherent uncertainty. To date this uncertainty has been typically addressed by including an arbitrary MOS in every TMDL. While several techniques are available to quantify TMDL-related uncertainties, additional research in this area is needed.

The EPA has set general guidelines for implementing TMDLs and more detailed guidelines for states to receive 319 funding for implementation. Perhaps the most important principle is adaptive implementation whereby limited actions are taken based on available data while continuous improvements are made as better information becomes available [51]. Shabman *et al.* [55] state, 'The central theory of adaptive implementation is that uncertainty can be reduced over time only by studying and/or modelling watershed and water quality responses to load reductions, implementing controls, and then carefully and methodically assessing the results in order to *learn while doing*'. Several policy tools are available to insure implementation of measures. Regulations are important but only apply to point sources. Financial or in-kind economic incentives are the most often used policy tool particularly for NPS pollution sources.

TMDLs must be comprehensive and well thought out, so that they are credible enough to convince stakeholders to spend time and money implementing them. Each approach for developing pollutant-specific TMDLs has its own strengths and weaknesses. Modelling approaches are most likely to produce credible plans, particularly if they

take uncertainty into account. However, regardless of the approach used, the process of developing TMDLs should emphasize educating stakeholders about their watershed through detailed watershed characterization. Education is best accomplished if stakeholders are able to actively learn and participate in the TMDL process. Engaging stakeholders will enhance implementation. However, meaningful stakeholder engagement requires that they be empowered to make decisions about outcomes relevant to their goals. As some observers have noted, this empowerment is a challenge given the narrow way in which the TMDL process is currently implemented. The approach used for developing TMDLs should be used with adaptive implementation so that estimated loadings can be revised, if necessary, as more and better data and knowledge about pollution processes become available.

Currently, federal and state programmes such as the USEPA 319 programme are major sources of funds for implementation projects. As more TMDL programmes are implemented, availability of public funds for implementation likely will decline relative to needs. As a result, TMDL implementation will increasingly depend on other means such as regulation, education and trading. These policy instruments will be more effective in areas with strong stakeholder support for TMDL plans. Stakeholder support for implementation can be enhanced by involving stakeholders early in the planning process and keeping them involved. For example, the allocation of loads and load reductions among sources can have large effect on stakeholders' incomes and economic opportunities. Yet little information is available on how allocations are actually determined. More research is needed on how load allocations are made and how stakeholders are engaged. Such research might show additional opportunities for increasing stakeholder support for TMDL processes by more active consultation in decisions about load allocations. Research is also needed on other ways of educating and engaging stakeholders in TMDL development and implementation.

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## References

1. Center for TMDL and Watershed Studies. TMDL Knowledgebase Clearinghouse. 2007 [cited 18 July 2007]. Available from: URL: <http://www.ext.vt.edu/cgi-bin/WebObjects/TMDL.woa>

