FINAL REPORT

Demonstration and Evaluation of Optimal Design Tools for Determination of TMDL Allocations

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Abstract

In this study, a genetic algorithm (GA) optimization model to minimize pollutant load reductions from different pollutant sources was developed and evaluated as an optimal design tool for the determination of TMDL allocations. The objectives and constraints of TMDL allocations were quantitatively defined in the model. The optimization model generates potential allocation scenarios, evaluates these potential allocation scenarios, and finds the optimal solution. To calculate water quality responses for each potential load reduction scenario, the simulation model, Hydrological Simulation Program – Fortran (HSPF), was linked with the optimization model. The GA optimization model was used in two case studies, the Moore's Creek Watershed and the Cottonwood Creek Watershed. Two different reduction strategies, uniform reductions by land use and minimum reductions in load contributions, were demonstrated for each case. The uniform reduction approach maximizes equity while the minimum reduction approach maximizes efficiency. In Moore's Creek case study, optimized load reduction scenarios allow for about 10% more load contributions than the scenario approved by the U.S. Environmental Protection Agency. In Cottonwood Creek case study, optimized scenarios determined by minimum reductions in load contributions permit about 11% more loads entering the waterbody than those determined by uniform reductions by land use.

1 Introduction

1.1 Background

Section 303d of the Clean Water Act (CWA) specified water quality management using a Total Maximum Daily Load (TMDL) approach. A TMDL is a watershed level concept that requires each watershed system to be analyzed to determine the total mass of any particular contaminant that can be released into the watershed without degrading the environmental quality of the overall system. The TMDL approach recognizes that environmental systems will differ in their sensitivity to contaminant stresses.

A series of lawsuits, beginning in the 1990's, have forced the U.S. Environmental Protection Agency (USEPA) to rapidly implement a nationwide TMDL program as required by the original CWA. The rapid gear-up of a potentially immense regulatory program has left states scrambling to implement TMDL analyses. Typical of many states, due to the force of litigation, Virginia has entered into a legal record of agreement with the EPA that specifies the rate at which the state will establish TMDLs. For Virginia, the expected rate is approximately equivalent to completing one TMDL analysis per week for the next ten years. Given the complexity of even a single TMDL analysis, this goal is essentially unachievable. In Virginia and throughout the country, there is a desperate need for management tools that can accelerate TMDL establishment and facilitate community involvement.

1.2 TMDL Overview

The EPA's requirements for a TMDL study continue to evolve, and the most current description of the program can be found on the EPA's web site (USEPA 2003). In general, a TMDL analysis is performed at the state level, with the TMDL submitted to the EPA for approval. The preliminary step is the state's development of the 303d list of all impaired waters within the state. Typically, a waterbody is considered impaired if it repeatedly fails to meet the state or federally-specified water quality standards. Once a watershed is listed as impaired, a TMDL must be established. A TMDL study specifies not only what the maximum mass of contaminant or load per time that can be sustained in the watershed without water quality impairments, but it also must allocate the allowable load among existing sources (both point and nonpoint). Given that the first TMDLs are being developed for impaired waters, the load allocations are typically expressed in terms of the amount of load reductions required of each source in order to bring the watershed into compliance with water quality standards. Once met, however, the watershed should become a sustainable system that maintains its water quality.

The EPA requires the load allocations to be based on the highest level of contaminant transport modeling that is reasonable for the given system. Allocations must consider variability, seasonality, and uncertainty. Furthermore, a margin of safety (MOS) must be incorporated into the analysis. When feasible, the EPA prefers a watershed-level water quality model. In Virginia, the State has selected the EPA model, BASINS (USEPA 1998), as the standard watershed model for TMDL development. The BASINS model integrates a Geographic Information System (GIS) with the water quality/quantity model, Hydrologic Simulation Program-FORTRAN (HSPF). The GIS system allows simulation of spatially variable land use practices, each with different nonpoint source characteristics. The HSPF model can predict stream flow and in-stream water quality resulting from variable weather and both nonpoint and point source loads (Bicknell, 1997). Furthermore, HSPF is supported by both the USEPA and U.S. Geological Survey.

While the HSPF model is a highly sophisticated watershed model, it is also data-intensive and highly parameterized. Required input includes land use data, weather data, point source flows and concentrations, nonpoint source loading information, and physical characteristics of the watershed. A few of the parameters associated with each land use include infiltration rates into the surface and the deep aquifer, percent impermeability, and seasonally variable plant uptake rates. Weather data includes temperature and precipitation. Calculation of agricultural nonpoint source loads typically requires knowledge of agricultural practices including amounts and scheduling of chemical and natural (manure, etc.) fertilizers, crop rotations, planting and harvesting schedules, and confinement and pasturing practices for livestock. Human, livestock, and wildlife populations are typically required. The numbers and locations of septic systems and the percentage of failing septic systems may be required. Physical watershed properties include the spatially varying stream dimensions and slopes.

Clearly, the data collection phase alone for a TMDL is daunting. In addition to the input data, a sufficient record of both stream flows and water quality concentrations is required to provide a base for model calibration. Calibration is a two-step process. The hydrology of the watershed must first be calibrated before simulation of water quality can proceed. Model calibration is an iterative process where model parameters are varied within reasonable ranges until the model results adequately match observed measurements. Once hydrological calibration is complete, the analyst must then perform the water quality calibration. Overall, calibration is yet another challenging, time-consuming phase.

Finally, after calibration, load allocation begins in which the analyst must systematically reduce the significant loads in the impaired system until the model predicts that the water quality standards will be met, given a MOS. Typically, the load contributions to the stream, which are the portions of the load actually reaching the waterbody of interest, are reduced. A simulation model, such as HSPF, can determine the load contributions. In practice, load contributions may be reduced by either reducing the original load in the watershed (such as reduce the amount of fertilizer applied) or by instituting appropriate best management practices that may reduce the load that can reach the waterbody (such as adding forested buffers around the streams). Throughout this work, reductions will be in terms of load contributions.

Unfortunately, since multiple significant sources often exist, there can be thousands of feasible combinations of loads that result in approximately the same water quality levels. Therefore, effectiveness and equity of allocations should be used to help select between possible load allocation plans.

The allocation phase is technically challenging due to the large number of parameters that may need to be altered to model each possible scenario. For instance, nitrate contamination in the Muddy Creek watershed was the focus of Virginia’s first TMDL to include significant contributions from both point and nonpoint source loads (Culver et al. 2000). The Muddy Creek watershed was divided into 8 subwatersheds, and loads were simulated as varying monthly. Thus, even a very simple load reduction simulation could require modification of nearly 100 loading parameters.

Federal requirements also specify community involvement throughout the TMDL process. Community members are critical assets in accurately determining input information for the model and understanding the important loads within the watershed. Furthermore, the community must come to believe in the TMDL process and be willing to implement the load reductions. Thus, the community should be a key player in the selection of the final load allocations. Theoretically, the state and local analysts should work to build consensus in the community in support of TMDL allocations. Clearly, community involvement is yet another stage in the TMDL process that cannot be completed in a few days.

1.3 Project Goals

The overall goal of this project is to develop, demonstrate and evaluate the utility of using an optimization tool to facilitate the determination of a TMDL and associated TMDL load allocations. There are three major components in this project. First, a genetic algorithm (GA) optimization model to determine optimal allocation scenarios is developed. Second, the GA optimization model is tested on two watersheds, the Moore's Creek Watershed and the Cottonwood Creek Watershed. The optimally determined loads are compared to those determined through the typical trial-and-error process. Third, the technical expertise and time required to utilize the GA optimization model for the determination of TMDL allocations are discussed. Each of these components is described in the following chapters.

2 Technical Approaches

The allocation phase of TMDL development includes three main steps. The first step is to specify a potential load allocation scenario consisting of the requisite reductions in pollutant load contributions for each pollutant source. Once a scenario is specified, the second step is to modify the loading parameters in the HSPF input files to correspond to the potential load allocation scenario. Then the third step is to run HSPF and to evaluate the performance of the allocation scenario. The analyst needs to repeatedly cycle through these steps in order to be able to compare the performance of a variety of allocation scenarios. In consultation with the stakeholders, the selection of the “best” allocation scenario can then occur; selection of the best scenario may implicitly consider issues like equity and the minimum change in loads required to meet the water quality goal. To accomplish this process manually is tedious and time consuming.

The entire process can be incorporated into the framework of an optimization model. In this research, a GA optimization model was developed for TMDL development and allocation. Potential TMDLs and allocation scenarios are automatically generated during the optimization. The simulation model HSPF was linked with the optimization model and used to calculate the water quality responses for each allocation scenario. A GA modified the allocation scenarios to systematically search for the optimal allocation scenario.

