

Economic total maximum daily load for watershed-based pollutant trading

A. Z. Zaidi · S. M. deMonsabert

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Abstract Water quality trading (WQT) is supported by the US Environmental Protection Agency (USEPA) under the framework of its total maximum daily load (TMDL) program. An innovative approach is presented in this paper that proposes post-TMDL trade by calculating pollutant rights for each pollutant source within a watershed. Several water quality trading programs are currently operating in the USA with an objective to achieve overall pollutant reduction impacts that are equivalent or better than TMDL scenarios. These programs use trading ratios for establishing water quality equivalence among pollutant reductions. The inbuilt uncertainty in modeling the effects of pollutants in a watershed from both the point and nonpoint sources on receiving waterbodies makes WQT very difficult. A higher trading ratio carries with it increased mitigation costs, but cannot ensure the attainment of the required water quality with certainty. The selection of an applicable trading ratio, therefore, is not a simple process. The proposed approach uses an *Economic TMDL* optimization model that determines an economic pollutant reduction scenario that can be compared with actual TMDL allocations to calculate selling/purchasing rights for each contributing

source. The methodology is presented using the established TMDLs for the bacteria (fecal coliform) impaired Muddy Creek subwatershed WAR1 in Rockingham County, Virginia, USA. Case study results show that an environmentally and economically superior trading scenario can be realized by using *Economic TMDL* model or any similar model that considers the cost of TMDL allocations.

Keywords Bacteria TMDL · Best management practice · Economic TMDL · Optimization · Water pollution · Water quality trading

Introduction and background

There is always a risk of environmental noncompliance in nonpoint source pollutant trading due to the complex nature of nonpoint pollutants. The variable effects of pollutants on receiving waterbodies make it difficult to ascertain the outcomes of trading pollutants from diverse sources. One unit of a given pollutant from a certain source is not necessarily equivalent to the same level of reduction of that pollutant from another source in the watershed. To overcome this uncertainty, US Environmental Protection Agency (USEPA) endorses pollutant trading under its total maximum daily load (TMDL) framework. The hydrologic model used to develop a certain TMDL may also be used to determine equivalence ratios among pollutants depending on watershed conditions, pollutant transportation mechanisms, and where these pollutants enter the waterbody. Since pollutant trading is considered to be a viable economic tool, a limitation of this approach is the missing economic consideration in the traditional TMDL process that is required for calculating the costs of alternate pollutant reduction scenarios. This paper proposes an improved mechanism by using an already developed *Economic TMDL* model (Zaidi and deMonsabert 2008) that calculates

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A. Z. Zaidi (✉)
Institute of Space Technology, 28-Gulzar-e-Hijri, Off Univ. Rd.,
Karachi 75270, Pakistan
e-mail: azaidi@gmualumni.org

A. Z. Zaidi
e-mail: arjumand.zaidi@ist.edu.pk

A. Z. Zaidi
e-mail: arjzaidi@gmail.com

S. M. deMonsabert
George Mason University, Fairfax, VA 22030-4444, USA
e-mail: sdemonsa@gmu.edu

the costs associated with pollutant reductions from different sources of fecal coliform. The costs are compared for both TMDL and trading scenarios that enable a cost-effective trading between pollutant sources.

The Muddy Creek (Fig. 1) subwatershed WAR1 in Rockingham County, Virginia, is selected as a case study to present the strengths of the proposed methodology. USEPA approved the Muddy Creek watershed TMDL in 1999. The Muddy Creek TMDL (VADEQ 2000) and Implementation Plan (MapTech 2001) reports are used as the primary reference documents. An in-depth discussion about recorded and simulated loads along with the model calibration and validation results is provided in the approved TMDL report. The implementation plan contains a detailed description of the loading from the potential point and nonpoint sources, watershed characteristics, the type of control measures, and their costs and TMDL allocations. Information regarding the control measures and the associated cost estimates for the Muddy Creek watershed TMDL is also acquired from these reports. It is important to note that despite this information, these reports do not present any detail about the effectiveness of the control measures in achieving TMDL goals.

Pollutant trading and TMDL

Total maximum daily loads (TMDLs)

The Clean Water Act (CWA) of the USEPA regulates the discharge of pollutants into US waters with an objective to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Under the CWA, two approaches are considered: end-of-the-pipe technology-based effluent limitations and ambient water quality-based standards. The technology-based approach is addressed in the National Pollutant Discharge Elimination System (NPDES) permit limits. The water quality standards (WQS) are based on the quality of the receiving waters. The total maximum daily load (TMDL), also called the 303(d) program, is part of CWA's water quality approach. "A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive without violating the surface water quality standards" (USEPA 2013). USEPA requires that TMDLs should be developed for impaired waterbodies on the 303(d) list. The TMDLs are used to restore impaired streams by allocating allowable loads to the polluters.

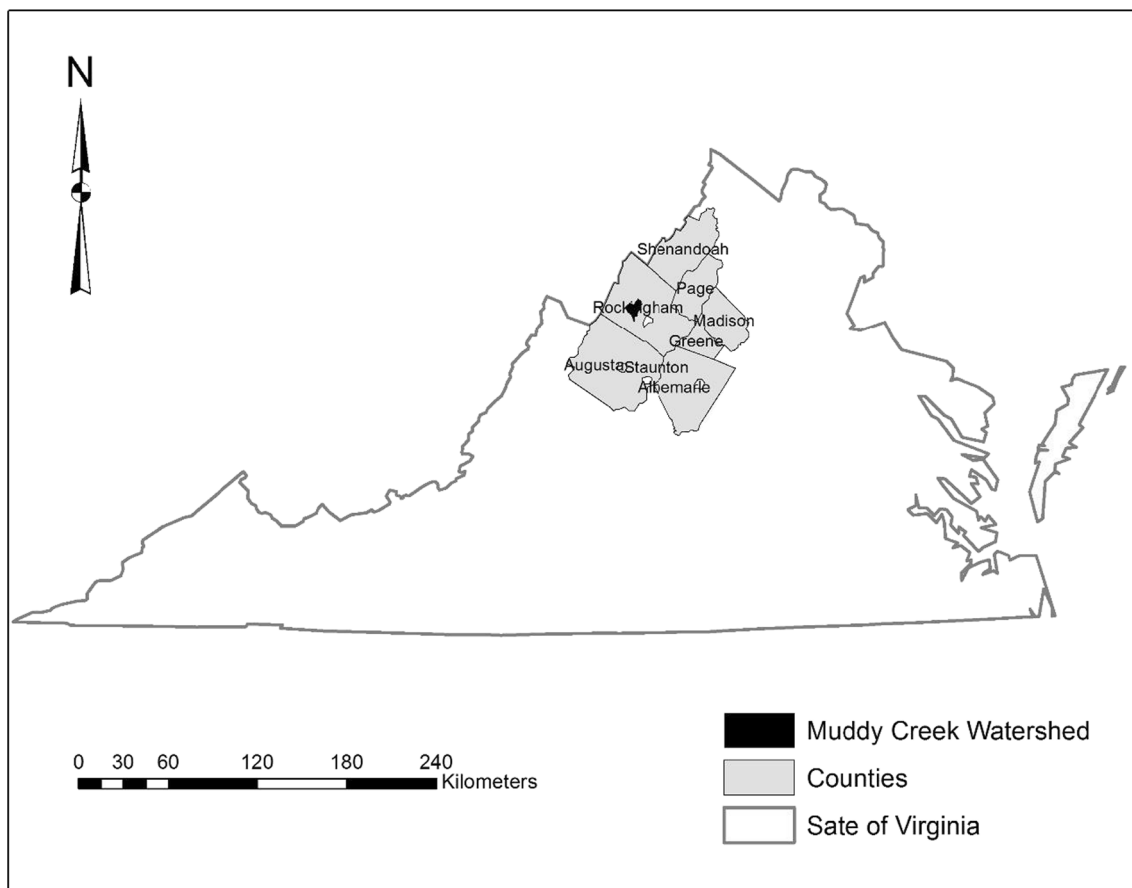


Fig. 1 Muddy Creek watershed

Pollutant trading

Pollutant trading is a market-based approach to attain specific environmental objectives while minimizing the overall pollution control costs (Powers 2003). This approach allows dischargers with low unit pollutant reduction cost to sell their excess pollutant credits to those with substantial higher unit pollutant reduction costs. In accordance with the USEPA Water Quality Trading Policy, the term “credit” is used for pollutant reductions in addition to the regulatory requirement. Generally, “trading ratios” are used to justify the inherent variation in the response of different pollutant loadings on water quality in a watershed. A trading ratio represents the pollutant reduction a source must purchase from another source to offset one unit of the pollutant load.