2. USEPA. Guidance for Water Quality-based Decisions: The TMDL Process. Technical Document EPA 440/4-91001. US Environmental Protection Agency, Office of Water (WH-553), Washington, DC; 1991.
3. USEPA. National Section 303(d) List Fact Sheet. 2007 [cited 22 May 2007]. Available from: URL: [http://oaspub.epa.gov/waters/national\\_rept.control](http://oaspub.epa.gov/waters/national_rept.control)
4. Jarrell WM. Getting Started With TMDLs. Oregon Institute of Science and Technology, Portland, OR; 1998.
5. EPA. TMDL Case Study: West Fork of Clear Creek. Report No. EPA841-F-93-003. 1992. [cited 2 August 2007]. Available from: URL: <http://www.epa.gov/OWOWtmdlcs3cs3.htm>
6. Mississippi Department of Environmental Quality. Fecal Coliform TMDL for Cypress Creek, Tombigbee River Basin, Oktibbeha County, Mississippi. Final Report. 2006 [cited 9 August 2007]. Available from: URL: [http://www.deq.state.ms.us/MDEQ.nsf/pdf/TWB\\_TombigbeeRBCypressCreekFecalColiformJul06/\\$File/TombigbeeRBCypressCreekFecalColiformJul06.pdf?OpenElement](http://www.deq.state.ms.us/MDEQ.nsf/pdf/TWB_TombigbeeRBCypressCreekFecalColiformJul06/$File/TombigbeeRBCypressCreekFecalColiformJul06.pdf?OpenElement)
7. Bonta JV, Cleland B. Incorporating natural variability, uncertainty, and risk into water quality evaluations using duration curves. *Journal of the American Water Resources Association* 2003;39:1481–96.
8. Stiles TC. Incorporating hydrology in determining TMDL endpoints and allocations. In: *Proceedings of the National TMDL Science and Policy 2002 Water Environment Federation Specialty Conference, Water Environment Federation, Alexandria, VA; 2002.* pp. 13.
9. KDHE. Bureau of Water, the Basics of TMDLs. Web site [cited 29 May 2007]. Available from: URL: <http://www.kdheks.gov/tmdl/basic.htm>
10. Dunbar L, Becker ME. Development of Total Maximum Daily Loads (TMDLs) for Indicator Bacteria in Contact Recreation Areas Using the Cumulative Frequency Distribution Function Method. Connecticut Department of Environmental Protection, Hartford, CT; 2005.
11. Nebraska Department of Environmental Quality. Nebraska's Approach for Developing TMDLs for Streams Using the Load Duration Curve Methodology. Nebraska Department of Environmental Quality, Division of Water Quality Planning, Lincoln, NE; 2002.
12. Nevada Division of Environmental Protection. Load Duration Curve Methodology for Assessment and TMDL Development. Reno, NV; 2003 [cited 8 August 2007]. Available from: URL: <http://ndep.nv.gov/bwqp/loadcurv.pdf>
13. Benham BL, Baffaut C, Zeckoski RW, Mankin KR, Pachepsky YA, Sadeghi AM, *et al.* Modeling bacteria fate and transport in watersheds to support TMDLs. *Transactions of the ASABE* 2006;49:987–1002.
14. Bonta JV. Framework for estimating TMDLs with minimal data. In: *ASAE Total Maximum Daily Load (TMDL) Environmental Regulations: Proceedings of the Conference; 11–13 March 2002, Fort Worth, TX; St. Joseph, MI; 2002.* p. 6–12.
15. Cleland B. TMDL Development from the 'Bottom Up' – Part II: Using Duration Curves to Connect the Pieces. ASIWP-CA/WEF National TMDL Science and Policy 2002 Specialty Conference, Phoenix, Arizona, Session 8, Paper 4 [cited 22 May 2007]. Available from: URL: <http://www.tmdls.net/tipstools/docs/BottomUp.pdf>
16. Havens KE, Walker WW. Development of a total phosphorus concentration goal in the TMDL process for Lake Okeechobee, Florida (USA). *Lake and Reservoir Management* 2002;18:227–38.
17. DePinto JV, Freedman PL, Dilks DM, Larson WM. Models quantify the total maximum daily load process. *Journal of Environmental Engineering* 2004;130:703–13.
18. Borah DK, Bera M. Watershed-scale hydrologic and nonpoint-source pollution models: review of mathematical bases. *Transactions of the ASAE* 2003;46:1553–66.
19. Chapra SC. Engineering water quality models and TMDLs. *Journal of Water Resources Planning and Management* 2003;129(4):247–56.
20. Neilson BT, Hornsburg JS, Stevens DK, Matassa MR, Brogdon JN. EPRI's Watershed Analysis Risk Management Framework (WARMF) vs. USEPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). In: *ASAE Proceedings of the Total Maximum Daily Load (TMDL) Environmental Regulations II; Albuquerque, NM, USA; St. Joseph, MI; 2003.* p. 460–70.
21. Borah DK, Yagow G, Saleh A, Barnes PL, Rosenthal W, Krug EC, *et al.* Sediment and nutrient modeling for TMDL development and implementation. *Transactions of the ASABE* 2006;49:967–86.
22. Bosch DJ, Ogg C, Osei E, Stoecker AL. Economic models for TMDL assessment and implementation. *Transactions of the ASABE* 2006;49:1051–65.
23. Muñoz-Carpena R, Vellidis G, Shirmohammadi A, Wallender WW. Evaluation of modeling tools for TMDL development and implementation. *Transactions of the ASABE.* 2006;49:961–5.
24. Vellidis G, Barnes P, Bosch DD, Cathey AM. Mathematical simulation tools for developing dissolved oxygen TMDLs. *Transaction of the ASABE* 2006;49(4):1003–22.
25. Benham BL, Brannan KM, Yagow G, Zeckoski RW, Dillaha TA, Mostaghimi S, *et al.* Development of bacteria and benthic total maximum daily loads: a case study, Linville Creek, Virginia. *Journal of Environmental Quality* 2005;34:1860–72.
26. Hyer KE, Moyer DL. Enhancing fecal coliform total maximum daily load models through bacterial source tracking. *Journal of the American Water Resources Association* 2004;40:1511–26.
27. Moyer DL, Hyer KE. Use of the Hydrological Simulation Program-FORTRAN and Bacterial Source Tracking for Development of the Fecal Coliform Total Maximum Daily Load (TMDL) for Accotink Creek, Fairfax County, Virginia. Final Report. Department of Water-Resources Investigations – USGS; 2003 Report No. WRI 03-4160. Washington, DC. Available from: URL: <http://pubs.usgs.gov/wri/wri034160/wri03-4160htm>
28. Shen J, Sun S, Wang T. Development of the fecal coliform total maximum daily load using Loading simulation program C++ and tidal prism model in estuarine shellfish growing areas: a case study in the Nassawadox coastal embayment, Virginia. *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances and Environmental Engineering* 2005;40:1791–807.
29. Bai S, Lung WS. Three-dimensional modeling of fecal coliform in the Tidal Basin and Washington Channel, Washington, DC. *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances and Environmental Engineering* 2006;41:1327–34.
30. Borsuk ME, Stow CA, Reckhow KH. Integrated approach to total maximum daily load development for Neuse River Estuary using Bayesian probability network model