2.1 Model Formulation

Typically, the objective of TMDL allocation is to determine the minimum reductions in load contributions that will bring a system into compliance with water quality standards. Minimizing reductions in load contributions is a surrogate for minimizing costs, assuming that costs increase as load reductions increase. Mathematical expressions that represent the objective function and each of the constraints on TMDL allocation must be formulated and incorporated into the optimization problem. The TMDL allocation problem can be expressed as an optimization problem as follows:

$$Min \quad TL = \sum_j \left[\sum_i \left(W_{ij} * L_{ij} * X_{ij} \right) \right] \tag{1}$$

$$V \leq V^{*} \tag{2}$$

$$X_{\min ij} \leq X_{ij} \leq X_{\max ij} \tag{3}$$

where

TL = total reduction in load contributions;

L_{ij} = current pollutant load contribution from pollutant source i in subwatershed j;

X_{ij} = reduction percentage for pollutant source i in subwatershed j;

W_{ij} = weight for pollutant source i in subwatershed j;

V = vector of simulated water quality concentrations at the water quality sampling points;

V^{*} = water quality standard;

$X_{\min ij}$, $X_{\max ij}$ = lower and upper bounds, respectively, on the reduction in load contribution from pollutant source i in subwatershed j.

Weights may be assigned to each pollutant source to account for the relative difficulty or the relative cost of reductions in load contributions among different pollutant sources. Equation 2 states that the in-stream concentrations are limited by water quality standards, which are often represented in terms of concentration, such as the daily mean concentration or the 30-day geometric mean of daily concentrations. Since the in-stream concentrations that result from a given allocation scenario are predicted by a simulation model, such as HSPF, V can be expressed as:

$$V = HSPF(L, X) \tag{4}$$

Equation 3 ensures that decision variables remain within reasonable ranges based on the physical limitations for the effectiveness of the controls and any minimum removal requirement.

Other management requirements for TMDL allocation could be incorporated through additional constraints. For instance, it could be specified that no load reductions will be applied to wildlife sources or that all point sources will have a 20% reduction. This type of approach can be used to determine the best management options, given that the reduction for one or more sources is held fixed. Appropriate use of these additional constraints may also help an analyst explore equity issues. For example, to increase equity, the load reduction percentage among the same kinds of pollutant sources could be specified as equal.

2.2 Optimization Method

A GA was selected as the optimization algorithm to solve the problem formulated in the previous section. GAs are probabilistic, combinatorial search methods, based on the mechanisms of genetics and natural selection (Holland 1975). As a derivative-free optimization method, a GA has an advantage over classical optimization, since no assumptions as to convexity, smoothness, or continuity are required (Goldberg 1989). Therefore, complex systems like watersheds and a wide range of objective functions can be addressed with GA optimization.

Figure 2.1 shows a typical GA. First, an initial population of potential management policies, in our case a set of potential allocation scenarios, is created. Each policy is represented as a string of numbers that correspond to the values of the decision variables. Binary encoding, which represents individual decision variables as patterns of 1s and 0s, is often used. For instance, several binary bytes in the string may represent the percentage reduction in a specific source. During initialization the values of the strings are randomly assigned.

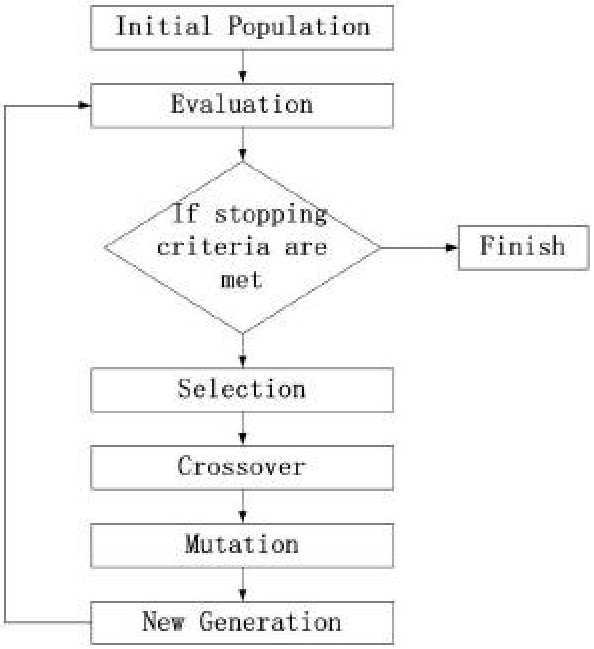

Figure 2.1 A typical process of a genetic algorithm

After initialization, the population of strings is evaluated to determine the fitness of each string, which is a measure of how well a policy performs based on the objective function and the constraints. An elitist approach is typically utilized where the string (or a specified number of strings) with the best fitness value is always copied to the new generation.

Next, the selection process starts. The most common selection method is tournament selection in which two strings are selected randomly, and the one with the better fitness value is copied into a temporary mating pool. This procedure is repeated until the number of strings in the temporary mating pool reaches the desired number of replacement strings. Crossover is then applied to exchange information between two strings. This procedure leads to the creation of two new strings. Crossover is performed on each randomly picked pair with a certain probability, referred to as the crossover probability. The mutation operator alters some of the bytes on the strings. Similar to crossover, mutation is applied with a certain probability referred to as the mutation probability. Mutation keeps the population diverse and minimizes premature convergence to a local optimum. Since both crossover and mutation occur with specified probabilities, selected pairs that do not undergo crossover or mutation will become members of the next generation without modification.

Mutation completes a generation of the GA, resulting in a new generation of strings with the same number of strings as the previous generation. The performance of the new generation of strings is then evaluated. The cycle of probabilistic transformation of a population of strings (selection-crossover-mutation-evaluation) is repeated until a stopping criterion is met.

2.3 GA-Watershed Model

The GA algorithm presented above provides a mathematical structure to systematically search for the best performing string. For the TMDL problem formulated in section 2.1, the performance of a string is dependent upon whether the water quality constraints are met. Thus for evaluation of each string, a simulation model must be run to predict in-stream water quality as specified in Equation 4. A software linkage between the simulation model and the GA is needed to facilitate the evaluation step that must occur for each string in each generation.

Some researchers have linked watershed models to evolutionary algorithms for various purposes. Nicklow and Muleta (2002) linked the SWAT model (Arnold et al. 1998) with an evolutionary algorithm to facilitate optimal management of erosion from agricultural lands. Chetan et al. (2001) have linked HSPF with a GA to form an integrated package known as BASINS-STAR. The GA in BASINS-STAR can be used to explore water quality management in terms of land use development. GAs have also been used to facilitate calibration of water quality models (Muleta and Nicklow 2002; Zou and Lung 2002).

The original intention of this study was to utilize the BASINS-STAR software. The developers had agreed to provide the software and had assured us that it could be used for determination of load allocations for TMDL analysis. However, it was found that the only current decision variables in BASINS-STAR were the percentage of different land uses. While exploring the impact of land use change is an important tool in rapidly developing areas, modification of land use distributions is not typically the primary control option for TMDL management. The developers of BASINS-STAR are currently working on making the package more amenable to TMDL analysis.

In the interim, to complete this study, we developed our own GA and linked it to the HSPF simulation package. A GA program, that provides the capabilities of the GA algorithm presented in section 2.2, was written in Fortran 77. Some GA subroutines were based on the source code of a GA driver (Carroll 2001).

The simulation model HSPF is used in this research for the simulation of hydrologic and water quality processes in the watershed. To complete the linkage of the GA and the simulation model, the binary strings must be translated into an appropriate form to run the HSPF model. A subroutine, uci-writer, was developed that interprets the GA's binary strings as reductions in load contributions and then writes an appropriate loading input file (uci file) for HSPF that corresponds to the specified reductions. HSPF is then automatically run, and information on the predicted water quality is fed into the Evaluation subroutine. Violations of the water quality constraints result in reductions in the fitness associated with a particular string. Figure 2.2 shows the linkage of GA and HSPF within the structure of the GA model.

