Stormwater Quality Management: Evaluation, Optimization, and Maintenance

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ABSTRACT

Urban stormwater runoff is a major cause of water quality degradation and impairment of beneficial uses of the nation's rivers and lakes. Stormwater quality management to address these pollution concerns differs by watershed, receiving waters characteristics, and the responsible agencies. Limited resources, legal authority, and insufficient funding often lead to inconsistent water quality outcomes.

In this dissertation, stormwater management planning is examined to identify critical components necessary to ensure that water quality goals are attained and beneficial uses are preserved. Four types of evaluation methods are reviewed: chemical and physical pollution control, biological character and processes of the receiving water, ecological health of the receiving water, and economic performance.

A genetic algorithm (GA) based watershed management optimization model is developed to evaluate stormwater management alternatives for a watershed. The optimization model is used to study how characteristics of watershed, receiving water, and stormwater quality management practices (SWQ-MPs) might influence stormwater quality management decisions and furthermore, how these factors might be considered and incorporated into the stormwater quality planning process.

Consideration of maintenance in managing stormwater quality is evaluated using an economic method to optimally schedule maintenance and incorporate maintenance aspects into management practice design. The optimal maintenance schedule can be either incorporated into the development of stormwater management plans to aid in the selection of economically efficient management practices or used to preserve the performance of existing facilities to protect receiving water quality and beneficial uses.

Results of these analyses suggest that the selection of evaluation method for stormwater quality management development should be based on the tradeoff between data requirements and level of detail in watershed and receiving water representation and potential improvements in water quality and associated benefits. Precipitation variability and SWQ-MP effectiveness uncertainties were found to be the most important factors in selecting stormwater quality management practices, particularly when striving to meet stringent water quality standards. Incorporating maintenance into the planning process is essential for ensuring that high maintenance SWQ-MPs are avoided, more economically efficient stormwater management programs are developed, and that receiving water quality meets the planning expectations.

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1 INTRODUCTION

I would feel more optimistic about a bright future for man if he spent less time proving that he can outwit Nature and more time tasting her sweetness and respecting her seniority. E. B. White

Purpose of Dissertation

Urban stormwater runoff is the fourth most extensive cause of water quality impairment of the nation's rivers and the third most extensive source of water quality impairment of lakes (National Research Council, 1992). Urban runoff is a significant source of pollution largely because of the impervious nature of urban surfaces. Imperviousness generates high velocities and flows leading to erosion. In addition, imperviousness provides grounds for pollutant accumulation thereby increasing frequency and loading of pollutants. Major stressors responsible for water quality degradation include: excessive inputs of nutrients and organic matter, hydrologic and physical changes, siltation, introductions of nonnative species, acidification, and contamination (National Research Council, 1992). Zoning designations within urban areas tend to generate different magnitudes and types of pollution in runoff. Residential and open lands tend to produce high nutrients from fertilizer use whereas oil and organic compounds may characterize runoff from commercial properties. Runoff from transportation areas such as freeways, railroads, and parking lots tend to have higher metal concentrations. As population densities increase, a corresponding increase can be detected in pollutant loadings generated from human activities that enter surface waters via runoff without undergoing treatment (SWRCB, 1999draft). Impairment of receiving water quality may degrade or eliminate beneficial uses such as recreation, water supply, and habitat attributed to receiving waters. It is therefore important to address these pollution concerns to preserve the value and uses of receiving waters.

Stormwater quality management may be implemented at three watershed levels. Source control measures, such as education, regulation of nutrient and pesticide applications, and controlled land development, can reduce pollutant production at sources upstream of the receiving waters. Structural measures, such as collection, infiltration, and detention basins, can reduce the amount of pollution transported to receiving waters through treatment and attenuation of flows. The third level of action occurs at receiving waters, with measures such as vegetation, dredging, aeration, and changes to receiving water hydraulics (e.g. mixing and residence time).

Selection of stormwater quality management alternatives depends on the watershed, receiving waters, beneficial uses, and the agencies responsible for its management. Watershed management plans vary in scope and depth from loosely defined programs based on practices developed over time to highly focused programs that respond to specific water quantity or water quality goals. Agencies and municipalities are limited by resources, legal authority, and available funding. In addition, selection of effective management can be difficult due to the highly variable and uncertain nature of water quality and hydrology and limited available information and knowledge. Continued monitoring and improved understanding of management effectiveness is gradually incorporated into management decisions. Commonly, the driving forces behind water quality management are permitting and regulatory processes.

Watershed Management

The original intent of stormwater quality management was to control and attenuate urban runoff to prevent flooding. Water quantity management efforts in urban areas are generally developed using rainfall-runoff relationships that are based on hydrologic methods such as the rational method and the unit hydrograph method. These hydrologic methods account for area and soil characteristics as well as infiltration (FHWA, 1996). Stormwater watershed models vary greatly in their representation of the watershed and hydrologic events. Models range from single-event lumped sum models such as the Penn State Runoff Model (PSRM) (Shamsi, 1994) and Technical Release 55 (TR-55) (USSCS, 1986; Viessman and Lewis, 1996) to more descriptive distributed hydrologic models such as HEC-1 (Feldman, 1995) and the Distributed Routing Rainfall-Runoff Model (DR3M) (Alley et al, 1980). Geographic information systems (GIS) have been incorporated into the modeling efforts to improve spatial representation of the modeled watersheds with detailed information on sub basins, streams, soils, and land uses (Greene and Cruise, 1995).

Water quality components were incorporated into watershed management models in response to increased awareness of water quality problems in receiving waters. Watershed models such as the Storage, Treatment, Overflow and Runoff Model (STORM) and the EPA's Stormwater Management Model (SWMM) added water quality components to existing hydrologic components used for flood control and flow attenuation. The Storage, Treatment, Overflow and Runoff Model (STORM) was developed by Water Resources Engineers, Inc. (WRE) for the Hydrologic Engineering

Center (HEC) of the US Army Corps of Engineers. STORM was originally developed to analyze runoff quantity and quality from urban basins as part of large scale planning. The model has been extended to aid in selecting storage and treatment facilities to control the quantity of stormwater runoff and land surface erosion (Nix 1994). Stormwater Management Model (SWMM) was developed by the USEPA as a comprehensive mathematical model for simulating urban runoff quantity and quality in storm and combined sewer systems. All aspects of the urban hydrologic and quality cycles are simulated, including surface runoff, transport through the drainage network, storage and treatment, and receiving water effects (Huber and Dickinson 1988).

Other watershed models include the Hydrologic Simulation Program- Fortran (HSPF) model (Crawford & Linsley 1966), the EPA's Quantity Quality Simulation (QQS) Model (EPA, 1980), and the Danish Hydraulic Institute's Systeme Hydrologique European (SHE) model (Abbott et al. 1986). These and other watershed models with water quality components are used to identify the sources, magnitudes of pollution, and areas in need of water quality management.

With increased water pollution and recognition of the role of stormwater runoff in polluting receiving waters, watershed management focus shifted to include measures that improve water quality in addition to runoff quantity control. The focus and depth of watershed stormwater quality management varies greatly. Many local agencies and municipalities are developing frameworks and guidelines for stormwater quality management. These guidelines and frameworks help in establishing program goals; compiling existing information; assessing water quality problems through collection and analysis of data and modeling of pollutant loads; identification, screening, and selection of appropriate control measures; and establishing a plan for implementation (Mumley, 1995).

Other, more specific management plans, utilize optimization techniques to improve design and identify appropriate locations for specific management practices such as detention ponds (Behera et al, 1999) and vegetative practices (Tilley and Brown, 1998) that improve and protect receiving water quality.

Urban development has greatly altered landscapes and significantly increased impervious areas thereby reducing infiltration, exacerbating flooding, and increasing loads to receiving waters. Recognizing these changes and the need to better understand their impact on receiving water quality has prompted the development of models (Chang et al, 1995) to evaluate and compare water quality parameters such as temperature (LeBlanc et al, 1997) under predevelopment and developed conditions.

Increasingly, stormwater quality management models address competing interests such as water quality preservation and financial and resource limitations (Li and Banting, 1999), costs and effectiveness of varying management designs (Yeh and Labadie, 1997), or management costs and compliance with regulations (Takyi and Lence, 1996). These models are used to develop tradeoffs between environmental and economic goals and objectives that can be used by policy makers in stormwater quality management.

The discipline of stormwater quality management is expanding in response to the immediate need to address water quality issues. Recent examples of stormwater quality management are limited in their focus on specific aspects of management such as design of specific management alternatives (treatment, land use, vegetation) or attainment of cost effectiveness. This limited focus in management can result in misleading conclusions, inefficient use of limited resources and funding, and regulatory incompliance. In this dissertation, common stormwater quality management evaluation methods are assessed for their reliability in addressing receiving water quality issues. In addition, the role of maintenance in selecting management alternatives, generally not included in management decisions, is examined.

Overview of Dissertation

The dissertation is presented in six chapters. This first chapter provides an introduction and literature review of the development of watershed and stormwater quality management. The second chapter reviews four types of evaluation methods that have been applied to the management of receiving water quality. The evaluation methods include chemical and physical pollutant standards, receiving water processes (eutrophication and toxicity), biodiversity, and economic efficiency. Chapter three describes the development of genetic algorithms based watershed management model. The model is used in chapter four to study the effects of evaluation method choice and natural variability in the watershed on management decisions. In chapter five an analytical model is presented and used to incorporate the cost of scheduled maintenance into the selection process of management options. Chapter six summarizes conclusions and observations based on the models' results as described in chapters four and five.

2 EVALUATION METHODS FOR RECEIVING WATER QUALITY

"Fear cannot be banished, but it can be calm and without panic; and it can be mitigated by reason and evaluation." Vannevar Bush (1890-1974) American electrical engineer, physicist

Introduction

Agencies and cities that discharge into receiving waters must comply with water quality standards as required by their NPDES permits to the maximum extent practicable. To meet regulatory requirements, agencies and cities develop stormwater management plans that generally include an array of structural management practices (detention basins), vegetative management practices (swales and buffer strips), and education measures. Selection of management practices depends on knowledge of available technologies and their effectiveness in reducing pollution and availability of funding for implementation, operation, and maintenance. Management choices may be based on existing knowledge and customary practice or based on evaluation methods that utilize studies and modeling of the affected receiving waters.

Despite significant efforts to improve receiving water quality, many of the nation's waters remain compromised. Thorough consideration and evaluation of suitable management practices can potentially improve the selection of management practices. A careful evaluation of management practices may lead to improved understanding of the receiving water system and processes, more effective control and protection of receiving waters quality, compliance with regulatory requirements, and better use of limited funding and available resources.

A variety of evaluation methods can be used to improve the selection of management practices. These methods can be based on the chemical and physical characteristics of the receiving water, the processes that affect receiving water quality, the population of aquatic organisms, or economic indicators. These evaluation methods require varying degrees of information and data and therefore the evaluation method used may depend on available resources and the receiving water evaluated. This chapter reviews common evaluation methods for management practices, provides examples, and compares their effectiveness in addressing urban water quality pollution problems.

Assessment of Evaluation Methods

An evaluation method can be assessed based on how well it achieves various criteria. In general, an evaluation method should improve the selection process within the confines of limited resources and funding. It is therefore important to consider both the cost and the benefits (in terms of improved water quality management) of the evaluation methods. This chapter provides a comparison of four types of evaluation methods based on four criteria:

1. <u>Relevance for receiving water (beneficial uses, objectives)</u>: Receiving water quality problems are often complex and multi-faceted. The ability of the evaluation method to capture as much of the receiving water processes in considering management alternatives can improve understanding of the aquatic system and help improve and preserve long-term water quality in the receiving waters.