## 10 Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources

- (Neu-BERN). *Journal of Water Resources Planning and Management* 2003;129:271–82.
31. Bowen JD, Hieronymus JW. A CE-QUAL-W2 model of Neuse Estuary for total maximum daily load development. *Journal of Water Resources Planning and Management* 2003;129:283–94.
32. Gelda RK, Effler SW. Application of a probabilistic ammonia model: identification of important model inputs and critique of a TMDL analysis for an urban lake. *Lake Reservoir Management* 2003;19:187–99.
33. French C, Wu L, Meixner T, Haver D, Kabashima J, Jury WA. Modeling nitrogen transport in the Newport Bay/San Diego Creek watershed of Southern California. *Agricultural Water Management* 2006;81:199–215.
34. Culver TB, Naperala TR, Potts AL, Zhang HX, Neeley KA, Yu SL. Case study of impact of total maximum daily load allocations on nitrate leaching. *Journal of Water Resources Planning and Management* 2002;128:262–70.
35. Litwack HS, DiLorenzo JL, Huang P, Najarian TO. Development of a simple phosphorus model for a large urban watershed: a case study. *Journal of Environmental Engineering* 2006;132:538–46.
36. Pickett PJ. Pollutant loading capacity for the Black River, Chehalis River system, Washington. *Journal of the American Water Resources Association* 1997;33:465–80.
37. Conrads PA, Martello WP, Sullins NR. Living with a large reduction in permitted loading by using a hydrograph-controlled release scheme. *Environmental Monitoring and Assessment* 2003;81:97–106.
38. Zou R, Carter S, Shoemaker L, Parker A, Henry T. Integrated hydrodynamic and water quality modeling system to support nutrient total maximum daily load development for Wissahickon Creek, Pennsylvania. *Journal of Environmental Engineering* 2006;132:555–66.
39. Caruso BS. Simulation of metals total maximum daily loads and remediation in a mining-impacted stream. *Journal of Environmental Engineering* 2005;131:777–89.
40. Herr JW, Chen CW, Goldstein RA, Herd R, Brown JM. Modeling acid mine drainage on a watershed scale for TMDL calculations. *Journal of the American Water Resources Association* 2003;39:289–300.
41. Vondracek B, Zimmerman JKH, Westra JV. Setting an effective TMDL: sediment loading and effects of suspended sediment on fish. *Journal of the American Water Resources Association* 2003;39:1005–15.
42. Guo L, Nordmark CE, Spurlock FC, Johnson BR, Li LY, Lee JM, *et al.* Characterizing dependence of pesticide load in surface water on precipitation and pesticide use for the Sacramento River watershed. *Environmental Science and Technology* 2004;38:3842–52.
43. Whittemore RC, Beebe J. EPA's BASINS model: good science or serendipitous modeling? *Journal of the American Water Resources Association* 2000;36:493–9.
44. Benham B, Zeckoski R, Yagow G. Lessons learned from TMDL implementation case studies. *Water Practice*. Under review 2007.
45. U.S. Environmental Protection Agency. Draft Handbook for Developing Watershed Plans to Restore and Protect our Waters. Report No. EPA 841-B-05-005. 2005 [cited 21 August 2007]. Available from: URL: [http://www.epa.gov/owow/nps/watershed\\_handbook/#contents](http://www.epa.gov/owow/nps/watershed_handbook/#contents)