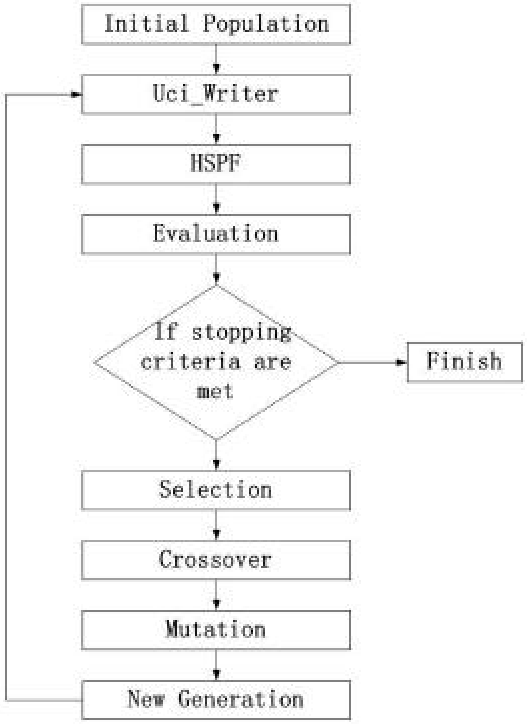

Figure 2.2 The linkage of GA and HSPF within the structure of the GA model

3 Case Study 1 Moore's Creek Watershed

The GA optimization model was applied to the Moore's Creek Watershed for the development of TMDL allocations. Two allocation strategies, uniform reductions by land use and minimum reductions in load contributions, were demonstrated in this case study.

3.1 Watershed Characterization

The Moore's Creek Watershed (VAV-H28R) is a sub-watershed of the Upper Rivanna River Watershed. The watershed drains 34.92 sq. miles of Albemarle County, Virginia, including the southern portion of the City of Charlottesville. The Moore's Creek flows approximately 11 miles from its source in the Ragged Mountains to its confluence with the Rivanna River in Charlottesville. The watershed is predominantly forested, with residential areas, grasslands, and urban areas the other major land uses (Culver et al 2002). Based on the stream network in the Moore's Creek Watershed, the watershed was divided into 11 subwatersheds, as shown in Figure 3.1.

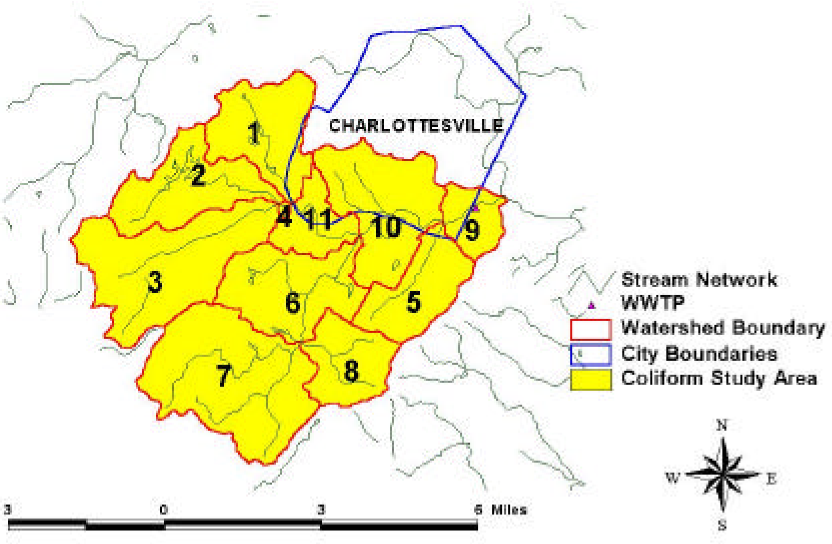

Figure 3.1 The Moore's Creek Watershed

Mooores's Creek was listed in Virginia's 1998 303(d) in 1998 due to the violation of the fecal coliform water quality standard. Fecal coliform bacteria sources in the Moore's Creek Watershed include both point and nonpoint sources. In the Moore's Creek Watershed, fecal coliform bacteria are discharged from two point sources, the Moore's Creek Advanced Wastewater Treatment Plant, operated by the Rivanna Water and Sewer Authority, and Southwood Mobile Home Park, which operates its own package treatment plant. Nonpoint sources include wildlife living in and around the waterways, livestock, pets, and humans. Cattle, horses, and goats contribute to the livestock load. Human loads come from septic systems, straight pipes, and leakage from sanitary sewers. Pet loads are primarily contributed from dogs. A bacterial source tracking study (Wiggins 2001) concluded that the system was dominated by wildlife impacts, followed by livestock.

While human sources did not dominate the samples in the bacterial source tracking study, human bacteria were consistently detected.

3.2 Load Allocations in the TMDL Report

A TMDL has been developed for fecal coliform at the Moore's Creek Watershed (Culver et al. 2002). TMDL allocation scenarios were developed to allocate fecal coliform loads to different sources in order to meet the water quality goal of maintaining the 30-day geometric mean of fecal coliform concentrations at or below the water quality standard of 200 cfu/100 ml. The fecal coliform loads in the TMDL were divided into three categories. One was the MOS that was explicitly added by achieving concentrations 5% below the 30-day geometric mean criterion of 200 cfu/100 ml. The remaining allowable 190 cfu/100 ml was divided between the allowable loading from point sources (termed the waste load allocation, WLA) and the allowable loading from nonpoint sources (termed the load allocation, LA).

The allocation scenarios were developed by the trial-and-error process and were expressed in terms of the required load reduction in each source's contribution to the in-stream fecal coliform bacteria level. There were no load reductions for the point sources that were already operating under VPDES discharge permits. The load allocations for the two point sources in the watershed were set to their legally permitted maximum level. Nonpoint source contributions were grouped into six categories: loads from cattle depositing waste directly to the stream (direct cattle), loads from septic tank due to straight pipes to streams (straight pipes), contributions from failing septic tank (septic NPS), leakage from the sewer network (sewage leakage), loads from wildlife in the stream (direct wildlife), and other nonpoint sources contributions (other NPS). Load contributions from other NPS were further grouped by land use. For all non-permitted sources of human fecal coliform bacteria, which include straight pipes, septic NPS, and sewage leakage, load contributions were reduced by 100%. Load contributions from direct cattle were also reduced by 100% through improving management practices.

After removal of all non-permitted contributions of human fecal coliform bacteria and of cattle-in-stream, the water quality goals for the Moore's Creek still were not met. Furthermore, due to the predominance of wildlife sources in this watershed, the addition of extreme reductions in the remaining nonpoint source contributions of fecal coliform that result from human activities (including agriculture) was insufficient to meet the water quality standards. Therefore, a 40% reduction in direct wildlife contributions in all subwatersheds was applied simply to make it feasible to meet the water quality goals. Contributions of fecal coliform bacteria from forest were assumed unchanged. To meet the water quality goal, reductions in contributions from residential lands were applied to the most developed subwatersheds that are either along or near the main stem of the Moore's Creek. A 30% reduction in grassland contributions was assigned to subwatersheds that held livestock. In addition, it was noted that there are a large number of feral goats in and around the stockyard in subwatershed 9. If the herd of feral animals is removed and best management practices are put in place around the stockyard, the grassland loading in subwatershed 9 could be reduced substantially. Thus a much higher reduction (85%) was assigned to the grassland in subwatershed 9. For subwatersheds with a significant urban area, urban contributions were reduced from 45% to 50%, with the highest reductions assigned to the subwatersheds near the main stem of the Moore's

Creek. The final selected and approved scenario for reductions in load contributions and the resulting TMDL for the Moore's Creek are shown in Tables 3.1 and 3.2, respectively.

Table 3.1. Approved scenario for reductions in contributions for TMDL allocation scenario for the Moore's Creek.

	Percentage Reductions in Contributions from									
						Other NPS: by land use				
SW#	Direct Cattle	Straight Pipes	Septic NPS	Sewer Leak-age	Direct Wild-life	For-est	Low Density Resid.	Med Density Resid.	Grass-land	Urban
1	0	100	100	100	40	0	0	0	0	45
2	0	0	100	0	40	0	0	0	0	45
3	100	100	100	0	40	0	0	0	30	45
4	0	0	0	0	40	0	0	0	0	0
5	0	0	100	100	40	0	30	30	30	50
6	0	100	100	100	40	0	40	40	30	45
7	0	100	100	0	40	0	0	0	30	0
8	0	0	100	0	40	0	0	0	30	0
9	0	0	100	0	40	0	50	50	85	50
10	0	0	0	100	40	0	50	50	0	50
11	0	0	0	100	40	0	50	50	0	50

Table 3.2. The Moore's Creek TMDL (10^{13} cfu/year)

ΣWLA	ΣLA	MOS[a]	TMDL
3.31	61.41	3.41	68.13

[a]Five percent of the TMDL

3.3 Optimization Base Case

For all the optimization analyses, it was assumed that there would still be 100% reduction on non-permitted human fecal coliform bacteria sources (straight pipes, straight pipes, septic NPS, and sewage leakage) and direct cattle. The base case for the optimization runs used these load reductions with no load reductions for direct wildlife or other NPS. Load contributions from different sources for this base case scenario are shown in Table 3.3.