Trading ratios The complexity of modeling nonpoint source pollutants and their impact on receiving bodies make it challenging to trade pollutant loads from different sources. Natural physical, chemical, and biological processes are involved in establishing a relationship between the amounts of a pollutant discharged from its source to its effect on the downstream water quality. The influence of the same amount of pollutant at the discharge point from different sources and locations is not identical. It means that reducing one credit of a certain pollutant from one source would not be equivalent to the same level of the reduction of that pollutant at another source in the watershed. Similarly, unit load reduction costs may vary significantly among polluters and for different level of reductions. To address these differences in impact on water quality, factors are used to make commensurate pollutant loadings from different sources in a watershed. These factors known as trading ratios account for the complexities inherent in calculations of nonpoint source loads and their reductions or long-term performance of the control measures. A trading ratio $n:1$ means that “ n ” units of pollutant reduction from a source are needed to offset one unit of pollutant from another source (by convention n is greater than 1).

Water quality trading

Watershed-based pollutant trading has a potential to achieve greater environmental benefits in terms of better quality of water that might be accomplished under other traditional methods (Ruppert 2004; USEPA 2003). According to USEPA's *Effluent Trading in Watershed Policy Statement*, effluent trading is valuable in terms of a number of economic, environmental, and social benefits. The *USEPA Water Quality Trading Policy* (2003) encourages states, interstate agencies, and tribes to develop and implement voluntary effluent trading programs, where possible, for pollutants like nutrients, sediments, and others to improve water quality at lower costs. The EPA supports trades for pollutants other than nutrients and

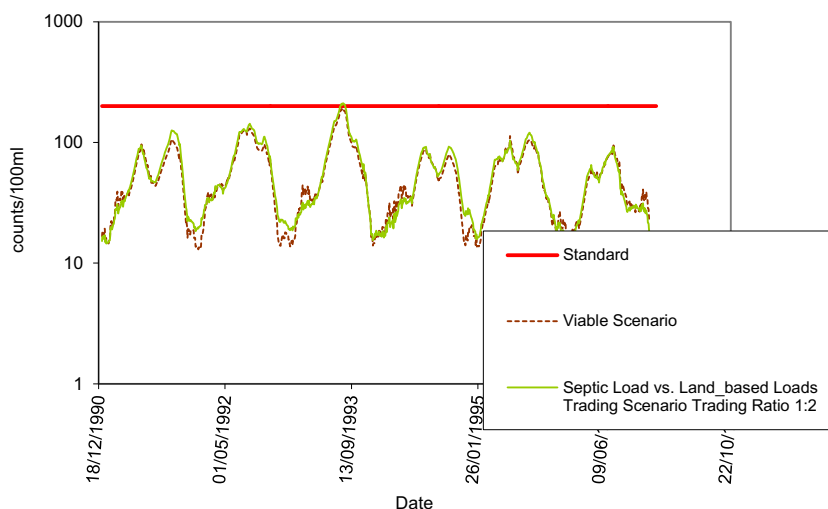
sediments with a requirement of prior approval on a case-by-case basis. The policy allows sources to meet their regulatory requirements by trading pollutant reductions with other sources in the same watershed. Several WQT programs are currently operating in several regions of the USA like states of Illinois, Minnesota, Michigan, Wisconsin, Colorado, Virginia, Maryland, West Virginia, and others (Morgan and Wolverton 2005; Ribaud and Gottlieb 2011). Many of these states have developed trading rules, frameworks, and guidance on the type of pollutants to be traded, potential trading sources, and market structures that may support such trades.

TMDL trading framework

EPA supports to establish a baseline for credits for an approved TMDL by considering its point and nonpoint source allocations. A baseline is the limit under which a pollutant reduction credit can be created by further reducing the pollutant loads (USEPA 2003). Variation in control costs and economies of scale between various sources of pollutants are the main factors that make effluent trading profitable for traders. Each contributing pollution source is allocated a percent of the TMDL for the watershed. Individual polluters produce surplus credits by reducing pollutant loads below their allocated loads. Other contributing polluters may later trade these credits.

EPA allows watershed-based trading only if the overall reduction of pollutant loads not just improves the water quality, but it should also be sufficient to meet water quality criteria. The use of trading ratios greater than 1 may offset some uncertainties linked with modeling of nonpoint source loads and performance of the control measures; however, it may not ensure meeting the WQS. Similarly, the higher trading ratios may unnecessarily drive up mitigation costs. Figure 2 illustrates an example in which failed septic loads are traded with the land-based loads with a trading ratio of 1:2 (1 unit of septic load reduction is offset by two units of land-based load reduction) in the WAR1 subwatershed of Muddy Creek. The viable scenario, as shown in the figure, meets the geometric mean fecal coliform water quality criterion with a 5 % margin of safety (190 counts/100 ml). The plot of trading scenario shows a violation of the WQS, which concludes that even with higher trading ratios, the water quality criteria may not necessarily be met. Although an optimal management of pollutant loads may have an effect on the selection of trading ratios (García et al. 2011), the effectiveness of the control measures may need to be evaluated first to ensure the effectiveness of the traded reductions. Instead of explicitly addressing the determination of the trading ratios, subjective selection methods based on project needs and literature case studies are also often employed in choosing the trading ratio. One such method has introduced a practical methodology to estimate trading ratios from a TMDL allocation matrix of viable scenarios (Zhang and Yu 2003). In his methodology, “equivalent

Fig. 2 Septic load versus land-based load trading scenario with a 1:2 trading ratio



trading ratios” are examined which correlate nonlinearly with selected pairs of allocation scenarios for an approved nitrate TMDL.

A number of factors like the uncertainty regarding the effectiveness of trading ratios and performance of control measures, lack of buyers and sellers will to trade and the absence of binding caps have increased the risk of nonattainment of the water quality trading goal and thereby limited the development of the trading market. The ultimate goals of trading are to improve and protect water quality, but if this goal is not being achieved due to the presence of the above-mentioned problems, trading may not remain a viable tool (Ribaudo and Gottlieb 2011). To overcome the uncertainty inherent in the use of trading ratios, a more reliable approach has been proposed in this study that uses an *Economic TMDL* optimization model to determine an economic pollutant reduction scenario that can be compared with actual TMDL allocations to calculate selling/purchasing rights for each contributing source. The amount and proportion of the loads from point/nonpoint sources govern the range and number of possible viable solutions. The proposed strategy for cost optimization among pollutant sources and for trading consideration can only be utilized if the load combination provides that flexibility. For that reason, there should be a significant difference between alternate viable load reduction scenarios.

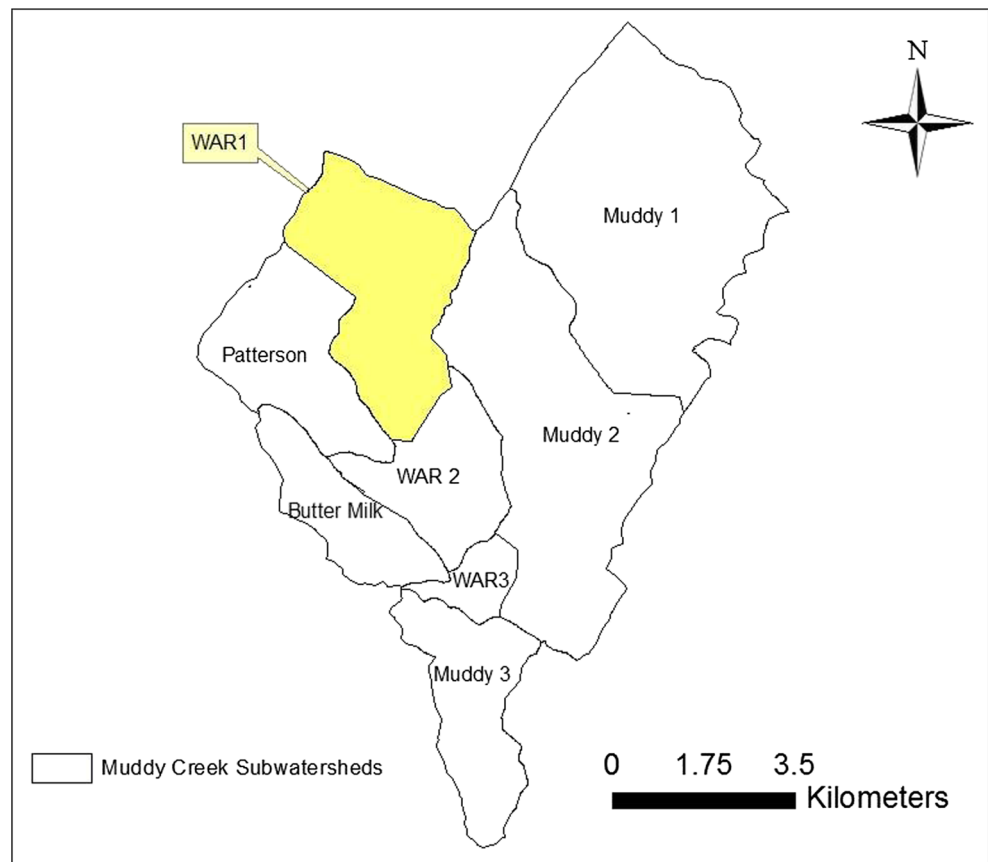
Materials and methods

Study area

The Muddy Creek watershed, approximately 81 km², is located in Rockingham County, Virginia. The dominant land uses in the Muddy Creek watershed are forest, cropland, and improved pasture. For water quality modeling, the watershed is

divided into eight subwatersheds (VADEQ 2000). Among eight subwatersheds of Muddy Creek, the most upstream subwatershed WAR1 having approximately 10.87 km² of land area (Fig. 3) is selected to demonstrate the proposed methodology. This subwatershed is selected because of its upstream location in the watershed. Due to the upstream location, this subwatershed is not receiving the pollution from other subwatersheds and could be independently modeled.