2. Data and resource needs and evaluation reliability: Practical and reliable evaluation results are contingent on the data supporting it; insufficient data will make evaluation difficult or lead to misleading conclusions. Data collection is also expensive and time-consuming with some types of data being more expensive and time-consuming to obtain than others. Therefore, it is important to identify the data requirements for developing a reliable evaluation. In using an evaluation method, the tradeoff between resources and funding spent on the evaluation and the benefit gained in terms of water quality improvements must be considered.

3. Consideration of uncertainties and variability: Given the inherent uncertainties and variability of pollution, flows, and the relationship between water quality and beneficial uses (human and ecological health), the ability of the method to capture these variabilities should be considered in determining the appropriateness of the evaluation method in selecting management practices.

4. Ease of enforcement and monitoring: Once evaluation results are implemented, monitoring and enforcement can be used to ensure that the desired results, in terms of water quality improvements, are observed. The ability to enforce evaluation results will provide assurance that the receiving water quality is indeed protected. Ongoing monitoring for enforcement can be an expensive and long-term data collection exercise.

Evaluation Methods

The Clean Water Act (CWA) mandates the protection and enhancement of the physical, chemical, and biological integrity of the nation's waters. However, evaluation of receiving waters and management practices to meet the CWA goals has been limited by information and resources available. The clearest evaluation criteria have been the numerical standards set by state and federal agencies. These numerical standards were set mainly to control point source discharges and therefore were less effective in addressing water quality issues related to nonpoint source pollution. The total maximum daily load (TMDL) authority was placed in the CWA in an effort to improve receiving water quality that may be affected by nonpoint source pollution. To meet the water quality goals specified by the CWA, evaluation methods have been applied to aid in management of receiving water quality.

Four types of evaluation methods are reviewed, with each type based on how water quality performance is assessed. The first group of evaluation methods is based on chemical and physical pollution control. The second type is based on the effect of pollution on the biological character and processes of the receiving water. The third type is based on the ecological health of the receiving water. The fourth type is based on changes in economic performance due to water quality changes. These methods are interrelated and can be considered as layers of information and evaluations as shown in Figure 2-1. The economic analysis is based on ecological assessment and the ecological assessment is based on understanding the chemical-physical nature of the receiving waters. Since more resources are needed with increased level of information and uncertainties accumulate with higher-level evaluations, it is important to understand how results from different evaluations affect management choices and receiving water quality improvements. Each evaluation method is defined and examples are provided to demonstrate the application of the evaluation in solving water pollution problems.

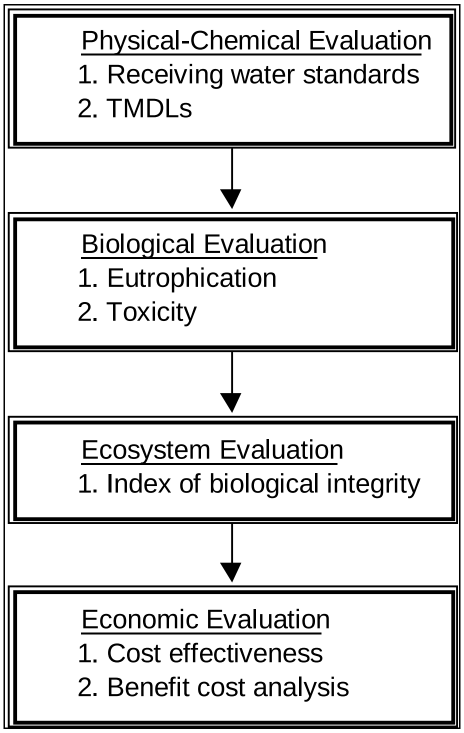

Figure 2-1: Levels of stormwater quality management analysis

Physical and Chemical Evaluation Methods

Several approaches are available for evaluating and managing receiving water quality from physical and chemical perspectives. These approaches are generally geared towards permit and regulatory compliance through either single source or watershed monitoring and evaluation. In this section two approaches, water quality standards and total maximum daily loads, are described.

Receiving Water Quality Standards

Water quality standards for rivers and lakes were required by Congress to achieve the federal Clean Water Act goal "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Water quality standards are based solely on the level of water quality needed to protect beneficial uses as determined by the responsible federal and state agencies regardless of economic difficulties. The USEPA provides recommended water quality limits that are adopted by the states. These limits are based on scientific studies showing levels at which pollutants have little or no adverse effect on designated beneficial uses (Baron, 1995). Water quality standards may be numerical or narrative. Numerical standards are chemical-specific concentration limits that are based on toxicological research data using one chemical in solution and selected test species (Kobylinski et al, 1993). In some cases, a range of concentrations is provided for varied ambient water conditions. For example, in the San Francisco basin, concentration limits for lead depend on salinity levels as well as time of monitoring. For receiving waters with salinity greater than 5 ppt, lead concentration based on 4-day average concentration shall not exceed 5.6 μg/L and based on 1-hr average concentration shall not exceed 140 μg/L. For receiving waters with salinity less than 5 ppt, 4-day average concentration limit for lead is only 3.2 μg/L and 1-hr average concentration limit is 81 μg/L (CWQCB, 1995). Narrative standards are used when numerical standards are not established or sometimes to supplement numerical criteria. Unlike more precise numerical standards, narrative standards typically consist of broad result-oriented requirements related mostly to the aesthetics of the water. Narrative standards are provisions to avoid settling that forms objectionable deposits; floating materials; objectionable color, door, taste, or turbidity; or nuisance to aquatic life (Baron, 1995). For example, a typical narrative standard for suspended material requires that receiving water shall not contain suspended material in concentrations that cause nuisance or adversely affect beneficial uses (CWQCB, 1995).

Implementation: Water quality standards defined by the USEPA are implemented through a permitting process. Any entity discharging into receiving waters must abide by the National Permit Discharge Elimination System (NPDES) permit requirements. The NPDES permit is required for all point discharges including stormwater[1] but does not consider diffused (nonpoint) sources. The NPDES permits contain chemical specific numerical effluent limits stringent enough to protect beneficial uses through compliance with water quality standards (Baron, 1995).

The NPDES permit consists of two parts. The first part requires locating and mapping all discharge locations to receiving waters. This requirement necessitates the collection and analysis of rainfall/runoff data and receiving water characterization. In addition to pollution characterization, the first part also requires a general pollution control plan. The second part of the permit is more extensive and has three elements: wet weather sampling program, a technical plan to reduce pollutants to the “maximum extent practicable”, and a financial arrangement to support management plans (Roesner and Rowney, 1996).

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[1] Stormwater discharged into receiving water via a pipe is considered point source pollution.

Data requirements: Setting water quality standards requires extensive laboratory testing and periodic monitoring to ensure permit compliance. Laboratory procedures are well established but are limited since generally they are based on one pollutant and its effect on specified species that may not be relevant for all receiving waters. Physical-chemical monitoring to determine compliance of water quality standards is relatively easy and well established and understood in terms of tests, procedures, and techniques.

Reliability of evaluation method: Physical- chemical measures give only an indirect measure of the health or biological quality of the aquatic ecosystem (Newman et al, 1994). Compliance with standards could potentially be difficult to achieve, requiring expensive technology. In addition, due to the variability in field conditions, it may be difficult to establish compliance from field sampling or monitoring.

Uncertainties and variability: Water quality standards as used today through the permitting process are not designed to handle the uncertainties and variability of the receiving waters and beneficial uses they seek to protect. Existing standards are based almost unavoidably on limited research. Generally a standard for a single chemical is based on laboratory tests that involve only the chemical and test species that may not be found at a particular receiving water. In most cases, standards are set for specific receiving waters without accounting for hydrologic and pollutant concentration variability. Since standards are set for the receiving water itself, no distinction is made between the effects of point sources and nonpoint sources on receiving water quality. In addition, physical-chemical standards account for particular acute effects and do not account for long-term effects on the ecosystem (Polls, 1994). The effects of contaminants on receiving waters and beneficial uses depend on a number of physical, chemical, and biological factors (Newman et al, 1994):

1. Receiving water's hydraulic characteristics including its volume, its mixing and dispersive characteristics, and retention time. These factors will affect the time that contaminants are retained within the body of water before being exported, sequestered, or degraded.

2. The behavior, fate, and toxicity of individual contaminants.

3. The contaminants' interaction with other contaminants once in the water. These interactions may be synergistic, additive or antagonistic.

4. Sensitivities of organisms at different life stages to contaminants.

5. The partitioning of contaminants between water and sediments. The partitioning will dictate bioavailability of contaminants in the water column. Sediment bound contaminants may not affect organisms in the water column but may affect sediment dwelling organisms.

In addition to inaccuracies in selecting water quality limits, monitoring, used to assess compliance with standards, is not done frequently enough to ensure compliance, management practice effectiveness, and receiving water quality conditions. Yet, long-term monitoring is probably the most effective way to reduce some uncertainties in setting water quality standards.

Ease of monitoring and enforcement: Since water quality standards are set for specific receiving waters, periodic monitoring can be used to determine compliance. Yet, due to the variability in receiving waters quality, it may be difficult to establish an appropriate monitoring schedule that would be representative of the receiving water's quality, making enforcement difficult.

Total Maximum Daily Load (TMDL)

TMDL, Total Maximum Daily Load is a program prescribed by the Clean Water Act (section 303d) to protect and enhance receiving water affected by point and nonpoint sources of pollution. TMDL is a program to be developed by the states that limits discharges to receiving waters based on the relationship between pollutants and the assimilative capacity of the receiving waters. For each season, a TMDL is required in receiving waters that do not meet water quality standards with technology based management practices. TMDL must include nonpoint-source loads, point source loads, margin of safety, and a growth factor (Chen et al, 1999).

TMDL evaluation generally follows five steps (USEPA, 1991):

Step 1: Define assessment goals and pollutants of concern: goals can be based on the impact of physical-chemical water quality conditions (e.g., dissolved oxygen or toxicant concentrations) or based on overall receiving water conditions based on water quality processes (e.g. eutrophication).

Step 2: Estimate water's assimilative capacity.

Step 3: Identify and estimate the relative contribution of pollution from all sources to the waterbody.

Step 4: Use predictive analysis of pollution in the waterbody to establish the total allowable pollution load.

Step 5: Allocate the allowable pollution among the different pollution sources in a manner that the goals are achieved.

In addition to these five steps, it may be important to incorporate variabilities and uncertainties into the evaluation. For traditional water pollution problems, such as dissolved oxygen depletion and nutrient enrichment, models can predict effects for expected levels of uncertainty. However, for pollution problems that result from nonpoint sources, predictive modeling may need to better account for variability and uncertainties.

<u>Implementation</u>: Several states have attempted to establish TMDL levels for receiving waters compromised with critical pollutants. The State of Washington developed loading capacity limits for the Black River to improve low dissolved oxygen levels (Pickett, 1997). In their field measurements and study, wetlands draining to the upper stretch of the river contributed to low dissolved oxygen levels irrespective of other point source discharges. TMDL levels were established for BOD, DO, and Phosphorus to prevent eutrophication and anoxic conditions that cause fish kills in the Black River. Loading capacities were developed to meet water quality standards based on data collected from three synoptic surveys and using the WASP5 model with a eutrophication component.

The allowed phosphorus levels were then allocated to point source discharges and nonpoint sources along the river.

In Idaho, a study at the Middle Snake River estimated limiting capacity and allocation for phosphorus (DEQ, 1997). Hession et al. (1996) incorporated a probability distribution of annual phosphorus load to a lake and the response of the lake to the load in developing a TMDL to control eutrophication represented by chlorophyll *a* concentration of 10 μg/L. Loading capacity for the lake was based on a eutrophication model. Variability in flow and pollutant concentration and uncertainties in establishing system properties were both included in the analysis. Rather than identifying a specific phosphorus loading, the model was used to evaluate the effect of management practices in meeting the eutrophication goal for the receiving water. The authors were able to identify management practices and the pollutant sources that needed remediation to produce the most effect on receiving water quality.