Table 3.3. Load contribution from point sources, direct wildlife and other nonpoint sources (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Med Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	5.88	5.16	
2	28.71	5.14		3.41	1.16	5.43	
3	39.68	19.15	0.82	41.74	1.82	6.05	
4	0.34		0.25	0.22	0.02	0.15	
5	13.77	2.78	3.19	24.36	3.89	3.53	
6	20.72	8.92	43.25	40.17	1.04	6.25	0.11
7	47.91	20.83	1.00	63.79	0.16	9.60	
8	14.22	4.45	2.96	20.66	0.27	3.91	
9	3.82	1.15	9.68	32.05	3.43	1.25	30.00
10	7.00	3.48	126.26	6.31	56.35	4.96	
11	5.28	2.29	38.80	1.05	7.30	1.88	

The GA optimization model was used to find the optimal reductions in load contributions from different land uses in each subwatershed. Load reductions for the direct wildlife were not optimized. Instead a level of reduction in the direct wildlife load was assumed and assigned to all subwatersheds. The remaining load contributions were then optimized. The optimization analysis was repeated using three different levels of reductions (35%, 40%, and 45%) in contributions from direct wildlife. Community groups can then compare different optimal reduction scenarios given different reduction levels of direct wildlife. This information would be helpful for selection of the final TMDL allocation scenario.

Furthermore, several steps were taken to simply all optimizations. First, it is assumed that the weights W_{ij} (in Equation 1) are all equal to 1, and thus W_{ij} will be removed from the objective function. In addition, in order to make direct comparison between optimized allocation scenarios with the approved scenario, the reductions in contributions are assumed to be zero ($X_{ij} = 0$) for the land use segments, for which no reductions in contributions were required in Table 3.1. Most of these land use segments had already been deemed as non-critical areas, that contributes few loads into the Moore's Creek. Therefore, the number of decision variables was effectively reduced to no more than 24 corresponding to the reductions in contributions from low density and medium density residential lands in 5 subwatersheds, from grasslands in 6 subwatersheds and from urban lands in 8 subwatersheds.

3.4 Uniform Reductions by Land Use

The objective of this optimization problem is to find a load reduction scenario with the least amount of reductions in load contributions from land uses, while still meeting the water quality goal and requiring equity. Equity among the 24 land use segments described above is enforced by applying the same reductions in load contributions for all land with the same land use, regardless of subwatershed. The only exception is for grasslands in subwatershed 9 where an unusually high reduction can be achieved. Therefore, there are five decision variables in this problem. They are the reduction percentages in load contributions on the following lands: low density residential lands, medium density residential lands, grasslands except grasslands in subwatershed 9, urban lands, and grasslands in subwatershed 9.

The water quality goal is to ensure the 30-day geometric mean of fecal coliform concentrations remains at or below 200 cfu/100 ml with an explicit 5% MOS. Thus the water quality constraint for this optimization problem is specified to maintain the 30-day geometric mean of fecal coliform concentrations at or below 190 cfu/100 ml.

The ranges of the reduction percentage are determined according to the achievability of the assigned reduction percentage for each source. The minimum reduction percentage of 0% and the maximum reduction percentage of 60% are assigned to all land use segments, except for grassland in subwatershed 9. Presuming that the feral goats are removed from this subwatershed, the range of reductions for this subwatershed is from 52.5% to 90%.

The complete model formulation is:

$$
\begin{aligned}
&Min \quad TL = (L_{15} + L_{16} + L_{19} + L_{1,10} + L_{1,11}) * X_1 \\
&+ (L_{25} + L_{26} + L_{29} + L_{2,10} + L_{2,11}) * X_2 + (L_{33} + L_{35} + L_{36} + L_{37} + L_{38}) * X_3 \\
&+ (L_{41} + L_{42} + L_{43} + L_{45} + L_{46} + L_{49} + L_{4,10} + L_{4,11}) * X_4 + L_{39} * X_5 \\
&subject \quad to \\
&Geomean_{30d}(V) \le 190 cfu / 100 ml \\
&V = HSPF(L, X) \\
&0 \le X_i \le 0.6 \qquad i = \quad 1, \quad 2, \quad 3, \quad 4 \\
&0.525 <= X_5 <= 0.9
\end{aligned}
$$

where

i = 1 for low density residential lands;

i = 2 for medium density residential lands;

i = 3 for most grasslands;

i = 4 for urban lands;

i = 5 for grasslands in subwatershed 9;

V = simulated fecal coliform concentrations (cfu/100ml) at the monitoring site at the wastewater treatment plant in subwatershed 9.

The above optimization model for uniform reductions was solved using the GA-HSPF model given three different reduction levels for the direct wildlife loads. The resultant optimal reductions in contributions are summarized in Tables 3.4, 3.5, and 3.6. Based on these reduction percentages and the load contributions from different land uses (Table 3.3), load contributions from different sources (Tables A.1, A.2, and A.3 in the

Appendix) can be calculated. The optimized TMDL allocations for these three reduction scenarios are shown in Table 3.7.

Table 3.4. Optimal uniform reduction scenario given a 45% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	60
2	0	0	0	60
3	0	0	0	60
4	0	0	0	0
5	0	36	0	60
6	0	36	0	60
7	0	0	0	0
8	0	0	0	0
9	0	36	52.5	60
10	0	36	0	60
11	0	36	0	60

Table 3.5. Optimal uniform reduction scenario given a 40% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	56
2	0	0	0	56
3	0	0	0	56
4	0	0	0	0
5	16	48	0	56
6	16	48	0	56
7	0	0	0	0
8	0	0	0	0
9	16	48	52.5	56
10	16	48	0	56
11	16	48	0	56

Table 3.6. Optimal uniform reduction scenario given a 35% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	60
2	0	0	0	60
3	0	0	0	60
4	0	0	0	0
5	52	52	0	60
6	52	52	0	60
7	0	0	0	0
8	0	0	0	0
9	52	52	52.5	60
10	52	52	0	60
11	52	52	0	60

Table 3.7. Optimal TMDL allocations for uniform reductions by land use given three different reduction levels in contributions from direct wildlife (10^{13} cfu/year).

Percentage reduction in contributions from direct wildlife	ΣWLA	ΣLA	MOS[a]	TMDL
45	3.31	70.68	3.89	77.89
40	3.31	68.08	3.76	75.15
35	3.31	66.22	3.66	73.19

[a] Five percent of the TMDL

The information in Tables A.1, A.2, and A.3 in the Appendix can be used to explore the sensitivity of the reductions in load contributions from other NPS to the reduction level for direct wildlife. Figure 3.2 demonstrates the trade-off between direct wildlife load contributions and land-based NPS load contributions. A small increase of direct wildlife load contributions by $0.5*10^{12}$cfu/year requires a large reduction in land-based contributions by $45.1*10^{12}$cfu/year.

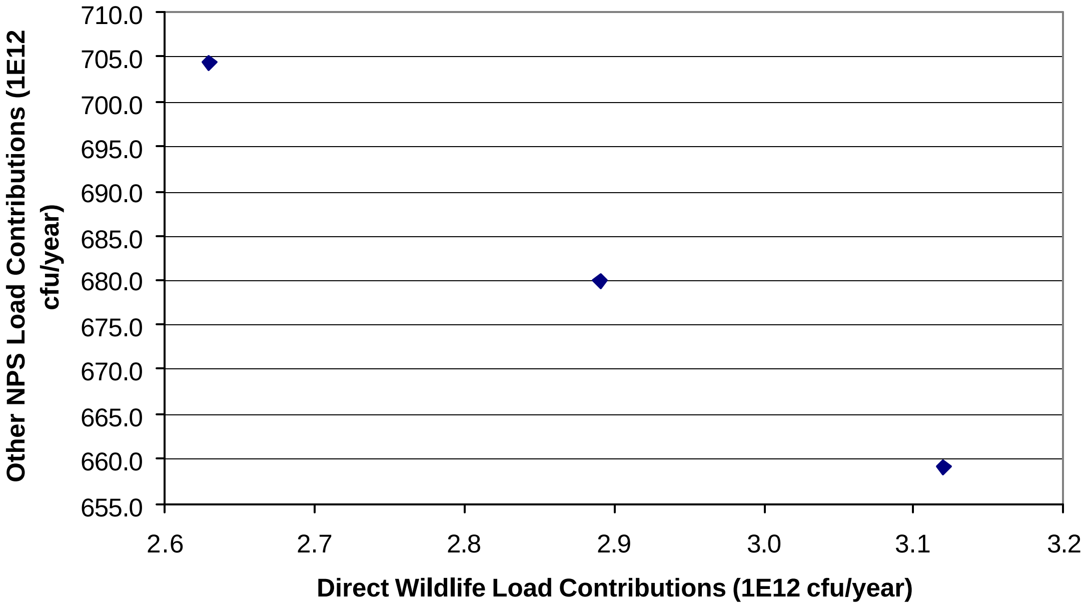

Figure 3.2 Tradeoff between optimal contributions between other NPS and direct wildlife

The sensitivity of the allowable land-based NPS contributions to the level of reduction in direct wildlife presents a challenge for the water quality managers and the community. As was described in section 3.2, because of the predominance of wildlife contributions within this watershed, the water quality goals could not be reached without reducing in-stream wildlife contributions. In practice, a watershed management plan will be developed to meet the specified reductions in contributions from other NPS. However, in this case, the plan will not actually institute reductions in contributions from wildlife, which are part of the natural background level. If water quality goals are not met after instituting the required reductions in other NPS contributions, it may be necessary to apply for a re-designation in the uses of this stream. A Use Attainability Analysis (UAA) can be completed, as described in the federal regulations under 40 CFR § 131.10(g) to demonstrate that there is no feasible means of meeting the swimming standard without removal of wildlife. If the approval is granted, the water quality standard would be effectively raised to accommodate high wildlife contributions. Unfortunately, there is no guarantee that the UAA will be approved. The higher the reductions on other NPS contributions, the more likely the community can justify the need for a re-designation.