Muddy Creek was initially placed on the Commonwealth of Virginia’s 1998 303(d) list of impaired waters for bacteria (fecal coliform) impairment. Fecal coliform bacteria are found in the intestinal tracts of warm-blooded animals from where these are excreted out through their feces. Higher levels of those bacteria in the water column may cause human illness associated with contact with water. The Muddy Creek fecal coliform target is a geometric mean of 200 counts/100 ml with 0 % violation. The impairment due to fecal coliform bacteria exceeded the state water quality criterion for not supporting primary contact recreation. Potential sources for fecal coliform include both the point and nonpoint pollution. The point sources are the permitted facilities of the Mount Clinton Elementary School and Wampler Foods. The fecal coliform bacteria sources are identified as the following: failed septic systems, land-based loads, wildlife load, and direct deposit. In WAR1 subwatershed, the nonpoint source pollutants are dominant that are responsible for the impairment. In Table 1, the land-based fecal loads and corresponding land use types and their areas are presented for the existing condition in the WAR1 subwatershed. The seasonal variation in fecal loads from different sources is explicitly taken care of by incorporating monthly fecal coliform concentration rate from each landuse dependent on temporal practices within watershed like grazing schedule, seasonal application of manure, varying number of livestock, the in stream during different months of a year, etc. The average annual modeled loads are based on the selected modeling period (VADEQ 2000).

Fig. 3 Muddy Creek subwatersheds

The TMDL report for Muddy Creek (VADEQ 2000) mentioned the use of a water quality model that performed TMDL allocations by simulating existing conditions of the watershed. According to TMDL report, an extensive modeling of the stream flows and pollutant loads is done from all contributing pollutant sources to ensure 100 % compliance with Virginia concentration-based geometric mean water quality criteria for

fecal coliform. US EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASIN) and the Nonpoint Source Model (NPSM) are selected for simulation of existing hydrologic characters, pollutant loading, target pollutant load allocations, and effect of load reductions on quality of the stream. Monthly average approach is considered in the analysis to account for seasonal variation in stream flow, climatic

Table 1 Fecal load distribution for nonpoint sources (NPS) in the WAR1 subwatershed

NPS category	Area (km ²)	Percent of subwatershed total area	Fecal load (average counts/year)	Percent of total load
Cropland	0.28	2.60	3.32E+09	0.017
Pasture 1	0.4	3.68	3.59E+10	0.180
Pasture 2	0.04	0.30	7.65E+09	0.038
Pasture 3	0.4	3.68	3.04E+11	1.521
Farmstead	0.05	0.46	2.54E+08	0.001
Built-up	0.4	3.68	1.90E+09	0.010
Loafing lots	0.00	0.00	0.00 E+00	0.000
Forest	9.3	85.60	2.45E+10	0.123
Barren	0.00	0.00	0.00 E+00	0.000
Direct cow	–	–	1.95E+13	97.590
Failed septic	–	–	1.04E+11	0.520
Total	10.87	100.00	2.00E+13	100.00

conditions, and pollutant loadings to protect water quality during low flows and high loading times when it is most vulnerable. Hydrologic and water quality calibrations are necessary to simulate the actual movement of water and pollutant through the watershed. US Geological Survey (USGS) daily observed flow data (gage#01621050) for April 1993 to September 1996 within the Muddy Creek Watershed are selected for model hydrologic calibration (Fig. 4). Fecal coliform data collected at VADEQ in-stream monitoring station (1BMDD000.40) within the Muddy Creek Watershed are used for water quality calibration (Fig. 5). Water quality calibration is done for the representative period of April 1993 to July 1996.

Once calibrated, the model is run to determine existing and allocated loadings for the time period of January 1991 through December 1995. In modeling simulations, a direct comparison with the geometric mean standard of 200 counts/100 ml is used by setting a target of zero (0) percent exceedance of the WQS. A scenario meeting the desired water quality target is selected, and the associated load reduction scheme may be considered as TMDL allocations among pollutant sources. Figure 6 shows the simulated 30-day geometric mean of fecal concentration in WAR1 subwatershed for the pre- and post-TMDL scenarios.

In this study, information on pollutant load sources and hydrologic and water quality simulation (BASINS and NPS files) is obtained from Virginia Department of Conservation and Recreation (VADCR). No further evaluation in terms of calibration or validation of the simulation is done as part of this research. In order to calculate alternate TMDL scenarios, different combinations of source reductions are applied to the existing input loads before running the calibrated/validated

model. With the calibrated model, scenarios are generated that represent the reduced pollutant loading required to bring the water segment into compliance with WQS. Every pollutant reduction scenario that results in water quality attainment of the questioned segment can be a potential candidate for the TMDL allocation.

Economic TMDL

Those involved with TMDL allocations have long identified the need for a cost-effective allocation process that may also support pollutant trading within the TMDL framework. The economic analysis is performed to ensure that load reductions required for meeting WQSs, when implemented, do not impose severe economic impacts on the polluters. Following the water quality model calibration and validation, an economic optimization model, appropriate for the Muddy Creek watershed, is developed. An earlier work by Zaidi and deMonsabert (2008) developed an optimization model *Economic TMDL* that minimizes the pollutant reduction cost from all sources for environmentally feasible allocations. Economic TMDL is a mathematical model that can be utilized to reach to the most economical TMDL allocations. This model uses a mixed integer nonlinear (MINL) optimization technique to minimize the costs of alternative TMDL allocations for bacterial impaired waterbodies. Economic TMDL is developed based on a proposition that water quality goals can be achieved in a more cost-effective and technologically feasible manner, if an optimization model is used during the TMDL load allocation stage with a consideration of nonlinear relationship between pollutant reduction efficiency and the corresponding reduction cost. Mixed integer nonlinear cost and

Fig. 4 Hydrologic calibration of Muddy Creek flow model

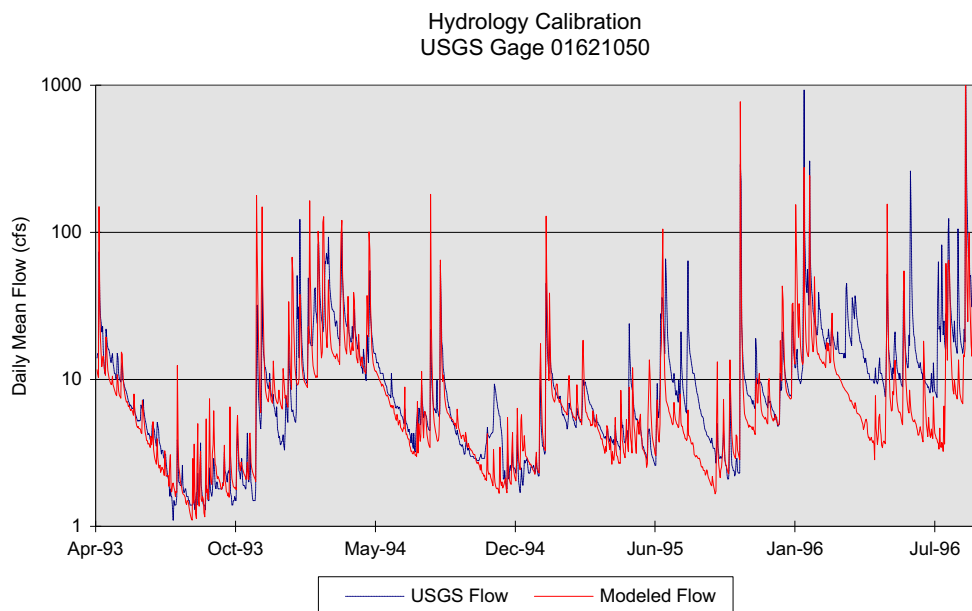
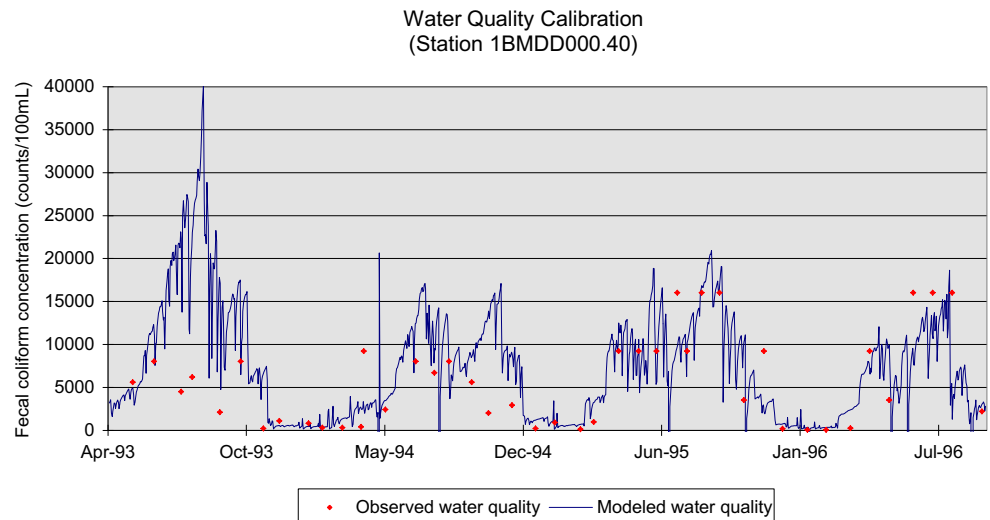