Chen et al (1999) developed a decision support system to calculate TMDLs of various pollutants for water quality limited sections within a river basin. The system model, including four components: a watershed simulation model, a database, a consensus-building model, and a TMDL model, was applied to the Catawba River Basin near Charlotte, North Carolina to develop BOD loading capacity. The system was used to develop several combinations of waste load allocation to meet water quality criteria and to allow regulatory agencies and local stakeholder to negotiate for an agreeable option.

Data requirements: TMDL evaluation requires a complete understanding of the relationship between the receiving water and its watershed and contributing sources of pollution, both point source and non-point source. Therefore, TMDL evaluation of receiving water quality requires intensive monitoring and study of the receiving water and its watershed. Data required for TMDL analysis include hydrodynamic and channel morphology measurements such as flow, channel cross-section, and velocity; physical and chemical field measurements-either continuous or grab samples, and laboratory analysis of chemical and biological parameters. Information obtained for the evaluation must account for all polluting sources and their relative effect on the receiving waters. In addition, a study of the physical, biological, and chemical processes in the receiving water must be completed to establish TMDLs for pollutants.

The cost of performing TMDL analyses depends on several factors, including: type of water body and its tributary watershed; complexity of water quality problems; number and type of pollutants; availability of data; complexity considered in analysis; and political and social importance of receiving waters (USEPA, 1996).

Reliability of evaluation method: The success of the TMDL evaluation depends on the identification of all substantial contributing polluting sources and extensive monitoring. Incomplete study of the receiving water and its watershed can lead to inefficient or ineffective results.

However, given required data and appropriate analysis, implementing results from TMDL evaluation can improve water quality and the analysis itself can improve understanding and awareness of water quality issues. In addition, information developed during the TMDL analysis can be useful in other water quality efforts.

Uncertainties and variabilities: The definition of a TMDL goal may vary from one receiving water to another depending on the beneficial uses and perceived importance of the waterbody. Generally, TMDL goals are based on receiving water quality standards. Yet, since TMDL evaluation is recommended for receiving waters where standards are not met with management practices, it may be impractical to perform TMDL evaluation based on these goals. Instead, goals may be better defined if social values and receiving water values are considered (Hession et al., 1996).

Uncertainties associated with both system characterization and natural variations (i.e. flow, pollutant concentration) can affect the outcome of a TMDL evaluation. The magnitudes and timing of stream pollutants are inherently uncertain and cannot be fully understood even with intensive monitoring. Such variabilities should be incorporated into the modeling exercise either with probability distributions or through sensitivity analysis. On the other hand, uncertainties related to understanding the system can potentially be resolved with research and monitoring.

Due to variability in flow and concentrations in tributary sources, TMDL may vary from day to day as a receiving water's capacity to assimilate pollutant loads varies. In managing receiving water, it is therefore impractical to consider these TMDL variabilities. Instead, an operational TMDL, where a constant daily load is defined, can still be useful in terms of management. An operational TMDL can be calculated based on the sum of the long-term average loadings from each source category that achieves water quality standards.

Ease of monitoring and enforcement: As with water quality standards, TMDL evaluation provides specific water quality goals that can be periodically monitored in the receiving waters. Furthermore, unlike water quality standards, TMDL evaluation allows flexibility by considering variability in receiving water quality and therefore monitoring can be scheduled more judiciously to more reasonably represent water quality conditions. Nevertheless, the enforcement of specific discharges into the receiving water to ensure compliance with a TMDL is difficult and for receiving waters that are mostly affected by nonpoint source pollution may be impossible.

Biological Evaluation Methods

Biological evaluation methods are based on water quality-related processes that are known to affect the aquatic community in the receiving water. The two most commonly used biological approaches are eutrophication and toxicity. Eutrophication, the degradation of water quality due to increased nutrients and oxygen depletion, can impinge on aquatic life and reduce the aesthetic value of the water. Toxicity due to increase levels of pollutants can alter and potentially destroy aquatic populations. Both eutrophication and toxicity are described and reviewed in this section.

Eutrophication

Eutrophication, the aging process of a body of water, is a major reason for water quality degradation. Though it is a natural process, eutrophication is greatly accelerated by human activities. Eutrophication is a multi-stage process that takes place in a surface water body in which organic matter production nourished by nutrients (natural and introduced) and minerals exceeds its loss by respiration, decay, grazing by higher organisms, and outflow (Novotny and Olem, 1994). The main states of eutrophication ranging from high quality water to highly impacted are shown in Figure 2-2. The physical, chemical, and biological indicators of these stages are summarized in Table 2-1.

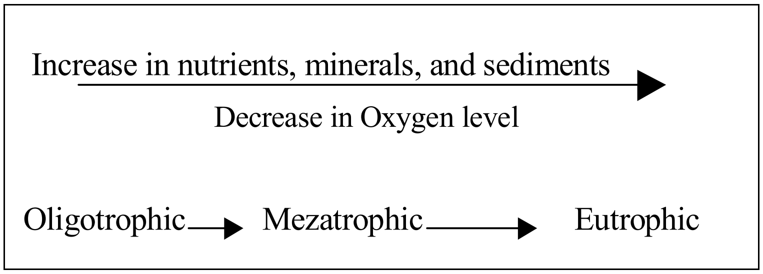

Figure 2-2: Eutrophication process

Table 2-1: Trophic status of lakes[1]

Water Quality	Oligotrophic	Mezotrophic	Eutrophic	Source
Total Phosphorus (μg/l)	<10	10-20	>20	USEPA (1974)
Chlorophyll-a (μg/l)	<4	4-10	>10	USEPA (1974)
Secchi disc depth (m)	>4	2-4	<2	USEPA (1974)
Hypolimnetic oxygen (% of saturation)	>80	10-80	<10	USEPA (1974)
Phytoplankton production (g of organic C/m^2-day)	7-25	75-250	350-700	Mason (1991)

[1] (From Novotny and Olem, 1994)

Eutrophication is evident by increased primary productivity. Increased nutrients from fertilizers and anthropogenic changes in watershed characteristics result in increased sediments laden with nutrients. These nutrients and sediments increase algae and turbidity interfering with light penetration, followed by decay of the primary producers and resultant declines in DO levels. Decay and low DO levels can impede beneficial uses such as recreation due to compromised aesthetics, shift fish and shellfish populations to less desirable species due to changing habitat conditions, and cause odor and taste problems for drinking water supplies.

Eutrophication Indices

Several indices have been proposed to assess the eutrophic state of a body of water. These indices are based on measurements of dissolved oxygen, total phosphorus, transparency by secchi disc, inorganic nitrogen, and chlorophyll-*a* concentration.

The Trophic Index by Carlson (1977) was developed for phosphorus limited lakes. The index is based on a correlation between transparency (secchi disc depth), algae concentration (chlorophyll-*a*), and phosphorus concentrations. The trophic status index (TSI) was defined based on sechhi depth (equation (2-1)), chlorophyll-*a* (equation (2-2)), and total phosphorus (equation (2-3)). The TSI for eutrophication phases based on lake observations is provided in Table 2-2. The TSI provides a general characterization of eutrophic levels. But because the TSI is based on annual loading and presumes only algae effects on the secchi depth, its predictive ability is limited.

$$TSI(SD) = 10\left(6 - \frac{\ln SD}{\ln 2}\right), SD = \text{Secchi disc depth, meters} \qquad (2\text{-}1)$$

$$TSI(Chl) = 10\left(6 - \frac{2.04 - 0.68\ln Chl}{\ln 2}\right), Chl = \text{chlorophyll-}a\ (\mu\text{g/l}) \qquad (2\text{-}2)$$

$$TSI(TP) = 10\left(6 - \frac{48/TP}{\ln 2}\right), \; TP = \text{Total Phosphorus } (\mu g/l) \tag{2-3}$$

Table 2-2: TSI for eutrophic states	
Lake type	TSI
Oligotrophic	<40
Mezotrophic	35-45
Eutrophic	>45
Hypertrophy	>60

Sawyer (1974) defined a eutrophic state based on algae nutrient uptake. Sawyer found that algal blooms occurred when concentrations of inorganic nitrogen and inorganic phosphorus exceeded 0.3 mgN/L and 0.001 mgP/L, respectively. Vollenweider (1975, 1976) developed an input-output model for phosphorus limited well-mixed lakes as represented by equation (2-4).

$$V\frac{dp}{dt} = W - \nu_s A_s p - Qp \tag{2-4}$$

Where:

V = Volume of lake (m^3)

p = Phosphorus in the lake (μg/l)

Q = Outflow (m^3/sec)

A_s = Surface area (m^2)

W = Phosphorus of watershed origin (g/sec)

ν_s = Settling rate of phosphorus (m/sec)

At steady state $\frac{dp}{dt} = 0$ and $p = \frac{W'}{q_s + \nu_s}$

q_s=hydraulic overflow rate $Q/As=H\rho$

H= Receiving water depth, m

$\rho=Q/V=1/\tau_w$ = flushing rate

τ_w =detention time in the lake

Since this representation does not account for the settling rate of phosphorus as it binds to sediments, this relationship was revised to incorporate an approximation for the settling velocity as $\nu_s = H\sqrt{\rho}$ and rewriting $p = \frac{W'}{H\rho(1+\sqrt{1/\rho})}$.

Receiving water eutrophication representations based on indices and the Vollenweider equation assume complete mixing and do not account for the system's hydrodynamics. Given that stormwater events are sporadic and nutrient loading is variable, these representations may not be sufficient to understand water quality conditions. To better understand water quality variability, several water quality models have been developed to account for the hydrodynamics, nutrient cycling, and nutrient and phytoplankton interactions.

Water Quality Analysis Simulation Program (WASP) is a generalized framework for modeling contaminant fate and transport in surface waters. WASP can be use to model biochemical oxygen demand and dissolved oxygen dynamics, nutrients and eutrophication, bacterial contamination, and organic chemical and heavy metal contamination. WASP has a special component, EUTRO5, designed to model dissolved oxygen/eutrophication. EUTRO5 can be used to simulate the transport, transformation, and interaction of up to eight state variables in the water column and sediment bed, including dissolved oxygen, carbonaceous biochemical oxygen demand, phytoplankton carbon and chlorophyll *a*, ammonia, nitrate, organic nitrogen, organic phosphorus, and orthophosphate (USEPA, 1996).

EPA's Enhanced Stream Water Quality Model (QUAL2E) is a water quality planning tool that can be used for developing TMDLs and can also be used in conjunction with field sampling for identifying the magnitude and quality characteristics of nonpoint sources. The model can simulate the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the dissolved oxygen balance in well mixed, dendritic streams. QUAL2E is set up to predict up to 15 water quality constituent concentrations and can be used to study diurnal dissolved oxygen variations and algal growth (EPA, 1999).

Implementation: Most available water quality models have a eutrophication component with varying degrees of complexity. Models vary in their representation of the food chain interactions, pollutant exchange between sediment and water, seasonal variations, number of nutrients and pollutants modeled, and spatial and temporal representation (Jorgensen, 1995). De Ceballos et al (1998) assessed 14 parameters commonly used for water quality characterization and were able to narrow down the list to two groups of parameters (7 total) that were sufficient to characterize a receiving water's quality with respect to eutrophication. These two groups are associated with algae biomass and eutrophication levels. The 7 parameters include fecal coliform, turbidity, orthophosphate, nitrate, dissolved oxygen, BOD_5, and pH.