In the approved TMDL for the Moore's Creek (Table 3.2), a 40% reduction was assigned to direct wildlife load contributions. Through optimization, an optimal uniform reduction scenario (with 40% reduction for direct wildlife) was found that required less reductions than the approved TMDL. The optimized uniform reduction TMDL allows for 10% more non-point source contributions than the approved TMDL. Relaxing the requirement for reductions in contributions will thus reduce the investment necessary to meet the water quality goals. This result shows the advantage of the optimization model, which can more effectively search through potential reduction scenarios than by trial-and-error process alone.

3.4 Minimum Reductions in Load Contributions

Although uniform reductions by land use provide equity between the same type of land uses, the optimal results tend to be inefficient because, with uniform reductions, spatial variability is not considered. Reductions in contributions in some non-critical areas may be required to be at the same level as reductions in contributions at critical areas with the same land use. While the minimum reduction approach does not consider equity, it is the most technically effective approach. Each land use in each subwatershed is assigned a separate variable.

Thus the complete model formulation is

$$\begin{aligned}
&Min \quad TL = L_{41} * X_{41} + L_{42} * X_{42} + L_{33} * X_{33} + L_{43} * X_{43} + L_{15} * X_{15} \\
&+ L_{25} * X_{25} + L_{35} * X_{35} + L_{45} * X_{45} + L_{16} * X_{16} + L_{26} * X_{26} + L_{36} * X_{36} + L_{46} * X_{46} \\
&+ L_{37} * X_{37} + L_{38} * X_{38} + L_{19} * X_{19} + L_{29} * X_{29} + L_{39} * X_{39} + L_{49} * X_{49} + L_{1,10} * X_{1,10} \\
&+ L_{2,10} * X_{2,10} + L_{4,10} * X_{4,10} + L_{1,11} * X_{1,11} + L_{2,11} * X_{2,11} + L_{4,11} * X_{4,11} \\
&subject \quad to \\
&Geomean_{30d}(V) \le 190 cfu/100ml \\
&V = HSPF(L, X) \\
&0 \le X_{ij} \le 0.6 \qquad X_{ij} \quad except \quad X_{39} \\
&0.525 \le X_{39} \le 0.9
\end{aligned}$$

where j = 1, 2, …, 11 indicates the subwatersheds as shown in Figure 3.1.

The model above is solved with the GA-HSPF model again given three different levels of reductions (45%, 40%, and 35%) in load contributions from direct wildlife. The resultant optimal minimum reduction scenarios are shown in Tables 3.8, 3.9, and 3.10.

Table 3.8. Optimal minimum reduction scenario given a 45% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	60
2	0	0	0	60
3	0	0	0	48
4	0	0	0	0
5	0	36	0	56
6	0	32	0	8
7	0	0	0	0
8	0	0	0	0
9	8	52	52.5	60
10	8	36	0	60
11	16	36	0	60

Table 3.9. Optimal minimum reduction scenario given a 40% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	48
2	0	0	0	56
3	0	0	0	40
4	0	0	0	0
5	12	40	0	48
6	0	48	0	32
7	0	0	0	0
8	0	0	0	0
9	32	60	52.5	60
10	4	60	0	60
11	0	0	0	60

Table 3.10 Optimal minimum reduction scenario given a 35% reduction from direct wildlife (%).

SW#	Low Density Residential	Medium Density Residential	Grassland	Urban
1	0	0	0	60
2	0	0	0	60
3	0	0	0	56
4	0	0	0	0
5	52	52	0	60
6	52	52	0	60
7	0	0	0	0
8	0	0	0	0
9	52	52	52.5	60
10	52	52	0	60
11	52	52	0	60

As before, the resultant load contributions from different sources (Tables A.4, A.5, and A.6 in the Appendix) and the optimal TMDL allocations (Table 3.11) for these three reduction scenarios can be calculated.

Table 3.11. Optimal TMDL allocations for minimum reductions in load contributions given three different reduction levels in contributions from direct wildlife (10^{13} cfu/year).

Percentage reduction in contributions from direct wildlife	ΣWLA	ΣLA	MOS[a]	TMDL
45	3.31	70.72	3.90	77.92
40	3.31	68.41	3.77	75.50
35	3.31	66.23	3.66	73.20

[a] Five percent of the TMDL

Due to the exclusion of some non-critical areas in the uniform reduction scenarios, as discussed in section 3.3, little room is left for further improvements to the uniform reductions. Consequently, the difference of the optimal solutions between the two allocation strategies is very small. To better illustrate the potential improvement of the reduction efficiency by using the minimum reductions in load contributions, in the next case study non-critical areas will not be excluded from the optimization analysis.

4 Case Study 2 Cottonwood Creek Watershed

4.1 Watershed Characterization

This case study used a watershed model originally developed by the Office of Water, USEPA, for the fecal coliform TMDL study at the Cottonwood Creek, Idaho. BASINS Nonpoint Source Model (NPSM) was used to represent the hydrology and the fate and transport of fecal coliform bacteria in the watershed. The calibrated NPSM model files can be downloaded from USEPA's web site, http://www.epa.gov/ost/basins/. This model is also used by the EPA as a case study for the application of BASINS. For the demonstration of the GA-HSPF model, the original calibrated NPSM model was modified to create a HSPF model. Due to the lack of sufficient information on the original TMDL analysis, the model results shown in the TMDL report (USEPA 2000) cannot be reproduced. Therefore, the HSPF model files used in this case study should not been seen as the calibrated model files for the simulation of hydrologic and water quality processes in the Cottonwood Creek. However, these HSPF model files are realistic enough for the demonstration of TMDL allocations using the GA-HSPF model.

Cottonwood Creek is a tributary to the South Fork Clearwater River located in Idaho County, in Northwest Idaho. It flows roughly from west to east and the mainstem is about 30 miles long. The creek has dramatic runoff in the spring from snow melt, severe soil erosion in the winter, and low flows during the summer. Cottonwood Creek watershed is relatively small, having an area of approximately 192 square miles (USEPA 2000). The watershed is predominately forested, with croplands, rangelands, pasture, and urban areas. Based on the stream network in the Cottonwood Creek watershed, the watershed was divided into 7 subwatersheds, as shown in Figure 4.1.

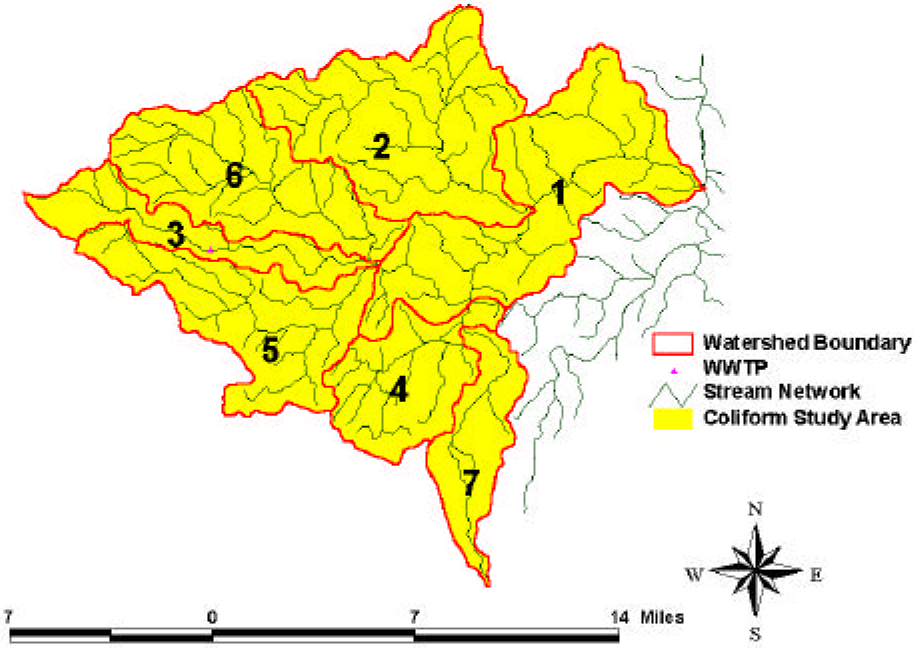

Figure 4.1 The Cottonwood Creek Watershed

Monitoring of Cottonwood Creek watershed at seven sampling locations from 1996 to 1998 repeatedly showed violations of Idaho's primary and secondary fecal coliform standards. The only point source in Cottonwood Creek watershed is Cottonwood

Wastewater Treatment Plant. Nonpoint sources include wildlife living in and around the waterways, livestock, and humans. Hogs, dairy cattle, and beef cattle contribute to livestock. Human loads come from failed septic systems. A detailed description of the watershed is available at the TMDL modeling report by the Office of Water, USEPA (2000).