Fig. 5 Modeled and observed fecal coliform concentration



performance equations are used in the water quality modeling. The central feature of the optimization model concentrates on minimizing the annual cost. This model not only minimizes the cost for an allocation but also proposes the least cost environmentally feasible allocation for a given watershed. To achieve this, *Economic TMDL* allocates pollutant loads among polluters for minimum costs of load reductions without violating the water quality criteria. Since the *Economic TMDL* model may optimize the potential costs associated with alternative allocation strategies at the subwatershed level, it may also be used to break down the TMDL implementation cost among different pollutant sources for a cost-effective allocation. If the final allocation scheme is different from, or economically, inferior to the cost-effective allocation, then the potential exists for trading pollutant loads to achieve pollutant reductions at a reduced cost. The estimation of pollutant

abatement efficiency and associated costs of control measures is fundamental to *Economic TMDL*. Several types of best management practices (BMPs) are chosen to restore impaired streams by reducing water quality violations that prevent them from supporting their designated uses and in order to meet the watershed protection objectives. The choices of BMPs may differ according to the local settings of a watershed. The cost-effectiveness relationships are developed for different pollutant control measures.

Control measure costs

For BMP cost estimates, literature is searched, and a range of costs is acquired. The Muddy Creek TMDL Implementation Plan (MapTech 2001) and USDA/NRCS Conservation Practice Average Cost Estimates for Virginia (NRCS 2003) are

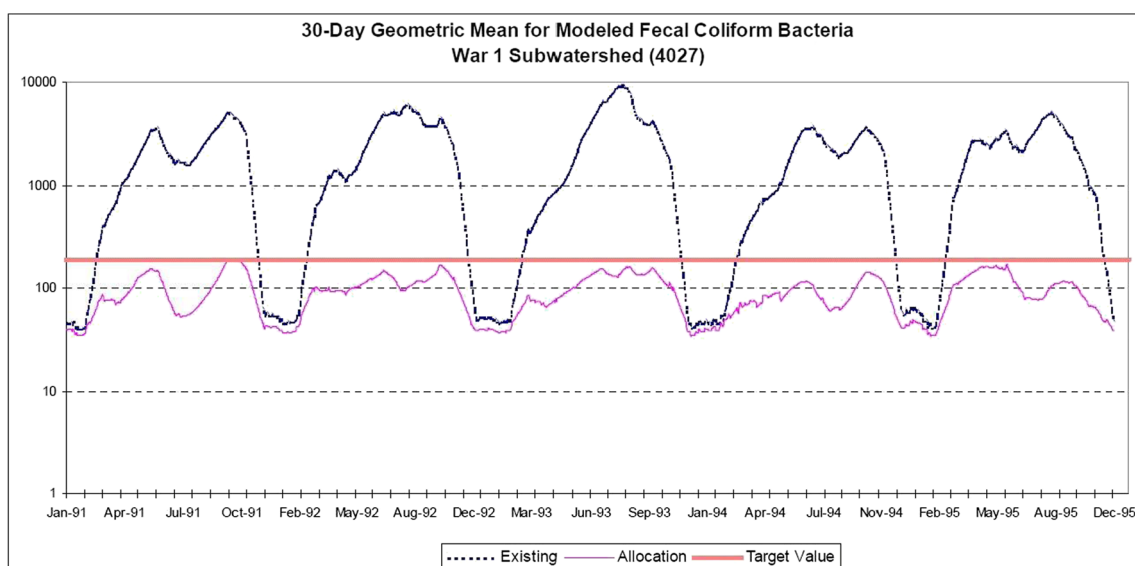


Fig. 6 Thirty-day geometric mean fecal coliform (counts/100 ml) concentrations in the WAR1 subwatershed (USEPA TMDL Case Study: Fecal Coliform Bacteria TMDL Development for the Muddy Creek Watershed. Prepared by Virginia Environmental Protection Agency (EPA) Region 3 (page I-25))

Table 2 Estimated average costs of vegetative buffer strip

Items	Year	\$/km ^{2a}
Seed	1st	15,271
Fertilizer/Lime	1st	19,867
Labor/Equipment	1st	2,965
Total fixed cost		38,103
Mowing	Annual	12,355
Total annual cost		12,355

^a Actual costs in \$/acre are converted into SI units for this study

referred for control measure costs, and assumptions are made wherever required. NRCS 2003 cost estimates, although a decade old, but are selected to match the time period of the MapTech report. If annual maintenance costs are unavailable, a conservative estimate of 10 % of the total installation cost is adopted. Not only the level of load reduction is the main factor in cost calculations but these costs also depend upon the types of control strategies selected here. In this study, various control strategies are analyzed for their cost and effectiveness relationships in WAR1 subwatershed. *Streamside fencing* for direct cattle loads, *vegetative buffer strips* for land-based loads, *system repair or installation* for failed septic system loads, and *wildlife management system* for wildlife (deer) direct loads are considered as load reduction measures. Similar relationships for other relevant control measures could also be developed and incorporated into the model. Annual costs are calculated with fixed initial costs amortized at 5 % interest rate for 15 years of the planning horizon. A brief discussion about the cost and effectiveness of these control measures is provided in the following sections, whereas an in-depth description can be found in an earlier work of Zaidi (2005).

The implementation cost of each BMP has two components: fixed initial capital cost for establishment of control measure and its annual operating and maintenance expenses. Fixed costs are amortized at a rate of return of 5 % for 15 years. The total annual cost for each control measure is obtained by adding its amortized fixed and operating costs.

Vegetative buffer strip In this study, filter strips are considered along the streamside edges of the pastureland and cropland areas in order to improve the quality of in-stream water. These grassed or vegetated areas are intended to treat polluted runoff from adjacent areas by reducing its velocities and filtering out the pollutants in the runoff. The land-based load reductions are calculated for cropland and three types of pasturelands in

Table 3 Estimated average cost for wildlife management system

Items	Year	\$/# of deer
Deer removal	1st	250
Maintaining constant population	Annual	250

Table 4 Estimated average costs for correcting failed septic systems

Items	Year	\$/system
Pump out and inspection	Annual	200
Septic system repair	Annual	2,500

parcels of Muddy Creek WAR1 subwatershed through buffer strip application. Moore’s equation (1988) is utilized for estimating the percent reduction of indirect (land-based application) fecal waste concentration for buffer strips as a function of their widths and slopes (Eq. 1). The same relationship is presented in SI units in Eq. 2.

$$PR_{lb} = 11.7 + 4.26(S) \tag{1}$$

Or

$$PR_{lb} = 11.7 + 14(S)_{SI} \tag{2}$$

where

- PR_{lb} Land-based percent removal of bacteria (not to exceed 75 percent) (%)
- S Ratio of vegetation buffer width (ft) and buffer slope (%) (width > 10 ft and 0 < slope < 15 %)
- (S)_{SI} S in international system of units (SI)

The above equation is embedded in the *Economic TMDL* model that optimizes the reduction in land-based bacteria load at minimal cost. The natural land slope is considered as a fixed parameter in the optimization model, and the buffer width is varied by the model to achieve an optimal (or required) bacteria load reduction. The buffer width can then be multiplied with the total length of the vegetative buffer strip to calculate the buffer area. The total length of the vegetative strip in each parcel of the watershed is acquired using Geographical Information System (GIS) tools by overlaying land use layer with the stream network. Another expression to be used in the optimization model is for the cost of the buffer strip that can be estimated by multiplying the average unit cost of

Table 5 Fencing system unit cost

Items	Year	Unit	\$/Unit
Fence	1st	\$/meter	6.9
Alternative water source (AWS)	1st	\$/system	13,000.00
Hardened crossing (HC)	1st	\$/system	2,000.00
Fence maintenance ^a	Annual	\$/meter	0.69
AWS maintenance ^a	Annual	\$/system	1,300.00
HC maintenance ^a	Annual	\$/system	200.00

^a Assume 10 % of the initial installation cost

Table 6 Total annual costs of control measures at 5 % interest rates and 15 years of planning horizon

Control measure	Fixed initial cost	Annual (operating) cost	Amortized fixed cost at 5 %	Total annual cost at 5 %
Buffer strips (\$/km ²)	38,103	12,355	3,672	16,027
Fencing (\$/meter)	6.9	0.69	0.66	1.35
Alternate water system (\$/system)	13,000.00	1,300.00	1,252.5	2,552.5
Hardened crossing (\$/system)	2,000.00	200.00	192.7	392.7
Septic system (\$/system)	2,500.00	2,500.00	240.86	2,740.86
Septic system pump out(\$/system)	200.00	200.00	19.27	219.27
Wildlife management (\$/animal removed)	250.00	12.89 ^a	24.09	36.98 ^a

^a Depends on percent deer load reduction and deer population growth rate, and these values are for maintaining deer population of 56 (after 76 deer removal of trading scenario) at 7 % deer growth rate

buffer strips with buffered area. The cost of installing and maintaining filter strips may include the cost of seed, land rental, and maintenance. The cost of land to be consumed by the buffer strip is considered negligible in the cost calculation. The estimated average costs of developing the vegetative strip for a unit buffer area are shown in Table 2.