46. U.S. Environmental Protection Agency. Christina River Basin High-Flow TMDL [cited 16 October 2007]. Available from: URL: [http://www.epa.gov/reg3wapd/tmdl/pa\\_tmdl/ChristinaMeetingTMDL/index.htm](http://www.epa.gov/reg3wapd/tmdl/pa_tmdl/ChristinaMeetingTMDL/index.htm)
47. Cabrera-Stagno V. Developing effective TMDLs: an evaluation of the TMDL process. In: *Water Environment Federation. CD-ROM Proceeding of TMDL 2007*; 24–27 June 2007; Bellevue, Washington; 2007. p. 443–53.
48. North Carolina Department of Environment and Natural Resources. Phase II of the Total Maximum Daily Load for Total Nitrogen to the Neuse River Estuary, North Carolina, Final Report. 2001 [cited 16 October 2007]. Available from: URL: [http://h2o.enr.state.nc.us/tmdl/Docs\\_TMDL/Neuse%20TN%20TMDL%20II.pdf](http://h2o.enr.state.nc.us/tmdl/Docs_TMDL/Neuse%20TN%20TMDL%20II.pdf)
49. Virginia Department of Environmental Quality. Benthic TMDL for Toms Brook in Shenandoah County, Virginia, Final Report. 2004 [cited 10 October 2007]. Available from: URL: <http://www.deq.virginia.gov/tmdl/apptmdls/shenrvr/tomsbrk.pdf>
50. Marano JJ, Mehlhoff S. Minimizing the costs associated with implementing TMDL allocations. In: *Water Environment Federation. Proceeding of TMDL 2007*; 24–27 June 2007; Bellevue, Washington; 2007. p. 724–33.
51. National Research Council. *Assessing the TMDL Approach to Water Quality Management*. Contract No. X-82880401. Sponsored by the US EPA. National Academy Press, Washington; 2001.
52. Dilks DW, Freedman PL. Improved consideration of the margin of safety in total maximum daily load development. *Journal of Environmental Engineering* 2004;130:690–4.
53. Reckhow KH. On the need for uncertainty assessment in TMDL modeling and implementation. *Journal of Water Resources Planning and Management* 2003;129:245–6.
54. Shirmohammadi A, Chaubey I, Harmel RD, Bosch DD, Muñoz-Carpena R, Dharmasri C, *et al.* Uncertainty in TMDL models. *Transactions of the ASABE* 2006;49:1033–49.
55. Shabman L, Reckhow K, Beck MB, Benaman J, Chapra S, Freedman P, *et al.* *Adaptive Implementation of Water Quality Improvement Plans: Opportunities and Challenges*. Durham, North Carolina, Nicholas School of the Environment and Earth Sciences, Duke University; 2007. 98 pp. Available from: URL: <http://www.nicholas.duke.edu/institute/adaptive-water.pdf>.
56. Myers CF, Wayland III RH. Memorandum: Supplemental Guidelines for the Award of Section 319 Nonpoint Source Grants to States and Territories in FY 2002 and Subsequent Years. Washington, DC: US EPA, Office of Wetlands, Oceans, and Watersheds. 2001 September Memorandum. Available from: URL: <http://www.epa.gov/nps/Section319/fy2002.html>
57. Revisions to the Water Quality Planning and Management Regulation and Revisions to the National Pollutant Discharge Elimination System Program in Support of Revisions to the Water Quality Planning and Management Regulation; Final Rules, 40 CFR Part 9 *et al.* (13 July 2000). Available from: URL: <http://www.epa.gov/owow/tmdl/finalrule/finalrule.pdf>
58. MDE. Maryland's 2006 TMDL Implementation Guidance for Local Governments. Final Report. Maryland Department of the Environment; Baltimore, MD, 24 May 2006. Available from: URL: [http://www.mde.state.md.us/assets/document/final\\_TMDL\\_Implementation\\_Guidance\\_for\\_LG.pdf](http://www.mde.state.md.us/assets/document/final_TMDL_Implementation_Guidance_for_LG.pdf).