4.2 Optimization Base Case

The formulation for this case study is similar to that used for the Moore's Creek case study. For the point source in the Cottonwood Creek watershed, Cottonwood Wastewater Treatment Plant, pollutant loads were allocated based on its legally permitted maximum level. Nonpoint source were grouped into three categories, in-stream loads from cattle (direct cattle), failing septic tank loads (septic tanks), and other nonpoint sources (other NPS). Load contributions from other NPS were further grouped by land use. Due to the predominance of the load contributions from direct cattle and septic tanks on the in-stream fecal coliform bacteria levels in subwatershed 2 and 4, 100% reductions were assumed for these sources. The base case for the optimization runs used these load reductions with no load reductions for other sources. Load contributions from different sources in the optimization base case are shown in Table 4.1.

Table 4.1. Load contributions from different sources(10^{11}cfu/year)

SW#	Point source	Direct Cattle	Septic Tanks	Crop-land	Range-Land	Pasture	Forest	Urban
1			2.61	11.67	168.25	12.91	1.72	
2		0.00	0.00	12.27	64.69	10.39	0.11	0.21
3	2.07	14.40	2.61	16.78	0.30	38.35	0.85	2.57
4		0.00	0.00	3.73	4.70	21.88	0.02	0.06
5			7.57	23.87		153.84	0.16	0.46
6		51.30	7.57	17.20		83.48	0.09	0.06
7			6.01	3.75	1.69	35.56	0.04	4.89

The GA optimization model was used to find the optimal reductions in load contributions from different land uses in each subwatershed. Load reductions in contributions from direct cattle and septic tanks were not optimized through the optimization model. Equal percent load reductions were assumed for direct cattle and septic tanks in all subwatersheds except subwatersheds 2 and 4. It was assumed that load contributions from direct cattle and septic tanks could be reduced at three different levels, 100%, 95%, and 90%. The simulation results show water quality standard will be satisfied if direct cattle loads and septic tank loads are reduced by 100%, without reductions in contributions from other NPS. If the reduction level for direct cattle and septic tanks in subwatershed 1, 3, 5, 6, and 7, is 95% or 90%, further reductions in contributions from other NPS are needed. The optimization analysis was repeated using two different levels, 95% or 90%, of reductions in load contributions from direct cattle and septic tanks for subwatersheds1, 3, 5, 6, and 7. As the Moore’s Creek case study, the weights W_{ij} (in Equation 1) are set equal to 1 and removed from the objective function. All land use segments in the watershed, including rangelands in 5 subwatersheds, urban lands in 6 subwatersheds, and croplands and pastures in all subwatersheds, are chosen as the potential areas for load reductions.

4.3 Uniform Reductions by Land Use

The objective of this optimization problem is to find a reduction scenario with the least amount of reductions in load contributions from land uses, while still meeting the water quality goal and maintaining equity by grouping all lands of the same land use together. Load reductions are applied to 25 land use segments. They are croplands and pasture in each subwaterhed, rangelands in subwaterhed 1, 2, 3, 4, and 7, and urban lands in all subwatersheds except subwatershed 1. Contributions from Forest areas are assumed unchanged. Due to equity considerations, the same reduction percentage is assigned to the same type of land use. Therefore, four decision variables in this problem are the percentage reduction in load contributions from croplands, rangelands, pasture, and urban lands.

The water quality constraints, which include an explicit 10% MOS, maintain the 30-day geometric mean of the fecal coliform concentration at or below to 180 cfu/100 ml. The maximum reduction percentage is determined by the achievability of the assigned reduction percentage for each source. In the example TMDL modeling report provided by the Office of Water (USEPA 2000), the final load allocations in the Cottonwood Creek watershed require reductions as high as 88%. In this study, each decision variable is constrained to be between 0% and 75%.

The complete model formulation is

$$
\begin{aligned}
&Min \quad TL = \sum L_{ij} * X_i = (L_{11} + L_{12} + L_{13} + L_{14} + L_{15} + L_{16} + L_{17}) * X_1 \\
&+ (L_{21} + L_{22} + L_{23} + L_{24} + L_{27}) * X_2 + (L_{31} + L_{32} + L_{33} + L_{34} + L_{35} + L_{36} + L_{37}) * X_3 \\
&+ (L_{42} + L_{43} + L_{44} + L_{45} + L_{46} + L_{47}) * X_4 \\
&subject \quad to \\
&Geomean_{30d}(V_k) \leq 180 cfu/100ml \\
&V_k = HSPF(L, X) \\
&0 \leq X_i \leq 0.75
\end{aligned}
$$

where

i = 1 for croplands;

i = 2 for rangelands;

i = 3 for pasture;

i = 4 for urban lands;

j = 1, 2, …, 7 indicates the subwatersheds as shown in Figure 4.1;

k = 1, 2, …, 7 indicates water quality sampling points.

The optimal uniform reductions in load contributions with 95% or 90% reductions in direct cattle and septic tank loads are shown in Tables 4.2 and 4.3.

Table 4.2. Optimal uniform reduction scenario given a 95% reduction from direct cattle and septic tanks (%).

SW#	Cropland	Rangeland	Pasture	Urban
1	10	0	40	
2	10	0	40	50
3	10	0	40	50
4	10	0	40	50
5	10		40	50
6	10		40	50
7	10	0	40	50

Table 4.3 Optimal uniform reduction scenario given a 90% reduction from direct cattle and septic tanks (%).

SW#	Cropland	Rangeland	Pasture	Urban
1	55	0	40	
2	55	0	40	0
3	55	0	40	0
4	55	0	40	0
5	55		40	0
6	55		40	0
7	55	0	40	0

As in the previous case study, load contributions from different sources (Tables A.7 and A.8 in the Appendix) and the optimal TMDL allocations (Table 4.4) for these two reduction scenarios can be calculated.

Table 4.4. Optimal TMDL allocations for uniform reductions by land use given two different reduction levels in contributions from direct wildlife (10^{11} cfu/year)

Percentage reduction in contributions from direct wildlife	ΣWLA	ΣLA	MOS[a]	TMDL
95	2.07	545.54	60.85	608.45
90	2.07	514.09	57.35	573.52

[a] Ten percent of the TMDL

4.3 Minimum Reductions in Load Contributions

Without any equity requirement, reductions on each subwatershed are handled independently, significantly increasing the number of decision variable to 25. The complete model formulation is

$$
\begin{aligned}
&Min \quad TL = \sum_{i=1}^{4}\sum_{j=1}^{7}(L_{ij} * X_{ij}) \qquad where \quad ij \quad \neq \quad (4,1) \quad (2,5) \quad (2,6) \\
&subject \quad to \\
&Geomean_{30d}(V_k) \leq 180 cfu/100ml \\
&V_k = HSPF(L, X) \\
&0 \leq X_{ij} \leq 0.75
\end{aligned}
$$

The optimal uniform reductions in load contributions with 95% or 90% reductions in contributions from direct cattle and septic tanks are shown in Tables 4.5 and 4.6.

Table 4.5. Optimal minimum reduction scenario given a 95% reduction from direct cattle and septic tanks (%).

SW#	Cropland	Rangeland	Pasture	Urban
1	0	0	5	
2	15	0	20	70
3	5	60	0	10
4	55	35	0	40
5	0		45	35
6	5		20	45
7	15	10	0	5

Table 4.6. Optimal minimum reduction scenario given a 90% reduction from direct cattle and septic tanks (%).