Wildlife management In the Muddy Creek watershed, the deer population is considered as the single wildlife source of fecal bacteria; therefore, deer management is considered as the only wildlife management option for the watershed. For controlling the fecal load from deer habitat, deer removal by shooting or relocation away

from the watershed may be considered as control measures. This study does not include deer relocation methods since these are not only more costly as compared to the direct reduction of deer by shooting but may result in high mortality rates during capturing of deer for relocation (EDAW 2003).

Owing to the increase in deer population, the pollutant load from the wildlife source is not constant. Each year, there is an increase in deer population. The deer management should not only consider the number of deer removed as dictated by the TMDL allocation in the first year of implementation, but the increase in deer population each year should also be managed such that

Fig. 7 Methodological representation of pollutant trading using economic TMDL

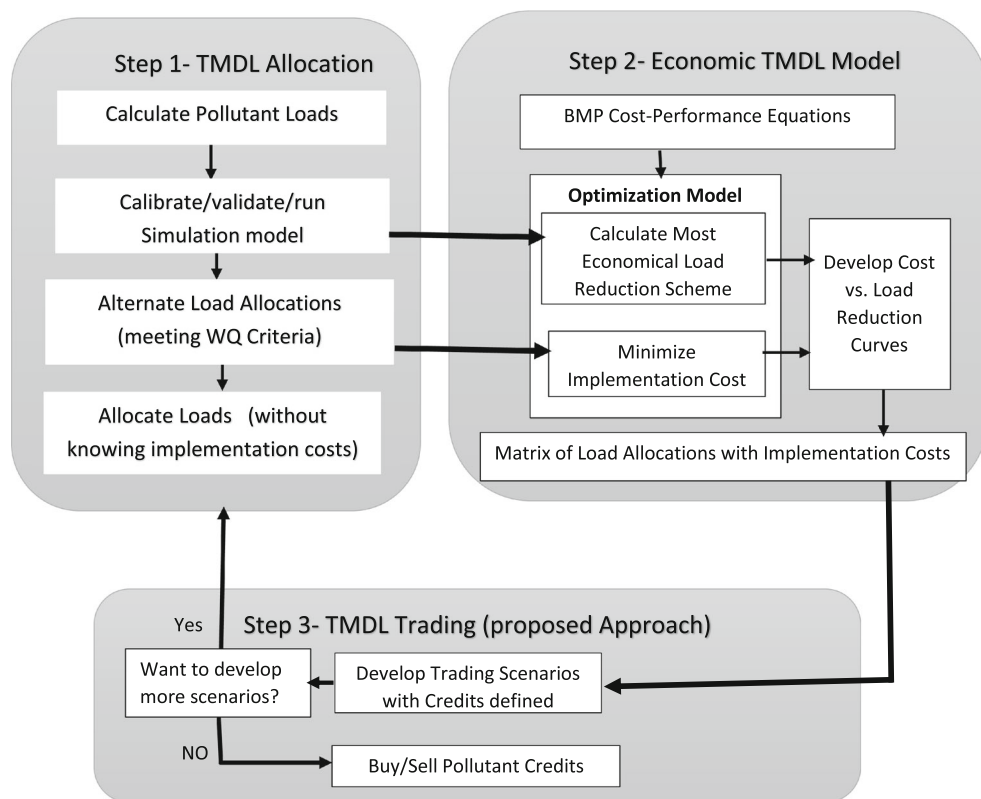
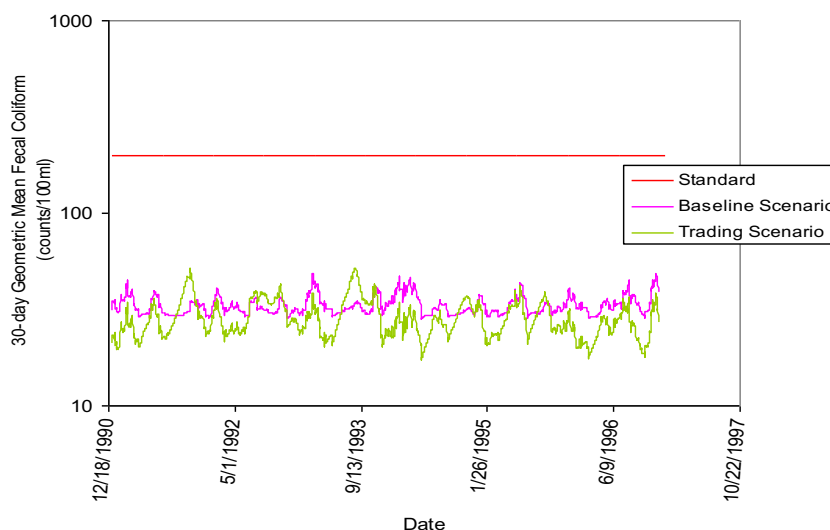


Fig. 8 Thirty-day geometric mean fecal coliform loadings under baseline and trading scenarios



the deer population in the watershed remains constant. For this reason, the optimization model takes into consideration the cost of deer removal in the first year and the cost of keeping the deer population (whatever remained after the reduction) stable in the watershed throughout the planning horizon (Table 3). Therefore, even if the wildlife allocation in the TMDL is zero, the cost involved to keep the population of the deer constant in the watershed must be considered.

Increase in deer population (IDP) can be calculated if the population growth rate (r) along with the existing deer population (ND) is known. The annual cost of maintaining the deer population in the watershed depends on the deer population (ND), the number of deer removed at the first year of implementation (NDR), and the deer growth rate (r). For this research, a seven (7) percent annual growth rate for deer population is assumed. The number of deer to be removed each year in order to keep deer population stable in the watershed (IDP) as a function of “NDR” or percent deer removal (PR_{wl}) and “ND” can be calculated by using the following relationships:

$$PR_{wl} = 100 \cdot \frac{NDR}{ND} \tag{3}$$

$$IDP = (ND - NDR) \cdot \frac{r}{100} = ND \cdot \left(1 - \frac{PR_{wl}}{100}\right) \cdot \frac{r}{100}$$

Table 7 Statistics for 30-day geometric mean fecal coliform concentration

Statistics	Baseline TMDL scenario (counts/100 ml)	Trading scenario (counts/100 ml)
Maximum	48.95	52.11
Median	32.14	27.38
Minimum	28.30	17.36

The total cost of deer removal is the sum of cost of deer removed in the first year of the implementation of the TMDL and the annual cost of maintaining the deer population in the watershed throughout the planning horizon.

Septic system inspection and repair The costs associated with septic system installation or repair are of two types. The inspection cost is fixed to determine which systems have failed and the type of that failure. Then, there is the fixed cost for each repair or installation. Table 4 displays the estimated average costs associated with the correction of failed septic systems. Assuming a prevailing septic system failure rate, each year the annual costs for inspection and repair of the failed systems are considered.

Streamside fencing The costs associated with streamside fencing in the animal access area are directly related to the linear length of installation. Table 5 presents the costs associated with the use of fencing as a potential control measure. Physical restriction of animals from streams requires provisions for alternative water sources and hardened crossings at animal stream crossing areas. The number of alternate water systems as well as hardened crossings depends on the extent of streamside fencing. A rule of thumb is utilized for the location of alternate water systems in a watershed with respect to the travel distance. Cattle should not be located more than 300 to 400 m from a water source. Personal judgment is used for the placement of both alternate water systems and hardened crossings in the WAR1 subwatershed.

A summary of the “Total Annual Cost” for each control measure as described in the above sections is shown in Table 6. The *Economic TMDL* model, where cost versus percent load removal equations (similar to Eq. 3) for each type of pollutant load are embedded, minimizes the total remediation cost for a given WQS.