59. California State Water Resources Control Board. A Process for Addressing Impaired Waters in California. Final Report. 2005 June Report No. 2005-50. California State Water Resources Control Board; Sacramento, CA.
60. VA DCR, VA DEQ. Guidance Manual for Total Maximum Daily Load Implementation Plans. Final report. Richmond (VA): Virginia Department of Conservation and Recreation (VDCR) and Virginia Department of Environmental Quality; 2003 July. Available from: URL: <http://www.deq.state.va.us/tmdl/implans/ipguide.pdf>
61. Freedman PL, Nemura AD, Dilks DW. Viewing total maximum daily loads as a process, not a singular value: adaptive watershed management. *Journal of Environmental Engineering* 2004;130:695-702.
62. Davenport TE, Kirschner L. An evaluation framework for NPS implementation. In: ASAE Total Maximum Daily Load (TMDL) Environmental Regulations II Proceedings; 8-12 November 2003; Albuquerque, NM; St. Joseph, MI; 2003. p. 405-12.
63. Texas Commission on Environmental Quality. Implementing Total Maximum Daily Loads in Texas. Final Report. Dallas (TX): Texas Commission on Environmental Quality, Total Maximum Daily Load Section Environmental Planning and Implementation Division Office of Environmental Policy, Analysis, and Assessment; 2004. p. 48.
64. The Center for TMDL and Watershed Studies. TMDL Implementation – Characteristics of Successful Projects. Contract No. EPA Project X7-831563010. Virginia Tech, Blacksburg, VA; 2006. p. 370.
65. Muench L, Streeter V. The Hook but not the fish: a community perspective on TMDLs. In: Getting It Done: The Role of TMDL Implementation in Watershed Restoration, 29-30 October 2003, State of Washington Water Research Center, Stevenson, WA; Pullman, WA; 2003. Available from: URL: [http://www.swwrc.wsu.edu/conference2003/pdf/Proceedings/Proceedings/Session%202B/ABSTRACT\\_Muench%20and%20Streeter.pdf](http://www.swwrc.wsu.edu/conference2003/pdf/Proceedings/Proceedings/Session%202B/ABSTRACT_Muench%20and%20Streeter.pdf)
66. Fowler DL, Duvall J. The Successes and Challenges of Implementing Sediment and Pathogen TMDL's in Stekoa Creek. In: Proceedings of the 2005 Georgia Water Resources Conference, Athens, GA (USA), 25-27 April 2005; 2005.
67. McClellan P, Petrauskas B, Kern J.. A case study of implementation plan development in three Virginia watersheds. In: ASAE Total Maximum Daily Load (TMDL) Environmental Regulations: Proceedings of the 11-13 March 2002 Conference, Fort Worth, TX, ASAE; 2002. p. 99-104.
68. Boman BJ, Thomas MV. Five years of BMP implementation outreach in Florida. In: ASABE. Watershed Management to Meet Water Quality Standards and TMDLS (Total Maximum Daily Load) Proceedings of the 10-14 March 2007 Conference, San Antonio, TX, St Joseph, MI: ASABE; 2007. p. 350-7.
69. Maguire LA. Interplay of science and stakeholder values in Neuse river total maximum daily load process. *Journal of Water Resources Planning and Management* 2003;129:261-70.
70. Chen CW, Herr J. Decision support system for stakeholder involvement. *Journal of Environmental Engineering* 2004;130:714-21.
71. Bosch DJ, Wolfe ML. Soil and water quality in agriculture, assessing and improving. In: Meyers RA, editor. *Encyclopedia of Environmental Analysis and Remediation*. John Wiley and Sons, Inc., New York, USA; 1998. p. 4373-403.
72. Ribaldo MO, Horan RD, Smith ME. Economics of Water Quality Protection from Nonpoint Sources: Theory and Practice. Final Report. U.S. Department of Agriculture, Economic Research Service, Washington, DC; 1999. pp. 106.
73. USEPA. MS4 Program Evaluation Guidance. Final Report. Report No: EPA-833-R-07-003. USEPA, Office of Wastewater Management, Washington, DC; 2007. pp. 171.
74. McElfish JM. Enforceable State Mechanisms for the Control of Nonpoint Source Water Pollution. Environmental Law Institute, Washington, DC; 1997.
75. Connecticut Department of Environmental Protection. Connecticut's Clean Water Fund. Website [cited 15 October 2007]. Available from: URL: [http://www.ct.gov/dep/cwp/view.asp?a=2719&q=325578&depNav\\_GID=1654](http://www.ct.gov/dep/cwp/view.asp?a=2719&q=325578&depNav_GID=1654)
76. USEPA. Water Quality Trading Policy. 2003. Washington, DC: USEPA, Office of Water. Website 2003 January 13 [cited 17 June 2007]. Available from: URL: <http://www.epa.gov/owow/watershed/trading/finalpolicy2003.pdf>
77. USEPA. Water Quality Trading Toolkit for Permit Writers. Office of Wastewater Management, EPA 833-R-07-004.
78. Stephenson, KL, Shabman LK, Boyd J. Taxonomy of Effluent Trading Programs. In: Younos T, editor. *Total Maximum Daily Load: Approaches and Challenges*. PennWell Publishers, Tulsa, OK; 2005. p. 253-85.
79. Shabman L, Stephenson K. Achieving nutrient water quality goals: bringing market-like principles to water quality management. *Journal of American Water Resources Association* 2007;43:1076-89.