Another example of eutrophication modeling application is the Chesapeake Bay system-modeling framework used to establish a credible basis to assist decision-making. The modeling effort included a watershed model, a three-dimensional hydrodynamic model, and a three-dimensional water quality model (nitrogen and phosphorus). The model was used to develop the level of controllability assuming 'all forest' conditions. The model was used to determine which nutrient should be controlled to reduce overall eutrophication and provide the optimal water quality improvement. Modeling efforts considered fall and spring seasons. They found that maximum reduction in primary production was mostly associated with phosphorus reduction in the upper region of the Bay. Zooplankton grazing could potentially be as important as limiting nutrients in improving eutrophication effects such as low DO (Thomann and Linker, 1998).

Reliability of evaluation methods: The process of eutrophication is well understood and therefore can be important for water quality assessment. Yet, using indices and information from sporadic monitoring can lead to unreliable results. Investing in more detailed modeling to better represent the variability and availability of nutrients can improve reliability.

Uncertainties and variability: Fluctuation in pollutant loading, availability, and seasonal conditions can have significant effects on eutrophication levels. The ability to account for these variabilities largely depends on monitoring efforts. Data obtained can then be included to varying degrees in eutrophication models. To realistically predict the effectiveness of management practices, it is essential to distinguish natural and atmospheric sources from anthropogenic sources. Application of models are limited since it may be infeasible and too costly to apply an advective-dispersive model for large drainage basins and water bodies. In these cases, completely mixed segments can be assumed to represent large reaches of a river network for management practices.

Ease of monitoring and enforcement: Enforcement of water quality based on a eutrophication evaluation requires monitoring and evaluation of nutrient concentration in the receiving water to estimate eutrophication levels. Enforcement may be difficult due to variability in weather conditions, nutrient loading, and changes in biological activities in the receiving water that can affect eutrophication levels.

Toxicity

Toxicity may be defined as an alteration or impairment of the normal function of organisms due to exposure to or ingestion of a compound/s. Toxic levels can be considered in terms of human health protection and the well being of aquatic life. The Clean Water Act (Section 502(13)) defines toxicity:

> The term “toxic pollutant” means those pollutants, or combinations of pollutants, including disease-causing agents, which after discharge and upon exposure, ingestion, inhalation or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will, on the basis of information available to the administrator, cause death, disease, behavioral

> abnormalities, cancer, genetic mutation, physiological malfunctions (including malfunctions in reproduction) or physical deformations, in such organisms or their offspring.

Though toxicity may be a natural phenomenon, it is generally considered in the context of human impact resulting from discharging contaminants. Toxic pollutants affecting receiving bodies of water include: Metals such as copper, lead, and mercury; organic compounds such as pesticides, PCBs, and solvents; dissolved gases such as chlorine and ammonium; anions such as cyanide and fluoride; and acids and alkalis. Toxic compounds may affect organisms via two pathways: adsorption and bonding of the compound by the organic matter of the organisms and through ingestion. For lower organisms, the adsorbed fraction is biologically unavailable and therefore toxicity is generally related directly to the dissolved fraction concentration in the water.

Sediment Toxicity

Aquatic sediments often contribute to toxicity in receiving waters. Sediment quality assessment is considerably more complex than water quality assessment due to factors such as bioavailability, sorption kinetics, and sediment characteristics. Several methods are available to assess and measure aquatic sediment toxicity. In general, available assessment methods for sediment toxicity can either provide limited information on dose-response relationships that is site specific or provide general information without identifying pollutants of concern but account for overall sediment toxicity (Adams et al, 1992). Some methods, such as equilibrium partitioning (EP) and spiked sediment toxicity tests, are site specific and derive dose-response relationship for specific chemicals and organisms. These methods are limited by field or laboratory data and do not account for the combined effect of mixed toxicants. The sediment quality triad approach and apparent effects threshold (AET) use chemical and biological data to statistically assess the effect of the sediment chemical characteristics on biota. The sediment quality approach and AET do not provide a direct cause and effect relationship, may not necessarily identify the true pollutants, and their results cannot be applied to other sites.

Toxicity measurements: Levels of toxicity are established using toxicity bioassay tests where test organisms ideally include representatives from four groups: microorganisms, plants, invertebrates, and fish. Data from bioassay tests are used to establish a functional dose (concentration)-response relationship (Novotny and Olem, 1994).

Chronic toxicity criteria are based on an observed long-term impact of the contaminants on the life functions of the organisms. Therefore, chronic toxicity tests expose organisms to relatively low concentrations but cover the entire reproductive life of the organisms. The goal of the chronic toxicity test is to establish the no observed effect concentration (NOEC) and the low (first) observed effect concentrations (LOEC).

Acute toxicity tests are short duration (less than 96 hrs.) representing a small fraction of the lifetime of the organisms. The concentrations are higher than those applied to chronic toxicity tests and the observed effects on organisms are severe. Acute toxicity is measured as lethal dose or concentration (LD or LC) and represents the concentration in which exposure results in organism death. The LD50 or LC50 represents the 50% survival dose or concentration. The effective dose or concentration (ED or EC) is measured when effects other than death are monitored. The developed toxicity criteria are related to the probability (frequency) of the exceedence of these concentrations (Novotny and Olem, 1994).

In assessing a chemical's toxicity, it is important to first establish its bioavailability, since only bioavailable pollutants will ultimately affect the ecosystem. In addition, when developing standards, the magnitude, duration, and frequency of exposure must be specified to completely address possible toxicity impacts.

Implementation: There are several cases where toxicity has been incorporated into an overall assessment of ecosystem health. The assessments generally include chemical fate and transport characterization and modeling, the accumulation of pollutants within the aquatic biota, and measures of the effects pollutants have on single or multiple species. A typical ecosystem assessment based on toxicity is shown in Figure 2-3.

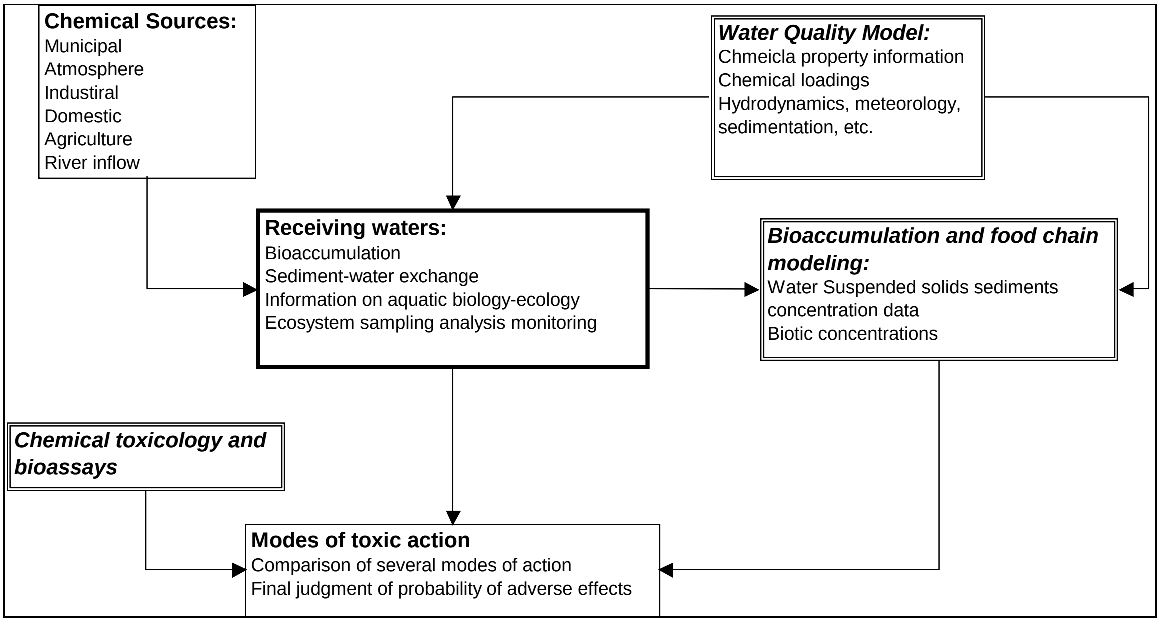

Figure 2-3: Critical Body Residues (CBR) integration in environmental risk assessment (Adapted from McCarty et al, 1993)

McCarty et al (1993) developed the Critical body residue (CBR) method to measure toxicity for water quality evaluation. The method is based on three steps (1) modeling and predicting the fate of chemicals in aquatic systems using EPA water quality models ‘Exposure Analysis Modeling System” (EXAMS) and ‘Water Quality Analysis Simulation Program (WASP), (2) Estimation of chemical residues accumulation in organisms and assemblies of organisms in the food web, (3) and relating the body/tissue concentrations to acute/chronic effects that are determined in toxicity/bioassays (including a consideration of combined effects of chemicals).

The Electric Power Research Institute (EPRI) developed the general toxicity model (GTM) to help assess the toxic impact of chemical mixtures on lake and stream ecosystems (base on selenium cycling and toxicity). The model accounts for toxic effects ranging from single species to the whole aquatic community. The GTM includes five components: (1) a biogeochemical model, which predicts toxicant exposure conditions, (2) a pharmacokinetic model, which predicts toxicant accumulation in aquatic life given exposure, including a physiological model for predicting distribution in fish tissues, (3) a food web transfer model, which tracks toxicant movement through the aquatic food web, (4) a toxic effects model, which predicts the effects of toxicant on growth, reproduction, and mortality, and (5) an ecosystem effects model, which predicts the effect on aquatic population and communities (Porcella, 1992).

Vanderkooij and Vandemeent (1992) summarized an approach to deriving a set of quality criteria for water systems based on the equilibrium partitioning method. The approach distinguishes between the water phase (dissolved), suspended particles, total (dissolved and particles), and sediments. In developing these toxic effects, data using ecotoxicological extrapolation methods are needed. Critical concentration in water is translated into solid concentration using the solid-water partitioning coefficient. In addition, product standards providing the maximum allowable concentration in fish for human health protection are translated into water concentration using bioconcentration factors.

Data Requirements: Accurate toxicity information depends on adequate sampling and laboratory testing. Since toxicity levels are specific to receiving waters, repeat sampling and testing can become costly and time consuming.

Reliability of evaluation method: The reliability of using toxicity as an evaluation measure largely depends on the level of sampling and testing performed. Errors in monitoring and variability in concentration can result in incorrect conclusions regarding toxicity in receiving waters. Furthermore, toxicity determination based on laboratory tests is subject to error due to variability between experiments or laboratory tests results, leading to inconsistent control management (Balch and Evans, 1999).

Regardless of the method used to determine toxicity, the availability and toxic impact of a chemical in the receiving water depends on its chemical form, individual species uptake rate, recycling, and toxicity. In addition, exposure to toxic compounds through bioaccumulation depends on the interactions of organisms at various levels of the food web chain. Toxicity monitoring and testing generally tends to be chemical specific and does not account for the chemical form and the interaction among species leading to inaccurate representation of toxicity conditions in the receiving waters. Toxicity testing in many cases is done for species that are not part of the aquatic ecosystem evaluated, so toxicity results may not be applicable.

Variability and uncertainties: Chronic toxicity is based on long-term exposure and acute toxicity depends on short-term exposure to high toxic levels. In both cases, only long term monitoring can identify the toxicity impact of pollutants. Therefore, monitoring may not provide sufficient information on variability in water quality and lead to inefficient management choices.

Ease of monitoring and enforcement: Enforcement of compliance regularly may be difficult since toxicity measures are time and resource intensive. In addition, toxicity may cause long-term effects that can be corrected only with ongoing management. Therefore it may require significant amount of time to see improvements in water quality and aquatic habitat and ensure compliance.