Table 8 Load reduction scenario

Nonpoint source	Total existing load (counts/year)	TMDL reduction		Potential trading reduction	
		(counts/year)	Percent	(counts/year)	Percent
Land-based loads	3.51E+11	1.68E+11	47.86	8.59E+10	24.47
Wildlife loads	2.67E+10	0.00E+00	0.00	1.47E+10	55.06
Failed septic system	1.04E+11	1.04E+11	100.00	0.00E+10	0.00
Direct deposit	1.95E+13	1.95E+13	100.00	1.95E+13	100.00
Total	2.00E+13	1.98E+13	99.00	1.96E+13	98.00

Pollutant trading using *Economic TMDL*

This research presents an unconventional approach for TMDL trading framework in which the transfer of allocations from one source to another can be done along with the attainment of the TMDL. It is not always straightforward to conduct pollutant trading since specific pollutants from two different sources can have an entirely different impact on the quality of the receiving waterbody. A *Trading Scenario Selection Method* is proposed here that does not require to calculate explicit trading ratios. Alternate trading scenarios based on various pollutant load allocations are simulated through water quality models. The allocations that do not result in the violation of WQs are selected as potential trading scenarios. The associated costs of pollutant reductions are compared for load allocation strategies including TMDL scenario. Since high variations in load reduction costs are required for water quality trading, this comparison may be helpful in screening of watersheds that are well suited for this purpose.

Once the load allocations between pollutant sources have been established, the mutual exchange of the pollutants' rights can commence. The *Economic TMDL* model calculates the

load reduction scenario costs; the model results may provide a platform for pollutant trading among various point and non-point sources by utilizing a decision matrix. A matrix of multiple acceptable load allocation scenarios indicating the costs associated with each scenario can provide a basis for mutual trading without considering the empirical trading ratios. A methodological representation of pollutant trading using *Economic TMDL* is shown in Fig. 7. In this figure, step 1 represents the traditional TMDL process, step 2 shows the *Economic TMDL model*, whereas step 3 is all about the proposed TMDL trading approach. Arrows of the figure show the linking of these steps.

Results and discussions

This section evaluates and compares nonpoint trading options for fecal coliform bacteria in the study area. The potential trading options or acceptable load allocations that meet water quality criteria are examined from an economy perspective. Then, the optimization model minimizes the mitigation costs for these allocations. Cost comparison of these allocation scenarios may provide a platform for further evaluation and selection of a potential trading option.

Fig. 9 Dollar per unit load reduction versus percent reductions for land-based loads

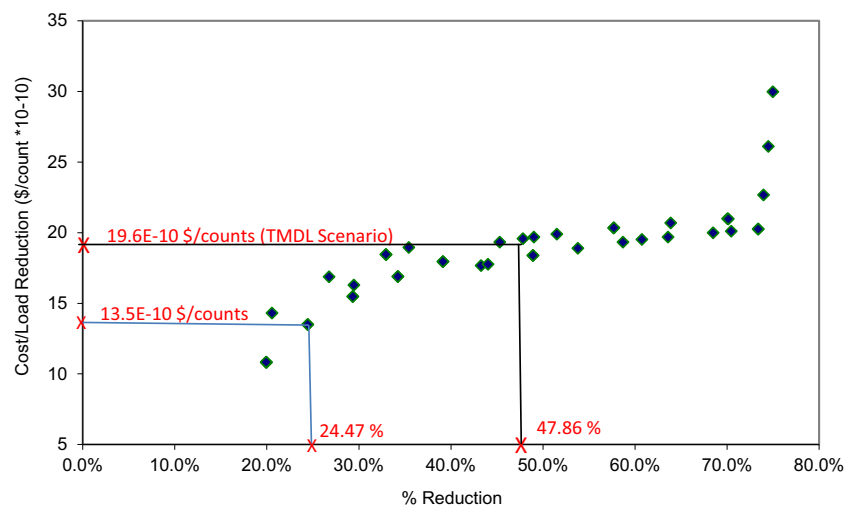


Table 9 Land-based load reduction costs

TMDL reduction			Potential trading reduction		
(counts/year)/Percent	Unit cost (\$/counts)	Annual cost (\$/year)	(counts/year)/Percent	Unit cost (\$/counts)	Annual cost(\$/year)
1.68E+11/47.86	19.6E-10	329.00 ^a	8.59E+10/24.47	13.5E-10	116

^a 19.6E-10 (\$/counts reduction)×1.68E+11 counts/year=329.00

Potential trading scenario

For Muddy Creek WAR1 subwatershed, a potential trading scenario is simulated using a calibrated water quality model. The TMDL allocations for WAR1 subwatershed (VADEQ 2000) are used as a baseline scenario in this analysis. The alternate trading scenario with lower reduction costs results in annual load reductions that are a little lower while comparing the baseline TMDL scenario but can still be considered as a viable scenario since it complies with the WQS. Modeled results are represented in Fig. 8; the alternate scenario produced a slightly higher maximum geometric mean of fecal coliform concentrations as compared with the baseline scenario.

Table 7 presents the statistics of the simulated 30-day geometric mean fecal coliform concentrations for the two scenarios. The maximum of the trading scenario is slightly higher than the baseline scenario maximum 30-day geometric mean concentration. The median and the minimum geometric mean fecal coliform concentrations for the trading scenario are, however, lower than those of the baseline scenario. Table 8 presents the baseline scenario as described in the TMDL allocation report (VADEQ 2000) and the potential trading scenario. The total load reduction of the trading scenario is though a little lower than the TMDL scenario, but it is an acceptable scenario since it meets the water quality requirements.

Pollutant reduction costs

Economic TMDL not only calculates the least cost pollutant reduction scenario satisfying the water quality criteria but also optimizes the costs of pollutant

Table 10 Estimated deer population in WAR1

Deer habitat	Areas (km ²)	Estimated number of deer
Forest	9.3	126
Built-up	0.4	5
Farmstead	0.05	1
Total	9.75	132

reductions for any other scenario. The cost versus reductions plotted for each nonpoint source in WAR1 are unique to the WAR1 subwatershed under the modeling procedure described in a previous study by Zaidi and deMonsabert (2008). In the following sections, the annual load reductions from each pollutant source and associated reduction costs are given.

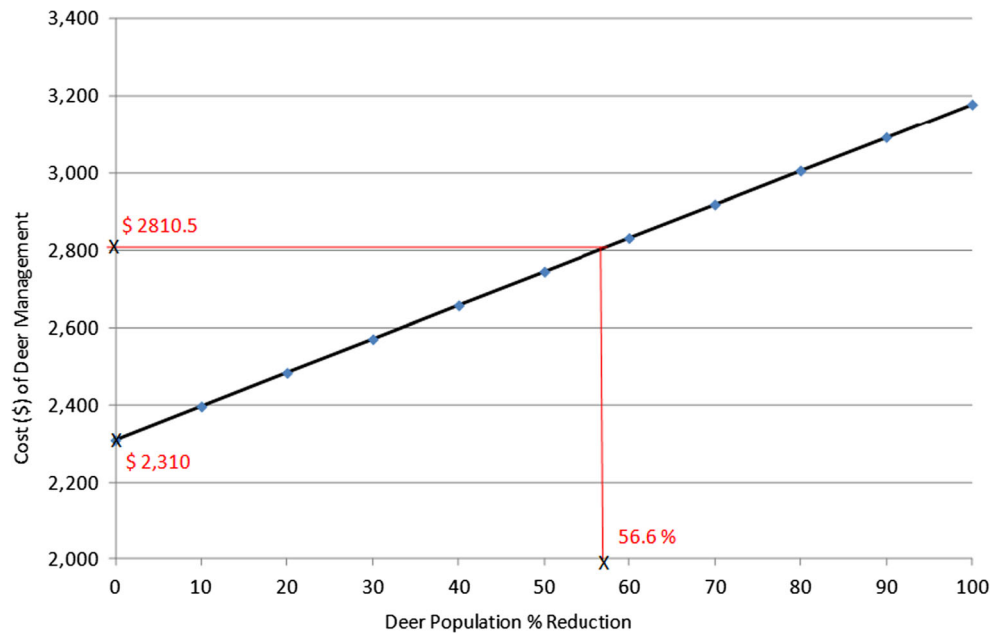
Land-based loads

To calculate the waste applied to the land surface, the different types of land uses in the watershed adjacent to a stream and the population of the grazing animals in these land use areas are considered. A description of Virginia land use classes indicates the animal distribution and animal traffic in each land use (VADEQ 2000). Reductions from pasture types 1, 2, and 3 and from the cropland are estimated with buffer strip applications in land parcels of WAR1 subwatershed. The cost is minimized using the optimization *Economic TMDL* model for several load reduction schemes. An optimization submodel is developed for this purpose using different load reduction schemes as its input. The costs are calculated against various levels of land-based reductions from all of these land uses. The unit cost (cost per load reduction) versus percent load reduction for land-based loads in the WAR1 subwatershed is presented in Fig. 9 that shows a nonlinear relationship between unit cost and the percent load reduction.