SW#	Cropland	Rangeland	Pasture	Urban
1	0	0	10	
2	15	0	25	5
3	0	55	0	10
4	0	70	0	65
5	65		30	45
6	10		60	20
7	5	40	0	40

For these two reduction scenarios, load contributions from different sources are shown in Tables A.9 and A.10 in the Appendix, and the optimal TMDL allocations are shown in Table 4.7.

Table 4.7. Optimal TMDL allocations for uniform reductions by land use given two different levels of load reductions in contributions from direct wildlife (10^{11} cfu/year)

Percentage reduction in direct wildlife loads	ΣWLA	ΣLA	MOS[a]	TMDL
95	2.07	603.50	67.29	672.85
90	2.07	579.75	64.65	646.47

[a] Ten percent of the TMDL

The optimal TMDLs for uniform reduction by land use and minimum reductions in load contributions are compared in Figure 4.3. By removing the equity constraints on the model formulation, the minimization of reductions in contributions provides more opportunities for further load reductions and improves the efficiency of the load reduction plans. Given two different reduction levels of load contributions from direct cattle and septic tanks, minimization of reduction in load contributions allows about 11% more loads entering the waterbody than uniform reduction by land use.

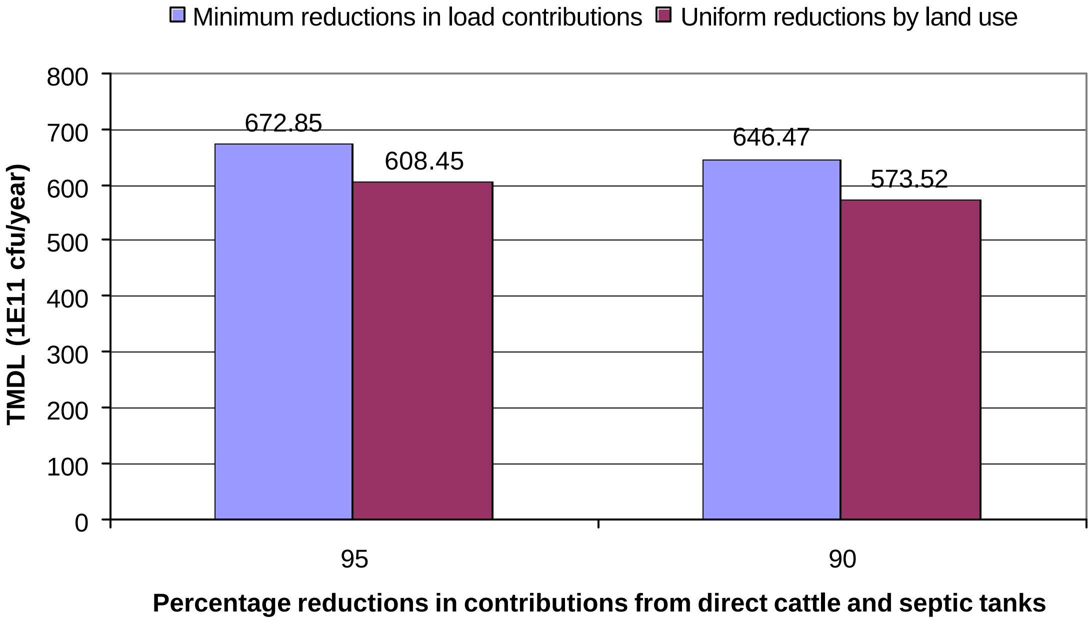

Figure 4.3. The Optimal TMDLs of the two allocation strategies given two different levels of reductions in contributions from direct cattle and septic tanks

5 Technical Expertise and Time Requirements

Typically, the analysts who are responsible for the TMDL development and simulation are also responsible for determining the load allocations. Ultimately, one can envision when optimal design tools for allocation will be seamlessly integrated into a watershed simulation package. The BASINS-STAR developers and others are working toward this; however, as indicated earlier, these tools are not yet ready for general distribution. It can be reasonably expected that within just a few years such tools will be available.

For this study, a GA optimization model was developed and linked to the simulation model for the Moore's Creek case study. To create the optimization algorithm required programming skills and familiarity with GAs. Linkage of the GA algorithm to the simulation model also required programming and knowledge of GAs, but at a significantly lower level. The entire process of developing the GA from scratch and linking it to the simulation model required approximately 2 months of labor.

The second case study, Cottonwood Creek watershed, provides a more realistic measure of the expertise and time requirement for optimization-facilitated allocations. In this case, the GA algorithm had already been developed and basic understanding of working with the GA had already been gained. Thus, in this case an analyst with basic skills had to perform the linkage of the GA to the simulation model and modify the objective function and constraints appropriately for the new problem. Given the flexible framework of GA-based optimization, modification of the objective function and constraints for different problems is straightforward. It is estimated that one week should be sufficient for most analysts, who are familiar with the simulation model and have at least a limited knowledge of GAs and programming, to modify the GA-based optimization model developed in this study (or other similar models) and use it in another TMDL allocation analysis. Allocation by trial-and-error analysis also requires time, probably also on the order of a week, and it may generate inferior alternatives.

6 Conclusions

This work demonstrates that the GA optimization model can be used as an effective optimal design tool for the determination of TMDL allocations. TMDL allocation problem can be quantitatively formulated as an optimization problem and solved via a GA-based optimization. The optimization model can find the optimal solutions based on different allocation strategies, such as uniform reductions by land use or minimum reductions in load contributions. In Moore’s Creek case study, optimized load reduction scenarios allow for about 10% more load contributions than the scenario approved by the U.S. Environmental Protection Agency. In Cottonwood Creek case study, optimized scenarios determined by minimum reductions in load contributions permit about 11% more loads entering the waterbody than those determined by uniform reductions by land use. Even if an analyst must link a simulation model to an existing GA, the amount of time required is expected to be similar to that required for trial-and-error analysis.

APPENDIX: Load contributions from different sources for different optimal allocation scenarios

Table A.1. Load contributions from different sources in the Moore's Creek Watershed for the optimal uniform reduction scenario given a 45% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	2.35	0.28	
2	28.71	5.14	0.00	3.41	0.46	0.30	
3	39.68	19.15	0.82	41.74	0.73	0.33	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	2.78	2.04	24.36	1.56	0.19	
6	20.72	8.92	27.68	40.17	0.42	0.34	0.11
7	47.91	20.83	1.00	63.79	0.16	0.53	
8	14.22	4.45	2.96	20.66	0.27	0.21	
9	3.82	1.15	6.20	15.22	1.37	0.07	33.00
10	7.00	3.48	80.81	6.31	22.54	0.27	
11	5.28	2.29	24.83	1.05	2.92	0.10	

Table A.2. Load contributions from different sources in the Moore's Creek Watershed for the optimal uniform reduction scenario given a 40% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	2.59	0.31	
2	28.71	5.14	0.00	3.41	0.51	0.33	
3	39.68	19.15	0.82	41.74	0.80	0.36	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	2.34	1.66	24.36	1.71	0.21	
6	20.72	7.49	22.49	40.17	0.46	0.38	0.11
7	47.91	20.83	1.00	63.79	0.16	0.58	
8	14.22	4.45	2.96	20.66	0.27	0.23	
9	3.82	0.96	5.03	15.22	1.51	0.07	33.00
10	7.00	2.92	65.65	6.31	24.79	0.30	
11	5.28	1.92	20.18	1.05	3.21	0.11	

Table A.3. Load contributions from different sources in the Moore's Creek Watershed for the optimal uniform reduction scenario given a 35% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	2.35	0.34	
2	28.71	5.14	0.00	3.41	0.46	0.35	
3	39.68	19.15	0.82	41.74	0.73	0.39	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	1.34	1.53	24.36	1.56	0.23	
6	20.72	4.28	20.76	40.17	0.42	0.41	0.11
7	47.91	20.83	1.00	63.79	0.16	0.62	
8	14.22	4.45	2.96	20.66	0.27	0.25	
9	3.82	0.55	4.65	15.22	1.37	0.08	33.00
10	7.00	1.67	60.60	6.31	22.54	0.32	
11	5.28	1.10	18.63	1.05	2.92	0.12	

Table A.4. Load contributions from different sources in the Moore's Creek Watershed for the optimal minimum reduction scenario given a 45% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	2.35	0.28	
2	28.71	5.14	0.00	3.41	0.46	0.30	
3	39.68	19.15	0.82	41.74	0.95	0.33	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	2.78	2.04	24.36	1.71	0.19	
6	20.72	8.92	29.41	40.17	0.96	0.34	0.11
7	47.91	20.83	1.00	63.79	0.16	0.53	
8	14.22	4.45	2.96	20.66	0.27	0.21	
9	3.82	1.06	4.65	15.22	1.37	0.07	33.00
10	7.00	3.20	80.81	6.31	22.54	0.27	
11	5.28	1.92	24.83	1.05	2.92	0.10	