Ecological Evaluation Methods

EPA's objective for ecosystem protection is to protect, maintain and restore the ecological integrity of the nation's lands and waters. A strategic plan to meet this objective includes: identifying stressed and threatened ecosystems, defining environmental goals, developing and implementing an action plan, measuring progress and adapting management to new information over time, and identifying tools and support that can be provided at a national level. Ecological indicators, such as biological integrity indices, have been proposed to help meet this objective (Jackson and Davis, 1994).

Biological Integrity

The CWA biological integrity requirement is not well defined and ways to measure successful attainment of this goal are lacking (Karr, 1990). Biological integrity of an ecosystem can be defined by three components: its elements, its processes, and its natural undisturbed conditions. The elements of an ecosystem can be defined as the biological diversity representing the number of species and their distribution. The processes provide the evolutionary context and refer to the survival and evolution of an ecosystem.

The rate of chemical, physical, and biological processes determines the ability of the system to support and maintain a balanced, diverse, and adaptive ecosystem. The natural undisturbed condition of the ecosystem, representing the ecosystem’s condition with little or no human influence, may be used as a benchmark of the ecosystem’s biological integrity. Unfortunately, due to human intervention, it has been difficult to separate natural changes from human induced changes (Angermeier and Karr, 1994).

The Index of Biological Integrity (IBI) was developed and has been used as a measure of biological integrity to evaluate human effects on streams and their watershed. IBI is based on five environmental factors that may affect the integrity of an aquatic biota: water quality, habitat structure, energy source, flow regime, and biotic interactions (Karr, 1990). The five components are shown in Figure 2-4.

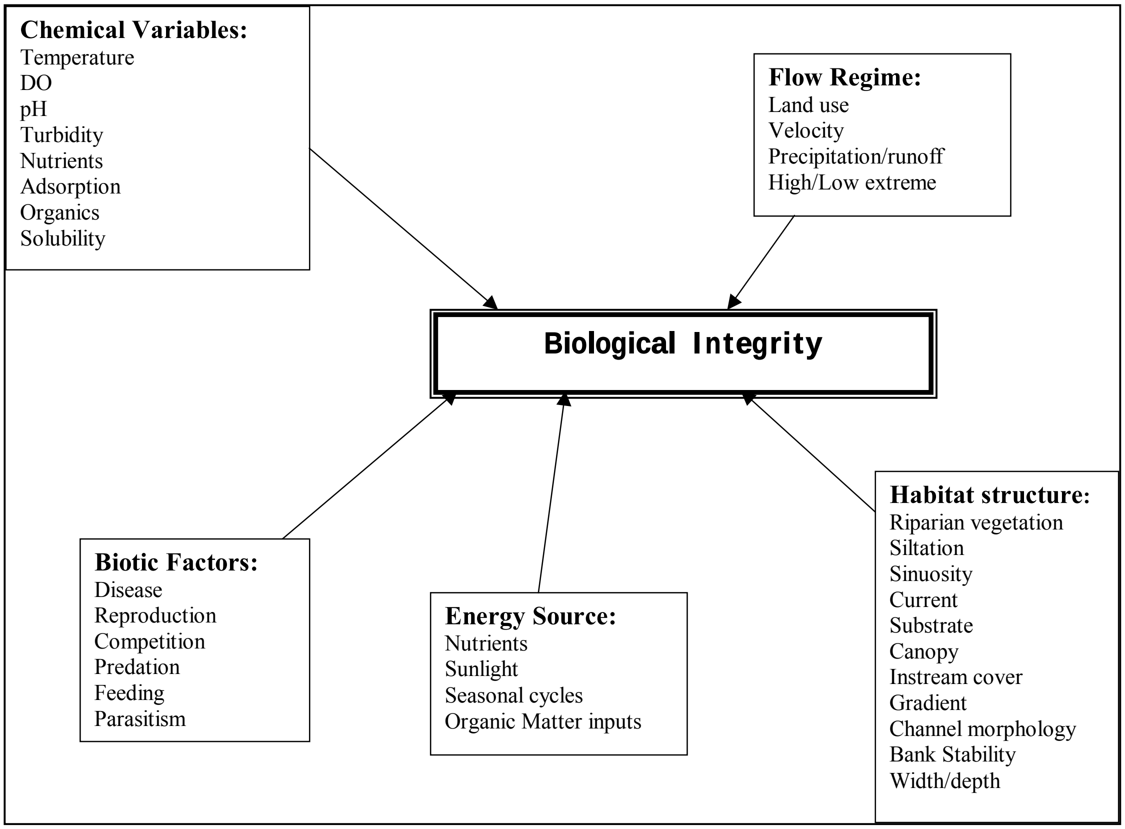

Figure 2-4: The five components of biological integrity

IBI assessment is based on the measurements of 12 biological attributes, termed metrics, of a fish community. These metrics quantify biologically meaningful aspects of the fishes in the aquatic system such as species richness and composition, trophic composition, and abundance and condition of fish. Biological integrity indicators account for the cumulative effect of habitat alteration, flow regulation, nutrient over enrichment, and the introduction of nonnative species on aquatic life and ecosystem (Jackson and Davis, 1994).

Implementation: Harig and Bain (1998) applied the IBI evaluation to 12 small isolated Adirondack lakes affected by nonnative fish species. Compromised lakes were compared to lakes with native fish communities and low recreational use that were assumed to have high IBI values. The authors identified six indicators related to dominance and abundance of native fish, *daphnia*, phytoplankton, and zooplankton species that were most sensitive to disturbance in the lakes. The indicators were found to be a powerful tool for identifying disturbance, providing target conditions of ecosystem recovery, and identifying disturbed lakes that would benefit most from intervention such as fish-community manipulation.

<u>Data requirements</u>: A comprehensive assessment of biological integrity is spatial and temporal by nature and includes both the elements and processes at multiple organization levels. Monitoring for biological effects in the ecosystem can be operationally difficult and expensive primarily because the attributes of biological organisms and communities monitored for responses to changes in water quality are variable and subject to change from other confounding factors such as species competition and physical changes in waterways.

<u>Reliability of evaluation method</u>: The inherent variability and uncertainties of the aquatic system evaluated can lead to unreliable IBI scores. Measurement of fish is generally done with electrofishing, which stuns fish at a site so they can be identified and released. Measurements cannot be repeated because of earlier effects of electrofishing. Generally, receiving waters with degraded water quality tend to have more variability in aquatic life than pristine waters, thereby making a single measurement an insufficient representation of the receiving water biological integrity (Fore, Karr, and Conquest, 1994). Errors in scores also can be attributed to the tendency of electrofishing to select larger rather than

smaller less obscure species thereby skewing the representation of aquatic life. Errors related to sampling such as inaccurate identification of species and counting can also offset IBI results.

In addition to uncertainties in measurements, variabilities due to seasonal effects such as spawning and migration can offset evaluation results. Rainfall and sunlight can affect patterns of reproduction and mortality that may change IBI scores. In developing IBI scores it is therefore difficult to differentiate changes due to anthropogenic and natural causes. The cumulative effect of chemical, physical, and biological stressors, the dynamic interactions within communities and between the biota and their physical environment must all be considered (Jackson and Davis, 1994; Polls, 1994).

Because biological systems are complex, measures of biological integrity may reflect biological conditions from genetic to individual, community and landscape levels and include evaluations of both the elements and the processes that are critical to an abundant and diverse biota.

IBI scores are developed relative to pristine conditions, yet historical records of water quality and ecosystem health are usually unavailable. Most receiving waters have been affected by human contact. Therefore, IBI scores are generally based on a comparison to other similar receiving waters.

<u>Uncertainties and variability</u>: Variability in water quality conditions are not measured explicitly using IBI. Instead, variability in selected species population is the basis for IBI scoring. Since the relationship between receiving water conditions (including quality)

and population variability is not well defined, it is difficult to apply information from IBI to selection of management practices to control water pollution.

Ease of monitoring and enforcement: Developing IBI scores require intensive sampling and analysis of data that may not be practical for managing agencies or enforcement agencies to perform. In addition, changes in biological integrity due to stormwater management may evolve over time and therefore may be difficult to monitor and observe.

Economic Evaluation Methods

Economic analyses are used to incorporate economic values into the selection process of management practices. Two economic evaluation methods are reviewed, cost effectiveness and benefit cost analysis.

Cost Effectiveness

Cost effectiveness compares several management practices in terms of their relative impact per dollar spent. Commonly, cost effectiveness is represented in terms of unit of residual reduced per dollar of cost or conversely, cost per unit reduced.

Implementation: There are numerous applications of cost effectiveness evaluation in management of water quality of receiving waters. Li et al (1997) applied a generic cost effectiveness based planning strategy for urban stormwater quality management in the Great Lakes that accounted for both ecosystem and economic goals to the City of Scarborough. Walker et al (1993) used marginal analysis based on change in cost per unit change in sediment concentration to select economically efficient management practices among nine treatment and source control options to control agricultural runoff into the middle Snake River in Idaho. Schleich and White (1997) applied linear programming to identify the least cost strategy for reaching specified phosphorus and total suspended solids reduction target for the Fox-Wolf basin in Northeast Wisconsin by controlling pollution from municipal and industrial treatment plants, urban storm runoff, construction site erosion, and agricultural runoff. Qiu and Prato (1998) evaluated the cost effectiveness of spatial pattern of farming systems (a combination of crop rotation, tillage system, and fertilizer and pesticide application rates) for improving water quality and evaluated the economic value of riparian buffers in reducing agricultural nonpoint source pollution in a Midwestern agricultural watershed. Mapp et al (1994) used an analytical framework, based on the tradeoff between production and fertilizer use, to demonstrate that target policies have higher economic and environmental potential than broad policies in five distinct sub regions across the Central High Plains region.

Data requirements: Cost effectiveness evaluations depend on correct representation of the effects of management practices on receiving water quality and inclusion of all relevant costs. Effects of management on receiving water quality are generally represented as reduction in pollution levels and depend on correct estimation of management effectiveness and levels of pollution generated in the watershed, proper representation of pollutant transport, and understanding of the hydrology and mixing processes in the receiving waters. Cost effectiveness analyses require data and models of physical-chemical, biological, and ecosystem processes. Relevant costs of management that may be considered in cost effectiveness evaluation include capital cost, maintenance, and monitoring and enforcement.

Reliability of evaluation method: Cost effectiveness evaluation can be limited since ranking management practices based on cost per pollution unit reduced does not guarantee sufficient level of water quality improvement and may lead to selection of cheap but ineffective practices. It is therefore important to consider water quality thresholds in selection of management practices. In addition, cost effectiveness evaluation may be limited due to the need to account for uncertainties regarding management effectiveness and loading estimates and assumption about unit cost of pollution reduction.

Uncertainties and variability: Uncertainties and variability in cost effectiveness analysis can potentially have great effect on the selection of appropriate management options. Both the management options and the receiving water exhibit varying degrees of uncertainties and variability. Management options efficiencies may vary from levels assumed during the design phase and in addition, may degrade over time. The watershed and the receiving water exhibit uncertainties and variability in pollution loads and flows that result in variable water quality.

Ease of monitoring and enforcement: Since cost effectiveness analysis is not based on specific water quality goals, enforcement is limited to the performance of the stormwater management in place. Monitoring and enforcement of management performance efficiencies may lead to better maintenance and improved water quality to ensure that cost effectiveness is achieved.

Benefit Cost Analysis (BCA)

BCA is used for quantitative comparison of the monetary-measured advantages and disadvantages of implementing specific management practices. BCA comparisons are generally represented as net benefits or benefit-cost ratios.