Land-based load reduction costs for both the TMDL and trading scenarios can be calculated for WAR1 subwatershed using the plot of Fig. 9. In TMDL scenario, for example, land-based load reduction is 47.86 % with a corresponding cost/load reduction of 19.6E+10 \$/counts. Multiplying this value with the actual loads reduced (1.68E+11 counts/year) the reduction cost that can be calculated (Table 9).

Wildlife loads

Deer habitat includes forest, built-up, and farmstead areas in WAR1 subwatershed. Deer density provided by the VADCR and obtained from the Virginia

Fig. 10 Wildlife management cost

Department of Game and Inland Fisheries is 35 deer per square mile (13.5 deer per square kilometer) of deer habitat in the Muddy Creek watershed. The total area of deer habitat and the estimated number of deer in WAR1 are shown in Table 10. The cost versus percent deer population removal for land-based loads in the WAR1 subwatershed is presented in Fig. 10. Wildlife load reduction costs for both TMDL and trading scenarios can be calculated for WAR1 subwatershed (Table 11) using the plot of Fig. 10.

Failed septic system

The implementation cost is directly related to allocation per failed system, the total allocation required, and the cost of finding and repairing the failure. The lack of knowledge regarding the exact location of the failed systems gives rise to an uncertainty about the required number of septic systems that need to be inspected and

therefore may raise the total inspection cost. Inspecting all of the systems may be very expensive and may produce marginal results (many inspections and few located failed systems). The costs for identifying and repairing the failed septic systems should be included in the optimization. The probability of finding the failed systems if plotted against the number of inspections may attain varying shapes depending on the number of failed septic systems and total systems in the watershed. The example of the Muddy Creek subwatershed WAR1 is presented in Fig. 11 which shows the number of inspections needed to find 4 failed systems out of 153 total systems at various probabilities. From this plot, the number of failed system inspections necessary to find all 4 failed systems with 0.5 probability is 129, and the corresponding annual cost of both finding and repairing the failure is \$39,250. Costs of Septic system installation and repair for both TMDL and trading scenarios are given in Table 12.

Table 11 Wildlife load reduction costs

TMDL reduction			Potential trading reduction		
(counts/year)	Percent	Annual cost (\$/year)	(counts/year)	Percent	Annual cost (\$/year)
0.00E+00	0.00	2,310.00 ^a	1.47E+10	55.06 ^b	2,810.50

^a This reflects the cost of maintaining the existing deer population of 132 in numbers (assuming 7 % growth rate). As such, it does not constitute a load reduction

^b 56.6 % removal in deer population (76 deer) will be translated into 55.06 % reduction of fecal deposit from deer habitat (forest, built-up, and farmstead areas)

Fig. 11 Cost of septic system repair with probability of finding four failed systems in “n” number of inspections

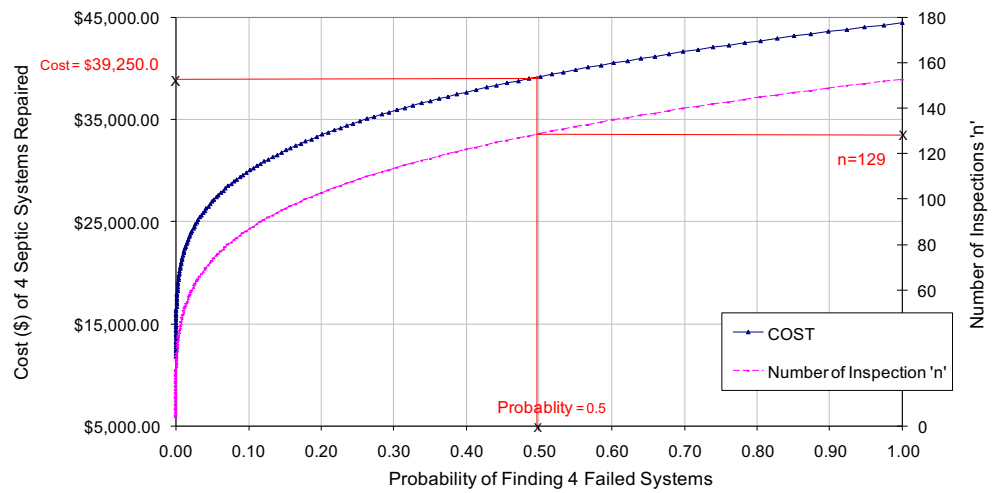


Table 12 Failed septic system load reduction costs

TMDL reduction			Potential trading reduction		
(counts/year)	Percent	Annual cost (\$/year)	(counts/year)	Percent	Annual cost (\$/year)
1.04E+11	100.00	39,250.00	0.00E+00	0.00	0

Fig. 12 Streamside fencing system requirements

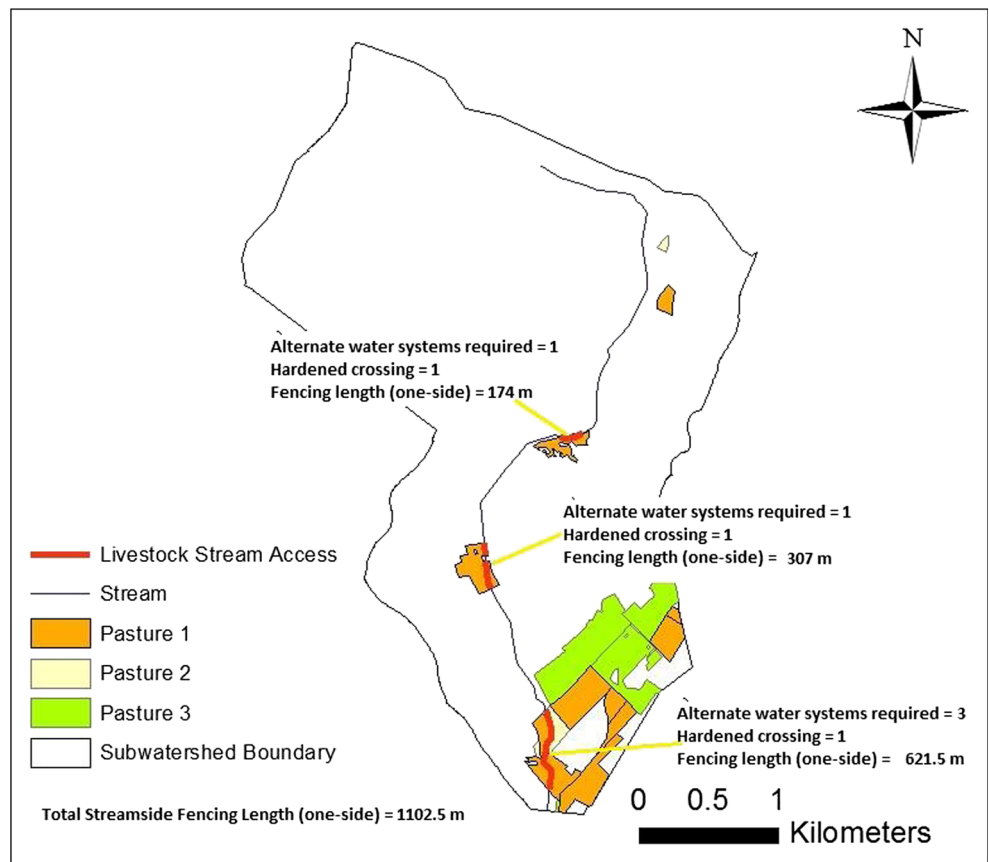


Table 13 Total cost of streamside fencing for 100 % reduction in direct deposition

Item	Units	Cost (\$/year)
Fencing	1102.5×2 ^a =2205 m	2205×1.35=2,977
Alternate water system	5	5×2,552.5=12,762.5
Hardened crossing	3	3×392.7=1,178
Total		16,917.5

^a Two-sided fencing is required in WAR1

Direct deposit

The direct load from cows is the dominant source contributing to the total fecal load in the Muddy Creek watershed. In this analysis, the streamside fencing is selected to keep the cattle away from the stream. The stream that runs along or through the cattle access lands needs to be fenced in order to provide a barrier that prohibits animal access to the stream. Figure 12 shows three parcels with cattle access lands and stream segments in the WAR1 subwatershed of Muddy Creek.

Information regarding stream side lengths, the number of hardened crossings, and alternate water systems as shown in Fig. 12 can be used to calculate the direct load reduction costs for both the TMDL and trading scenarios in WAR1 subwatershed (Tables 13 and 14).

Comparison of baseline (TMDL) scenario with trading scenario

Load reduction cost of potential trading scenario is evaluated with respect to the baseline scenario. The cost differential of the two scenarios is shown in Table 15. The annual load reduction cost for the alternate trading scenario is \$19,844, whereas for the baseline scenario, the annual cost is \$58,813.5. The cost savings presented by the alternate trading scenario from the baseline scenario are 66 % with no violation of the water quality criterion. The cost differential for each source is also presented in this table.