Table A.5. Load contributions from different sources in the Moore's Creek Watershed for the optimal minimum reduction scenario given a 40% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	3.06	0.31	
2	28.71	5.14	0.00	3.41	0.51	0.33	
3	39.68	19.15	0.82	41.74	1.09	0.36	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	2.45	1.91	24.36	2.02	0.21	
6	20.72	8.92	22.49	40.17	0.71	0.38	0.11
7	47.91	20.83	1.00	63.79	0.16	0.58	
8	14.22	4.45	2.96	20.66	0.27	0.23	
9	3.82	0.78	3.87	15.22	1.37	0.07	33.00
10	7.00	3.34	50.50	6.31	22.54	0.30	
11	5.28	2.29	38.80	1.05	2.92	0.11	

Table A.6. Load contributions from different sources in the Moore's Creek Watershed for the optimal minimum reduction scenario given a 35% load reduction from direct wildlife (10^{12}cfu/year)

SW#	Forest	Low Density Residential	Medium Density Residential	Grassland	Urban	Direct Wildlife	Point Sources
1	5.73	25.29	13.67	11.43	2.35	0.34	
2	28.71	5.14	0.00	3.41	0.46	0.35	
3	39.68	19.15	0.82	41.74	0.80	0.39	
4	0.34	0.00	0.25	0.22	0.02	0.01	
5	13.77	1.22	1.40	24.36	1.56	0.23	
6	20.72	4.28	20.76	40.17	0.42	0.41	0.11
7	47.91	20.83	1.00	63.79	0.16	0.62	
8	14.22	4.45	2.96	20.66	0.27	0.25	
9	3.82	0.55	4.65	15.22	1.37	0.08	33.00
10	7.00	1.67	60.60	6.31	22.54	0.32	
11	5.28	1.10	18.63	1.05	2.92	0.12	

Table A.7. Load contributions from different sources in the Cottonwood Creek watershed for the optimal uniform allocation scenario given a 95% reduction in contributions from direct cattle and septic tanks (10^{11}cfu/year)

SW#	Point source	Direct Cattle	Septic Tanks	Crop-land	Range-Land	Pasture	Forest	Urban
1			0.13	10.50	168.25	7.75	1.72	
2		0.00	0.00	11.04	64.69	6.23	0.11	0.11
3	2.07	0.72	0.13	15.10	0.30	23.01	0.85	1.29
4		0.00	0.00	3.36	4.70	13.13	0.02	0.03
5			0.38	21.48		92.30	0.16	0.23
6		2.57	0.38	15.48		50.09	0.09	0.03
7			0.30	3.38	1.69	21.34	0.04	2.45

Table A.8. Load contributions from different sources in the Cottonwood Creek watershed for the optimal uniform allocation scenario given a 90% reduction in contributions from direct cattle and septic tanks (10^{11}cfu/year)

SW#	Point source	Direct Cattle	Septic Tanks	Crop-land	Range-Land	Pasture	Forest	Urban
1			0.26	5.25	168.25	7.75	1.72	
2		0.00	0.00	5.52	64.69	6.23	0.11	0.21
3	2.07	1.44	0.26	7.55	0.30	23.01	0.85	2.57
4		0.00	0.00	1.68	4.70	13.13	0.02	0.06
5			0.76	10.74		92.30	0.16	0.46
6		5.13	0.76	7.74		50.09	0.09	0.06
7			0.60	1.69	1.69	21.34	0.04	4.89

Table A.9. Load contributions from different sources in the Cottonwood Creek watershed for the optimal minimum reduction scenario given a 95% reduction in contributions from direct cattle and septic tanks (10^{11}cfu/year)

SW#	Point source	Direct Cattle	Septic Tanks	Crop-land	Range-Land	Pasture	Forest	Urban
1			0.13	11.67	168.25	12.26	1.72	
2		0.00	0.00	10.43	64.69	8.31	0.11	0.06
3	2.07	0.72	0.13	15.94	0.12	38.35	0.85	2.31
4		0.00	0.00	1.68	3.06	21.88	0.02	0.04
5			0.38	23.87		84.61	0.16	0.30
6		2.57	0.38	16.34		66.78	0.09	0.03
7			0.30	3.19	1.52	35.56	0.04	4.65

Table A.10. Load contributions from different sources in the Cottonwood Creek watershed for the optimal minimum reduction scenario given a 90% reduction in contributions from direct cattle and septic tanks (10^{11}cfu/year)

SW#	Point source	Direct Cattle	Septic Tanks	Crop-land	Range-Land	Pasture	Forest	Urban
1			0.26	11.67	168.25	11.62	1.72	
2		0.00	0.00	10.43	64.69	7.79	0.11	0.20
3	2.07	1.44	0.26	16.78	0.14	38.35	0.85	2.31
4		0.00	0.00	3.73	1.41	21.88	0.02	0.02
5			0.76	8.35		107.69	0.16	0.25
6		5.13	0.76	15.48		33.39	0.09	0.05
7			0.60	3.56	1.01	35.56	0.04	2.93

Literature Cited

Arnold, J.G., R. Srinivasan, R.S. Muttah, and J.R. Williams, 1998, Large area hydrological modeling assessment part I: Model development, J. American Water Resour. Assoc., 34(1), 73-89.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigan, Jr., and R.C. Johanson, 1996, Hydrological Simulation Program – Fortran, User's Manual For Release 11, Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Carroll, D.L., 2001, source code of Fortran genetic algorithm (GA) driver version 1.7a, http://cuaerospace.com/carroll/ga.html.

Chetan, K., Dorn, J.L., Kuterdam, C.A., Murray, T.L., Parandekar, A., Whangbo, AJ., and Ranjithan, R., 2001, BASINS-STAR: An Evolutionary Algorithm-Based Decision Support Framework for Watershed Water Quality Management, Proceedings of the World Water & Environmental Resources Congress, EWRI, Orlando, Florida, May 20-24, 2001.

Culver, T.B., Zhang, X., Naparala, T., Potts, A., Neeley, K., Yu, S, Gregory, R., Martin, C., Bodkin, R., Mizell, T., Lazarus, D., Bennett, M., Wade, C., and Schneider, J., 2000, Nitrate Total Maximum Daily Load (TMDL) Development for Muddy Creek/Dry River, Virginia, the University of Virginia, the Virginia Department of Environmental Quality and the Virginia Department of Conservation and Recreation. Available on line at http://www.deq.state.va.us/tmdl/tmdlrpts.html.

Culver, T.B., Jia, Y., Tikoo, R., and Simsic, J., 2002, Development of the Total Maximum Daily Load (TMDL) for Fecal Coliform Bacteria in Moore's Creek, Albemarle County, Virginia, submitted by the Virginia Department of Environmental

Quality and the Virginia Department of Conservation and Recreation. Available on line at http://www.deq.state.va.us/tmdl/tmdlrpts.html.

Muleta, M.K. and Nicklow, J.W., 2002, Genetic algorithms for automatic calibration of physically-based distributed watershed models, Proceedings, 2002 Conference on Water Resources Planning and Management, EWRI, Roanoke, Virginia, May 19-22.

Nicklow, J.W., and Muleta, M.K., 2002, Integrative Decision Making for Watershed Management using Evolutionary Algorithms, Proceedings, 2002 Conference on Water Resources Planning and Management, EWRI, Roanoke, Virginia, May 19-22.

U.S. Environmental Protection Agency, 1991, Guidance for Water Quality-Based Decisions, the TMDL Process. Office of Water, Washington, D.C., EPA 440/4-91-001.

U.S. Environmental Protection Agency, 1998, "Better assessment science integrating point and nonpoint sources, BASINS, Version 2.0, User's Manual", USEPA, Office of Water, Washington, D.C.

U.S. Environmental Protection Agency, 2000, Fecal Coliform TMDL Modeling Report Cottonwood Creek Watershed Idaho County, Idaho, USEPA, Office of Water, Washington, D.C.

U.S. Environmental Protection Agency, 2003, *Total Maximum Daily Load (TMDL) Program*, http://www.epa.gov/owow/tmdl/.

Wiggins, B.A., 2001, Use of antibiotic resistance analysis (ARA) to identify nonpoint sources of fecal coliform contamination in the Moore's Creek Watershed, Final report to the Thomas Jefferson Planning District Commission.

Zou, R. and Lung, W.S., 2002, Robust water quality modeling with alternating fitness genetic algorithm, Proceedings, 2002 Conference on Water Resources Planning and Management, EWRI, Roanoke, Virginia, May 19-22.