Implementation: Effort has been directed towards developing benefit cost analyses methods to evaluate management practices. In managing agricultural runoff, benefits in some cases were related to crop production. Sun et al. (1996) looked at the economic feasibility of management practices (alteration in fertilizer application and irrigation water management) to protect receiving water from irrigation runoff by considering both the effects of alternative management on crop yield and levels of nitrogen contamination in the water. A more direct effort to account for water quality improvement benefits due to management practices has been proposed in England with a bill that required the consideration of both benefits and costs and an Interim Benefit Assessment Manual (IBAM) for valuing benefits and comparing to cost in both determining standards and setting management priorities (Tyson and Foster, 1995). Kalman et al (in press) used a preliminary Benefit-Cost Analysis (BCA) screening method to identify promising management practices and societal and economic tradeoffs for Ballona Creek, a major urban storm drain in Los Angeles, California. The BCA was found useful in evaluating and understanding stormwater management alternatives despite uncertainties and variability inherent in the system for this receiving water.

Data requirements: Benefit cost analysis depends on correct representation of the benefits gained from management in monetary terms and management costs. Though management costs for capital investment, maintenance, and monitoring may be available, representing benefits in monetary terms is difficult. Benefits can be developed by valuing the receiving waters' beneficial uses by means of contingent evaluations and benefit transfer (Kalman et al, in press). These methods require resources and expertise that may not be available to the managing agencies. In addition to monetary values, as with cost effectiveness evaluation, it is necessary to correctly represent the effects of management practices on the receiving water quality and its beneficial uses.

Reliability of evaluation method: Results of BCA can be highly dependent on how benefits are quantified; BCA can potentially be a better economic evaluation than cost effectiveness if benefits can be explicitly compared to costs. BCA can help direct funding and limited resources where most benefits can be realized. Therefore, BCA may result in an overall improvement of regional receiving waters' quality rather than improvement of specific receiving waters. But BCA will carry with it the unreliability of physical-chemical, biological, and ecological assessments used to quantify beneficial impacts and their values.

Uncertainties and variability: Uncertainties and variability in BCA are numerous. As with cost effectiveness analyses, loading and flows from the contributing watershed as well as pollution concentration in the receiving water can be laden with uncertainties and variability and management efficiencies can vary appreciably especially if SWQ-MPs are not correctly maintained. In addition, there is a large degree of uncertainty in valuing the beneficial uses of the receiving water and in developing a relationship between water quality and beneficial uses that can affect evaluation results. These uncertainties and variabilities can be tested with sensitivity analysis. Often BCA results are insensitive to uncertainties (Kalman, et al in press)

Ease of monitoring and enforcement: As with cost effectiveness, BCA is not based on specific water quality goals and therefore enforcement is limited to ensuring that the stormwater management performance is adequate as assumed in the evaluation.

Summary of Evaluation Methods

All four evaluation approaches have been widely used to solve water pollution problems. Yet, these methods differ in the extent of information and resources needed to complete the evaluation analysis and in their ability to handle the natural variability of the receiving water. In most cases, water pollution addressed is from agricultural sources rather than nonpoint source pollution or urban storm water runoff. A summary of the review based on the five criteria: data requirements, relevance to defining water quality degradation and beneficial use protection; cost; consideration of uncertainties and variability; and ease of enforcement is provided in Table 2-3.

Table 2-3: Summary comparison of water quality evaluation methods for selecting stormwater management practices

Evaluation Method	Relevance for receiving water (beneficial uses, objectives)	Data and resource requirements	Consideration of uncertainties and variability	Ease of monitoring and enforcement
Physical/Chemical				
Water Quality Standards (Baron, 1995;Roesner and Rowney, 1996)	Meeting water quality standards does not guarantee protection of beneficial uses.	Monitoring of receiving water quality.	Variability and uncertainties are not considered.	Requires monitoring to ensure water quality standards are achieved.
TMDL (Pickett, 1997; Hession et al., 1996; Chen et al., 1999)	Protection of water quality and beneficial uses may be achieved with extensive analysis.	Extensive monitoring and identification of all polluting sources.	May consider seasonal flow and pollutant concentration variation if information is available.	Requires seasonal monitoring to ensure that TMDL goals are achieved.
Biological				
Eutrophication (Jorgensen, 1995; De Ceballos et al, 1998; Thomann and Linker, 1998)	Appropriate only for receiving waters that are primarily affected by eutrophication.	Monitoring and modeling relevant constituents.	Depends on data available and choice of modeling.	Requires assessment of biological and chemical changes in the receiving waters.
Toxicity (McCarty et al, 1993;Porcella, 1992; Vanderkooij and Vandemeent, 1992)	Appropriate for receiving water that are primarily affected by toxicity. Does not consider physical and hydrological effects.	Sampling and toxicity testing tailored specifically to aquatic life in the water.	Does not account for variability in receiving water quality.	Requires extensive monitoring and laboratory testing. Enforcement may be difficult due to recovery time.
Ecological				
Biological integrity (Harig and Bain, 1998)	Limited due to difficulties in developing relationship between water quality and changes in biota.	Extensive population sampling and use of habitat indices.	Does not explicitly consider uncertainties and variability in population.	Difficult to enforce.
Economics				
Cost Effectiveness (Li et al, 1997; Walker et al, 1993; Schleich and White, 1997; Qiu and Prato, 1998)	May not lead to sufficient protection of beneficial uses.	Requires data on SWQ-MPs cost and effectiveness.	Not directly addressed in the evaluation.	Monitoring of management practices implemented
Benefit cost analysis (Tyson and Foster, 1995; Kalman et al, in press)	Dependent on value of beneficial uses and economic efficiency.	Requires data on SWQ-MPs cost and effectiveness, beneficial uses values, and relationship between beneficial uses and water quality.	Uncertainties and variability of beneficial uses values and water quality can be addressed with sensitivity analysis.	Monitoring of management practices implemented.

Summary and Discussion

Diverging from traditional management practices and using evaluation methods can help better meet regulatory requirements, improve receiving water quality, and use resources more efficiently. The evaluation methods vary in the degree that they can affect these goals.

Compliance with Regulatory Requirements

Of all evaluation methods, selecting management practices based on physical and chemical criteria theoretically can result in regulatory compliance since the criteria is directly related to water quality standards. Yet, management practices to meet these standards may be cost prohibitive and therefore may not be implemented. Selecting management practices based on either biological or ecological evaluation may lead to compliance if regulatory requirements are receiving water specific and based on the processes and water quality effects on the receiving water ecology. Of all methods, the economic evaluation methods are the least likely to result in compliance with current regulations since they are based on management practice effectiveness rather than water quality directly. Yet, economic approaches might speed acceptance and help identify funding for stormwater quality management. In some cases, benefit-cost analysis can identify when strictly environmental objectives should be sought.

Receiving Water Quality Improvement

Evaluation based on either biological or ecological criteria could potentially lead to the selection of management practices that are most likely to improve receiving water quality. Biological and ecological evaluations assess water quality directly in terms of processes and the biological community in receiving waters, thereby improving and protecting the receiving water's ecological beneficial uses. The effectiveness of chemical-physical evaluations depends on establishing a relationship between the pollutants and the receiving water's biological and ecological health. Economic evaluations will result in improved water quality for highly valued receiving waters and highest-valued beneficial uses within the receiving water (based on benefit cost analysis) or when relatively inexpensive but efficient management practices are available (based on cost effectiveness).

Efficient Use of Resources and Funding

The selection of management practices based on economic evaluation will most likely lead to the best use of resources since efficiency, cost, and the value of the receiving waters are considered. Biological and ecological evaluations may result in efficient allocation of resources since the evaluations concentrate on explicit pollution problems that most likely would benefit most from water quality management. The physical and chemical criteria evaluations are the least likely to yield efficient resource allocation since these methods are concerned with pollutant reduction regardless of cost or effect on receiving waters.

Selection of Evaluation Methods

Evaluation of a receiving water is complicated by the limited knowledge we have on natural conditions and variabilities of the system as well as resources and technology available for evaluating and protecting the receiving waters. None of the four evaluation methods can ensure complete protection and improvement of receiving water quality. Yet, each type of evaluation method can provide valuable information to the responsible agencies or cities. The economic evaluation methods can be used to identify receiving waters with critical pollution problems that are valued highly and therefore warrant the use of resources for protection. BCA tends to produce economic savings that would be applied to achieve overall environmental quality rather than achieving beneficial uses on a specific receiving water. Process evaluation methods such as eutrophication and toxicity can be used when distinct problems in receiving waters are identified but would be limited in receiving waters that are affected by different sources and pollutants. The water quality standards are very limited and do not necessarily lead to water quality improvements that ensure protection of beneficial uses while the TMDL is limited since it addresses one pollutant at a time and does not account for all contributing sources. The ecological evaluation is an appropriate method to assess receiving water health but is very difficult to implement because of the information required and the difficulties in establishing water quality base line. In general, the relevancy of evaluation methods for water quality protection depends on continuous monitoring to help characterize the receiving water quality condition and the contributing watershed.

In addition to the limited information that can be gained with each evaluation method, agencies must consider the level of information and resources that must be invested in evaluating management options. The least demanding option is the use of available technologies based on experience without evaluation of receiving waters. This may be a viable alternative when managing similar types of receiving waters and having experience with the effectiveness of known management practices. On the other extreme, ecological evaluation may require prohibitive amount of information including species composition and water quality base line. Therefore, in choosing an evaluation method for assessing promising management alternatives to protect a receiving water, it is important to define the goals of the water quality management program and consider the extent of data required to effectively accomplish the evaluation.

Conclusions

The evaluation methods reviewed are interdependent; the economic evaluations rest on some level of confidence in the biological understanding and modeling of the receiving waters while the ecological evaluation depends on accurate representation of the aquatic system's physical and chemical processes. Choosing an evaluation method for stormwater quality management selection to protect receiving water quality and beneficial uses largely depends on the extent of the water quality problem and value of the receiving water. Evaluation methods range in their data and resource requirements, complexity, and their ability to protect receiving water beneficial uses. It is important to define stormwater quality management goals prior to the evaluation process to ensure that evaluation results meet environmental needs. Specific water quality problems such as eutrophication and toxicity may be best addressed through process evaluation whereas funding issues may be best addressed with economic evaluation to ensure economically efficient allocation of resources regionally. Limited resources and receiving water value and quality problems may dictate the level of evaluation performed; potentially, the more the receiving water is valued the more resources may be allocated to perform extensive evaluation prior to selecting management alternatives.

3 WATERSHED MANAGEMENT MODEL USING GENETIC ALGORITHM

"Good management is the art of making problems so interesting and their solutions so constructive that everyone wants to get to work and deal with them." Paul Hawken

Introduction

This chapter presents the development of a genetic algorithm based watershed management optimization model. The watershed management model is designed to evaluate stormwater management alternatives for a watershed with several polluting sources and to select the most economically efficient set of management options for protecting receiving water quality and ensure compliance with water quality standards. In this chapter, the genetic algorithm structure is developed and commonly used operators are compared and selected to improve model reliability.

Optimization of Management Practices

Whereas watershed simulation models are numerous, optimization models are mostly limited to locating and sizing storage and detention facilities to meet water quantity or sediment removal objectives at least cost. Chao-Hsien and Labadie (1997) applied a successive reaching dynamic programming (SRDP) algorithm and a multiobjective genetic algorithm (MOGA) to watershed-level planning of storm water detention systems. The SRDP was used to locate and size the detention systems based on a single objective of water quantity. MOGA, a multiobjective evaluation, was used to develop trade-offs between system cost and detention effectiveness on water quality. Predeep et al. (1999) used dynamic programming (DP) to identify least cost pond designs for both single catchment and multiple catchment systems. The DP was based on different levels of control at individual catchments while satisfying the specified levels of pollution and runoff control at the outfall. The DP was based on the integration of water quality and quantity through the use of isoquants. The isoquants were developed for pollution control performance and runoff control based on two decision variables: the release rate from the pond and the active storage volume of the pond. These isoquants were then combined to identify the optimal release rate and used for the optimization with the objective of minimizing cost based on pond depth. Dorn et al (1995) used a genetic algorithm based optimization to develop a trade off curve between cost and sediment removal of detention pond systems. The trade off curve represented the level of sediment removal or maximum allowable cost specified by the decision maker.