Table 14 Direct deposit load reduction costs

TMDL reduction			Potential trading reduction		
(counts/year)	Percent	Annual cost (\$/year)	(counts/year)	Percent	Annual cost (\$/year)
1.95E+13	100.00	16,917.5	1.95E+13	100.00	16,917.5

Table 15 Cost comparison of trading scenario with baseline scenario

Nonpoint source	Baseline scenario (\$/year)	Trading scenario (\$/year)	Cost differential baseline trading scenario (\$/year)
Land-based loads	329.00	116.00	213.00
Wildlife loads	2,317.00	2,810.50	-493.50
Failed septic system	39,250.00	0.00	39,250.00
Direct deposit	16,917.50	16,917.50	00.00
Total	58,813.50	19,844.00	38,969.50

Cost of pollutant rights

The information regarding the cost differential between the baseline and trading scenarios from each contributing source can be utilized to calculate the pollutant rights for each polluter. Table 16 presents the cost of pollutant rights (either buying or selling) for each pollutant source. Trading is beneficial to each source if the value of the pollutant right is between the ranges shown in Table 16 for each source. Under the trading scenario, the land-based and failed septic system nonpoint sources have to reduce lesser loads as compared to the baseline scenario and therefore have to pay less treatment cost. They may purchase the pollutant rights from the wildlife source for much less than their savings. Wildlife management may also sell its pollutant rights and get more from this trade than what it has to pay as an extra treatment cost. The savings and costs shown in the table are with respect to the baseline scenario. The trading scenario provides better results from an economic perspective and satisfies water quality goals. This approach and result also satisfy the need for an economic analysis as part of the TMDL process during its load allocation phase.

Table 16 Pollutant rights

Nonpoint source	Cost (\$/year)	Savings (\$/year)	Pollutant rights (PRs) (\$/year)
Land-based loads	–	213.00	Purchase (PRs<213.00)
Wildlife loads	493.50	–	Sell (493.5<PRs<39,463)
Failed septic system	–	39,250.00	Purchase (PRs<39,463.00)
Direct deposit	–	–	–
Total	493.50	39,463.00	Combined PRs for land-based and septic systems >493.50

Conclusions

In comparison with the use of other water quality trading methods, the proposed approach provides an opportunity for cost savings along with an assurance of improved water quality. The *Economic TMDL* allocation outcomes for Muddy Creek subwatershed WAR1 are used to demonstrate the proposed approach. As presented in this paper, a solution with a higher load reduction does not guarantee the desirable water quality and may produce an environmentally and economically inferior solution. The proposed approach can help policy makers to assess the effectiveness of various trading options, both economically and environmentally while minimizing uncertainties of nonpoint pollutant trading. An option that improves water quality in an impaired stream with minimum cost of load reduction may become potential trading scenario.

The objective of pollutant trading is to attain the required water quality at the lowest cost, but the current TMDL approach does not talk about pollutant abatement costs. Knowledge of the abatement costs for the impairment pollutants relative to each source is essential for pollutant trading. In the absence of economic analysis as part of the TMDL process, pollutant trading within the TMDL framework cannot achieve its objective. For trading, it is imperative to evaluate various proposed allocation scenarios economically in order to determine the most economical solution. An *Economic TMDL* optimization approach may provide many advantages. Economic modeling that uses the unit remediation cost as a function of the pollutant reduction level during WQT under the framework of TMDL prefers only those allocations that meet both environmental and economic goals. A viable trading option produced using an *Economic TMDL* model may be the one with less pollutant reduction cost as compared to TMDL allocations while still meeting the water quality goal. A matrix of multiple acceptable load allocation scenarios indicating the costs associated with each scenario can provide a basis for mutual trading while ensuring water quality goals. The proposed approach can also determine the viability of a specific TMDL for watershed-based pollutant trading at the allocation stage. Moreover, the strategy can estimate the potential cost savings that may be achieved combining a pollutant trading with the TMDL load allocations.

The only limitation in the realization of the proposed approach may be due to the nonregulatory nature of nonpoint pollution control. Since nonpoint source load reductions are not regulated and, therefore, the success of nonpoint-nonpoint source trading highly depends on the commitment of the polluting sources toward voluntary pollutant reduction programs. Even with this limitation, there are monetary and nonmonetary benefits to the landowners in terms of maintaining a balanced biological system that will also result in improvement in goods and services through sustaining a resilient ecosystem. This is the main reason behind the substantial

increase in water quality restoration efforts in recent years in the USA that are now established as a billion dollar industry. A number of federal, state, and local programs, along with incentives from nonprofit organizations, are providing funding for such efforts (Harman et al. 2012). In addition to TMDL, grants provided by Section 319 of the Federal Water Pollution Control Act (Clean Water Act of 1972) and 2008 Mitigation Rule are some of the federal programs that support watershed management plans. Over the recent years, public inclination in watershed level ecosystem restoration and water quality improvements has increased due to an enhanced awareness about risks of water pollution to human health and aquatic life. Although agriculture is considered to be the primary source of land-based nonpoint source pollutants in the USA, farmers have always been participated in programs to control these pollutants at their sources to reduce their impacts on nearby streams. Several surveys done during the past few decades also show the interest of farmers in implementing best management practices to minimize the impact of nonpoint source pollutants on water quality. Besides that, in many states, financial incentives are available for farmers to encourage them to implement BMPs through agriculture cost share programs based on potential environmental benefits (Osmond et al. 2007). Last but not the least, a time has come to believe that a number of economic benefits depend on the quality of rivers and streams. They go hand in hand. Without saving rivers and floodplain habitats, it is difficult to maintain a healthy ecological environment to sustain life forms. Investments are imperative for water quality improvement programs either they come from polluters' side or provided as government grants.

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References

- EDAW (2003) Deer management plan: final internal scoping report: Indiana dunes national lakeshore national park service. EDAW, Inc. Denver, CO. February 5, 2003
- García JH, Heberling MT, Thurston HW (2011) Optimal pollution trading without pollution reductions: a note. *JAWRA J Am Water Resour Assoc* 47(1):52–58
- Harman WR, Starr M, Carter K, Tweedy M, Clemmons K, Suggs CM (2012) A function-based framework for stream assessment & restoration projects. US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC. EPA 843-K-12-006
- MapTech (2001) Fecal Coliform and NO₃ TMDL (Total Maximum Daily Load) Implementation Plan for Dry River, Muddy Creek, Pleasant Run, and Mill Creek, Virginia. MapTech Inc., Blacksburg VA. July 15, 2001

- Moore JA, Smyth J, Baker S, Miller JR (1988) Evaluating coliform concentrations in runoff from various animal waste management systems. Special Rep. 817. Agric. Exp. Stn., Oregon State Univ., Corvallis
- Morgan C, Wolverton A (2005) Water quality trading in the United States. National Center for Environmental Economics Working Paper, 05–07
- NRCS (2003) NRCS cost lists. The natural resource conservation service
- Osmond DL, Butler DM, Ranells NN, Poore MH, Wossink A, Green JT (2007) Grazing practices: a review of the literature. Tech Bull
- Powers A (2003) The current controversy regarding TMLDS: Contemporary Perspectives “TMDLS and Pollutant Trading”. Vermont Journal of Environmental Law Volume IV- 2002–2003, Pace University School of Law Faculty Publications. <http://digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1192&context=lawfaculty>
- Ribaudo MO, Gottlieb J (2011) Point-nonpoint trading—Can It Work? JAWRA Journal of the American Water Resources Association, 47(1), 5–14. <http://naldc.nal.usda.gov/download/48408/PDF>
- Ruppert TK (2004) Water quality trading and agricultural nonpoint source pollution: an analysis of the effectiveness and fairness of EPA’s policy on water quality trading. Vill. Envtl. LJ, 15, 1. http://digitalcommons.law.villanova.edu/cgi/viewcontent.cgi?article=1106&context=elj&sei-redir=1&referer=http%3A%2F%2Fscholar.google.com.pk%2Fscholar%3Fq%3DTMDL%2B%2Btrading%26btnG%3D%26hl%3Den%26as_sdt%3D0%252C5#search=%22TMDL%20trading%22
- USEPA (2003) Final water quality trading policy. United States Environmental Protection Agency, Office of Water. <http://www.epa.gov/owow/watershed/trading/finalpolicy2003.pdf>
- USEPA (2013) Impaired waters and total maximum daily loads. <http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/>. Accessed in May 2014
- VADEQ (2000) Revised Final Report: Fecal coliform TMDL Development for Muddy Creek, Virginia. The Muddy Creek TMDL Establishment Workgroup. <http://www.deq.virginia.gov/portals/0/DEQ/Water/TMDL/apptmdls/shenrvr/muddyfe.pdf>
- Zaidi AZ (2005) Economic TMDL allocation: An optimization framework. PhD Dissertation, George Mason University, Fairfax, VA
- Zaidi AZ, deMonsabert S (2008) How to include economic analysis in TMDL allocation. J Water Resour Plan Manag ASCE 2008:214–223
- Zhang HX, Yu SL (2003) Assessing the nutrient trading ratio and influencing factors from the TMDL allocation process. WEFTEC 2003, October 11–15, Los Angeles, CA