This chapter provides a systematic approach to setting a genetic algorithm based optimization model for watershed stormwater management. The model developed is specific to the watershed management problem and therefore results may not apply to other problems. A hypothetical example is used to select the most promising operators for a genetic algorithm model and demonstrate the capability of the model in evaluating management alternatives to protect receiving water quality.

Genetic Algorithms Overview

Genetic algorithms (GA) are adaptations of biological natural selection and adaptation processes to solving optimization problems. GA is based on the evolutionary concept that the characteristics of fit individuals in a population are promoted and evolved by means of recombination and mutations while weaker individuals die off. Fit individuals are promoted through selection based on environmental conditions, mating, and recombination of offspring carrying their parents' traits (Holland, 1992). This natural optimization process is mimicked in solving a variety of operation, scheduling, and management problems.

GA is configured based on the structure of natural evolution. The first GA component is the representation of the environment in which a population or system is undergoing adaptation. In GA, the environment is represented by the fitness function that is used to evaluate the population. The fitness function is developed based on the problems' objective function and constraints (Holland, 1992). Within the environment, a population exists based on an adaptive plan that includes selection, mating, and recombination. The population consists of strings (chromosomes) that define individuals in the population representing specific solutions to the problem. The strings are further divided into smaller bit-sets (genes) that define the unique characteristics of the individual and represent the population's diversity. A comparison of the natural evolutionary process and the genetic algorithm elements appears in Table 3-1.

Table 3-1: Comparison of evolution and genetic algorithms

Evolution	Genetic Algorithm
Environmental selection	Fitness function and Objective function
Population	Set of solutions
Individual/Chromosome	Solution string (set of decisions)
Genes	Bit sets (coded solution/decision variables)

Genetic Algorithm Operators

GA is a modified spacious hill climbing optimization method. Common "hill climbing" methods search iteratively for an optimum but may be limited when the solution space has multiple optima. GA addresses the challenge of multiple optima by searching through the whole solution space simultaneously through exploration (Everett, 1995). As in nature, GAs work by manipulating a population and creating future generations better adapted to the environment. Typical GA structure is shown in Figure 3-1. Four mechanisms control the GA: (1) initialization, (2) selection, (3) recombination, and (4) termination. Numerous GA operators have been described and used in the literature to perform these four mechanisms in efforts to enhance the reliability and convergence of GA solutions. Some of the promising and more commonly used GA operators are presented and reviewed.

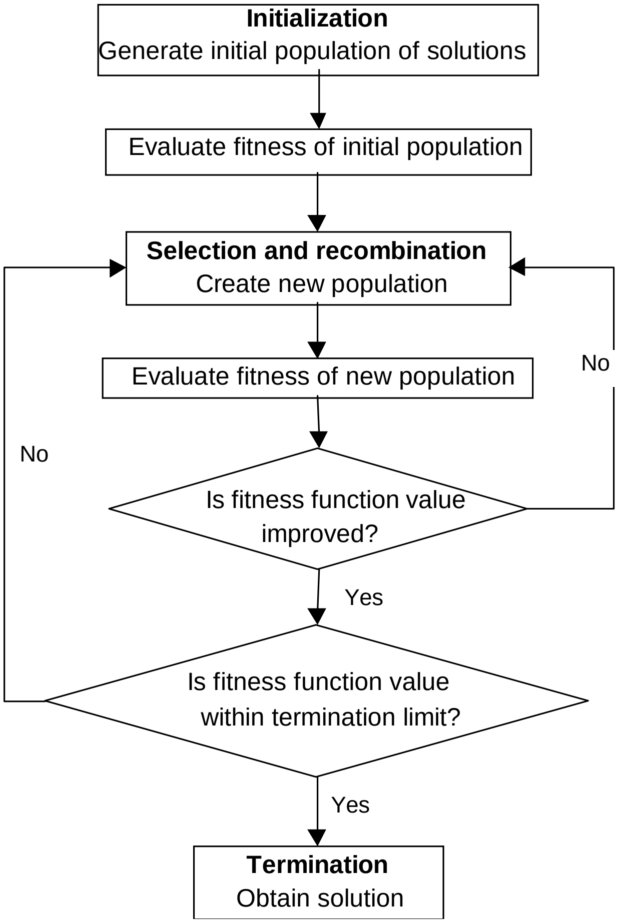

Figure 3-1: Genetic algorithm process

Initialization

The initialization of the genetic algorithm has two components: the manner of creating the initial population and the population's size. Generally, initialization is accomplished by a random assignment based on a normal distribution. To improve the search process, the initial population may be seeded with individuals that are representative of the solution space or with extended random initialization (ERI). The process of ERI is based on a random selection of individuals that are forced to compete for a place in the initial population based on their fitness (Bramlette, 1991).

In addition to the importance of the initial population makeup, population size can greatly influence the efficiency and ability of the GA to locate the global optimum solution. Typically, population size is constant and specified by the user. Some research has concentrated on developing methods to determine the optimal population size required to obtain reliable solutions (De Jong, 1975; Goldberg et al, 1993). Significant research has been done on methods such as crowding and generation gaps that provide dynamic population sizes, in efforts to improve GA efficiency (Mahfoud, 1995).

Selection

Selection operators are used to improve the average quality of the population by selecting more fit individuals for the development of subsequent generations. Selection operators help focus the search on promising regions in the search space. Selection operators are important both in driving the search towards better individuals and in maintaining a high genotypic solution diversity of the population. These dual roles of selection operators create the challenge of balancing exploration versus exploitation. Exploitation is the passage of a gene or a solution trait from a parent to its offspring. Exploration is a new representation of a gene in an offspring (Eshelman and Schaffer, 1993). Exploiting the population by selecting the best individuals may lead to a narrow search and early convergence that often leads to a local rather than global optimum solution. On the other hand, exploration with little bias and random selection may lead to unfocused and inefficient search.

Several selection methods have been proposed to balance exploitation and exploration. Selection methods can be described as either preservative or extinctive. Preservative selections are indiscriminant selections in which each individual has a chance to contribute offspring to the next generation while extinctive selections prohibit either weak or strong individuals from being selected for recombination. Generally, preservative selections produce higher diversity than extinctive selections at the risk of losing important information. Selection methods can be either Elitist or Pure. In pure selection, individuals do not compete with their offspring, but elitist selection allows some or all of the parents to undergo selection with their offspring, resulting in an ‘unlimited’ lifetime for super-fit individuals. The elitist selection in some cases may lead to premature loss of population diversity. Selection methods also can be generational in which a parent population is used solely for recombination, or steady state selection in which offspring that outperform their parents immediately replace their parents within the selection phase (Back and Hoffmeister, 1991).

The quality of the selection operators may be identified in terms of the time it takes the best individual to take over the population, the progress of the whole population, the average fitness changes, or the fitness distribution. Four common selections operators are described: the roulette wheel selection, random selection, tournament selection, and remainder stochastic sampling without replacement selection. Though the roulette wheel selection is most commonly used, the tournament selection method has been shown to be the most effective of the four operators in some cases (Goldberg and Deb, 1991).

The Roulette Wheel Selection

The most common selection method is the fitness-proportionate roulette wheel algorithm. In proportionate selection methods, the probability of selection (p_i) of an individual (i) can be calculated as the ratio of the individual's fitness (f_i) and the population average fitness as shown in Equation (3-1):

$$p_i = \frac{f_i}{\overline{f}} \tag{3-1}$$

The Roulette wheel selection algorithm was named for its likeness to allocating pie-shaped slices on a roulette wheel to population members, with each slice proportional to the member's fitness. Each roulette spin results in the selection of one parent. High performance individuals are assigned high selection probabilities (or larger slices on the roulette wheel) and therefore tend to be selected for generating new populations more often than individuals with low fitness values (Mitchell, 1996; Davis, 1991a; Bartlett, 1995). The roulette wheel selection algorithm is laid out in Figure 3-2.

1. Determine *Total fitness*, the sum of all individuals' fitness.
2. Choose a random number, R, uniformly distributed between 0 and *total fitness*.
3. Loop through the individuals in the population, summing the fitnesses until the sum is greater than or equal to R. The individual whose expected value puts the sum over this limit is the one selected.

Figure 3-2: The roulette wheel algorithm

Though roulette wheel selection works well for some GA applications, it has one major drawback that may reduce the GA's reliability. The selection can cause an inadequate selective pressure in which extremely fit individuals take over the population, leading to a loss of diversity and premature convergence early in the search. This drawback can be partially addressed by linear normalization and ranking to replace selection by fitness with selection by ranking to improve the selection pressure in the population (Falkenauer, 1998).

Random Selection

Random selection is the only selection method that does not consider fitness; individuals are randomly selected for recombination. This method provides high exploration but risks losing exploitation opportunities of highly fit solutions. Convergence to an optimal solution relies mainly on recombination and creation of new population operators.

Tournament Selection

The roulette wheel selection and random selection provide two extreme selection choices; the roulette selection depends on performance whereas random mating is indiscriminant. Tournament selection is an attempt to find a balance between the two methods. In tournament selection, n individuals randomly selected from the population (with or without replacement), compete for selection. The fittest selected individual is passed along to a parent generation that is used for recombination (Blickle and Thiele, 1995). The tournament selection algorithm is presented in Figure 3-3.

1. Select n individuals from the population for the tournament.
2. Compare the selected individuals' fitness and select the best for further genetic processing.
3. Repeat step 1 and 2 until the required number of parents to create a new population has been satisfied.

Figure 3-3: The tournament selection algorithm

Since each tournament is performed independently, this selection method may suffer from the same sampling errors as the roulette wheel selection. Yet, the tournament selection has shown to work well when models perform selections and tournaments that are limited to sub populations (Hancock, 1995; Goldberg and Deb, 1991)

Remainder Stochastic Sampling without Replacement Selection

This method attempts to improve the roulette wheel selection performance. As with the roulette wheel selection, fit individuals are allotted more chances to become parents. This selection method has two parts for selecting parents for recombination. First, an intermediate population is developed based on the fitness of the individuals in the population relative to the population's average fitness (based on the roulette wheel selection). This step is then followed by a random selection of parents from the intermediate population (Goldberg, 1995).

1. Select n individuals using a roulette wheel selection
2. Randomly select individuals from the pre-selected group to create a new population.

Figure 3-4: The remainder stochastic sampling without replacement selection algorithm

Recombination

Recombination methods use selected parents to develop new individuals in an effort to improve subsequent generations. The most common recombination method is the crossover in which two individual parents exchange part of their code to produce a new individual. As with selection, recombination can significantly influence the balance between exploration and exploitation. In addition to crossover recombination, some GAs incorporate a mutation operator to improve genetic diversity.

Crossover Method

The crossover method sections the chromosomes of two parents at randomly selected location(s) and switches the sections to create new offspring as shown in Figure 3-5. The point of crossover is randomly selected and the crossover probability is generally set between 0.5 and 0.8. The rate of crossover and the population size have been shown to be critical in converging to an optimal solution. De Jong (1975) found that population size ranging between 50 and 100 with crossover rate of 0.6 and mutation rate of 0.001 per bit works best for his problem formulation. Yet, selecting crossover rates is highly dependent on the problem and research has been limited to empirical data (Davis, 1991b). Some drawbacks have been identified with the use of a single point cross over. As the strings become longer, the single-point crossover method may lead to inefficient solutions since large portions of a string with information can be lost in the crossing process. Multiple point crossover operators have been suggested to resolve this problem. In addition, mutation is used to diversify the population by reintroducing solutions that may have been lost, particularly in advancing populations in which solutions are converging into optima. More generally, the success or failure of crossover largely depends on the fitness function, the encoding, and the interaction among all genetic algorithm operators (Mitchell, 1998).

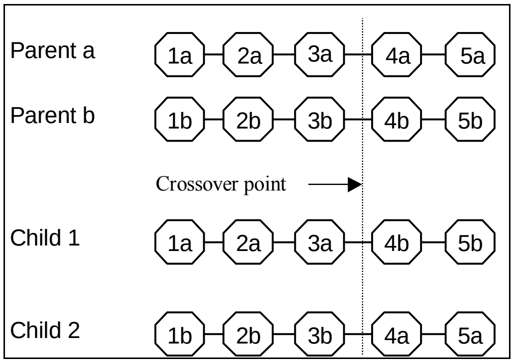

Figure 3-5: Crossover method

Uniform Crossover Method

The uniform crossover was developed in response to the loss of valuable information that was observed with a single-point crossover operator. Uniform crossover has been observed to be a reliable operator, particularly in combination with elitism (see description below) (Spears and De Jong, 1991; Schaffer et al, 1991). Uniform crossover can be regarded as a special case of the crossover operator. Each individual gene in the parents is randomly crossed to create two new offspring. For example, parents with five genes can be randomly crossed at five locations whereas with single-point crossover, random crossing would occur only at one location. Since uniform crossover selects genes randomly, mutation becomes less important in preserving solution information. As shown in Figure 3-6, the crossover probability can affect the GA reliability (probability that the final solution converges on the global optimum). Probability of 0.5 was chosen for the GA used in this research.

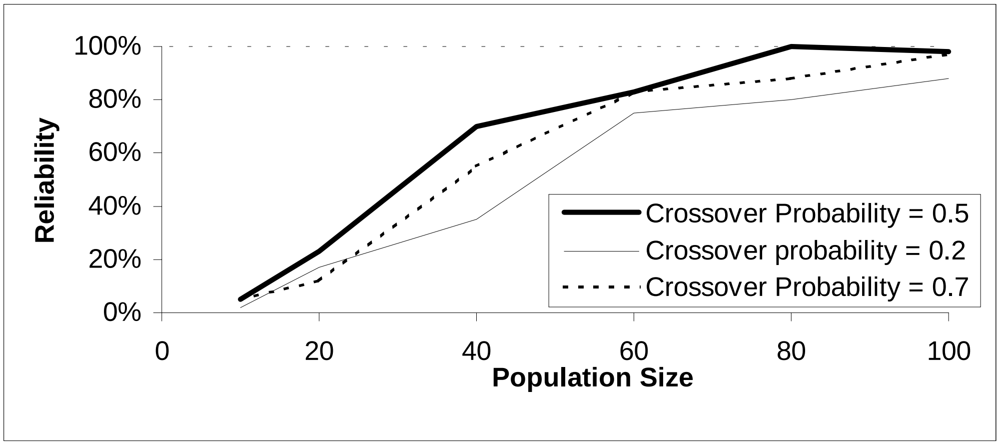

Figure 3-6: The effect of crossover probability on GA reliability

A range of crossover operators (single-point and multiple-points) has been compared with varying results depending on the fitness function used for testing. Spears and De Jong (1991) found that the uniform crossover, in which each gene in the solution is randomly selected for recombination, dominated over two-point crossover with small populations but the opposite was true with large populations. These results may have been due to high disruption exhibited by uniform crossover relative to the two-point crossover. Nevertheless, using low crossover probabilities, uniform crossover was superior to the two-point crossover.

Mutation

Mutation is a “background” operator used to ensure that the population does not fixate on a limited gene pool that may lead to local optima. Each bit in the solution string may randomly be replaced by another to yield a new structure (Holland, 1992). A low probability of mutation applied with the crossover method has been shown to improve the GA reliability (Schaffer and Eshelman, 1991).

Creation of New Population

Newly produced offspring are used to create subsequent generations. The creation of the new populations can be done by a simple replacement of parents with their offspring or by judicious comparison of existing and new individuals to ensure that the new generation is superior to the previous generations.

Replacement

In replacement, offspring replace their parents to create a new population regardless of the offspring fitness (Cavicchio, 1970). The assumption behind this method is that offspring are developed from fit individuals and therefore will generally be similar or better than their parents. This assumption greatly depends on the function being optimized.

WeakParent

In WeakParent, the offspring and their parents compete to be included in the new population. The offspring replace their parents only if they have higher fitness values. This comparison ensures that the offspring improve the fitness of the new population (Bartlett, 1995).

ChildRepWeak

As with the WeakParent operator, offspring must compete to be included in the new population. Rather than comparing offspring to their parents, offspring are compared to the whole population and replace the weakest individuals in the population if they display a higher fitness value. The drawback of this method is that information carried by weak individuals may be lost and result in early convergence to a local optimum (Eshelman and Schaffer, 1993; Bartlett, 1995).

Restricted Tournament

Restricted tournament is a crowding operator in which offspring are compared to a fixed number of randomly selected individuals in the population. The offspring are then compared to the individual that most closely resembles them in gene makeup (offspring and individual share the highest number of identical genes). The offspring are allowed to replace these individuals if their fitness is higher. The purpose of this operator is to improve the population without destroying information carried by other individuals prematurely (Harik, 1995). The tournament size can affect the convergence time to an optimal solution (Goldberg and Deb, 1991).

Other Operators

In addition to the recombination operators, other operators have been suggested to improve convergence to global optimum. These operators are used to control and improve the convergence rate and reliability of the GA model particularly for problems with complex solution space that have several local optima.

Elitism

Elitism was first introduced by De Jong (1975) to force the GA to retain a specified number of best individuals at each generation to ensure that they are not lost through selection or recombination. At the creation of a new generation, in addition to the new population operators, the elitism operator replaces the weakest individual with the fittest individual in the population with the hope of preserving fit information. Elitism was found by many users to improve GA performance. The main drawback of elitism is that although the population average fitness is improved, elitism may result in early conversion to a local optimum due to lost information (Mitchell, 1998).

Sharing and Niching

Sharing and niching are used to define the solution landscape by developing subpopulations. Subpopulations are composed of individuals that share common traits such as gene characteristics or similar fitness values. In sharing, individuals that belong to the same subpopulations are penalized in the selection process to account for their similarities. Niching limits selection to occur within subpopulations to avoid premature convergence of sub-optimal individuals taking over the population. Niching encourages subpopulations convergence while keeping overall population diversity (Ryan, 1995).

Termination

GA termination is generally based on either the number of generations as specified by the user or the GA fitness function performance. GA performance can be defined based on average population fitness, maximum fitness in the population, or rate of change of population fitness from one generation to the next.

Selection of Operators

The success of a GA in any application can only be determined by experimentation since the performance of selected population size, selection, and recombination operators is highly dependent on the type of problem solved (Bagachi et al., 1991). Much research has been done on evaluation methods in an effort to define which operators will be most reliable for a host of problem types. In addition, to control premature convergence, some have suggested adaptive plans for the operators in which operators and their rates change during the GA search (Rosca and Ballard, 1995; Davis, 1991).

Watershed Management Model Formulation

The objective of the watershed management optimization model is to identify promising cost effective sets of management practices to control pollution that affects receiving waters and ensures regulatory compliance.

Objective function and fitness function: For the watershed management application, the fitness function is the same as the objective function. The stormwater quality management practice (SWQ-MP) selection is based on cost effectiveness. The objective function is the minimization of SWQ-MP cost given management constraints as represented by equation (3-2).

$$\min \quad \sum_{s=1}^{S} \sum_{mp=1}^{MP} C_{mp,s} X_{mp,s} \tag{3-2 }$$

where:

$C_{mp,s}$ = Cost of SWQ-MP for pollution source s, \$/yr.

$X_{mp,s}$ = Binary decision variable for SWQ-MP use at pollution source s, 1 for use and 0 for no use.

Decision variables: The model decisions are the management practice choices at each pollution source. The decision variables are binary in form (on/off) as shown in Figure

3-7. The length of the solution string is S*MP where S is the number of polluting sources and MP is the number of available SWQ-MP at each source. For a watershed with three pollution sources and four feasible management practices for each source, the solution string length is 12 bits.

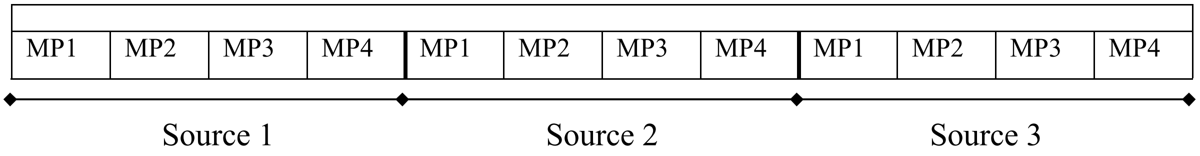

Figure 3-7: Solution structure

<u>Constraints</u>: The model has three constraints. The first constraint is based on the desired water quality of the receiving water, the second constraint specifies the SWQ-MP removal efficiency, and the third constraint ensures that pollutant concentration does not become negative.

1. Water quality standard

$$C_{RW} \leq C_{STD}, \qquad \forall \text{pollutants}$$

where:

$$C_{RW} = \frac{P_{rw}Q_{rw} + \sum_{s=1}^{S} P_s Q_s \sum_{mp=1}^{MP} (1 - E_{mp})}{Q_{rw} + \sum_{s=1}^{S} Q_s}$$, Receiving water pollutant concentration with SWQ-MP, µg/L.

C_{STD}= Water quality standard for the receiving water, µg/L

rw = Receiving water

E_{mp} = SWQ-MP removal efficiency, fraction

P = Pollutant concentration, µg/L

Q = Flow, L

2. Removal efficiency

$$E_{mp} = const, \qquad \forall MP$$

3. Non-negativity constraint

$$C_{RW} \geq 0$$

Example Case Study

A hypothetical watershed is created and used to evaluate various GA operators based on their performance reliability. Reliability is defined as the percent of performed independent model runs that result in consistent global optimum solution (found by enumeration). For this evaluation, 100 independent runs are used, each with randomly generated initial population. For the watershed model, termination was based on a fixed number of generations specified by the operator. In all cases, the GA converged (i.e., all solutions are equal) to a solution within 10 to 20 generations.

The hypothetical watershed has a single lake supporting aquatic life and recreational uses. Polluted flows from three sources discharge into the lake. Four management alternatives are available at each source to reduce pollution in the lake: screening, vegetation, sedimentation, and filtration. Summaries of the watershed characteristics and possible management practices are provided in Table 3-2 and Table 3-3, respectively.

Table 3-2: Case study watershed

	Source 1	Source 2	Source 3
Flow (cfs)	50	90	100
Pollutant concentration (μg/L)	30	40	40

Table 3-3: Feasible management practices

Management Practice	Cost ($)	Removal Efficiency (%)
Screening	100	10
Vegetation	400	60
Sedimentation	900	90
Filtration	1500	95

Given the existing pollutant loading from the three sources, the receiving water pollutant concentration is 38 μg/L. Assuming that the minimum regulatory pollution concentration is 20 μg/L and no other inflows, management options must be used to reduce pollution at the contributing sources.

Solution by Enumeration

To evaluate the reliability of the genetic algorithm operators, the watershed example was solved by enumeration. For the watershed management problem presented, four SWQ-MP options are available for each of the three pollution sources. Solving this problem by enumeration will require the consideration of 2^{4*3} or 4,096 possible solutions. The optimal watershed management required to ensure concentration limit of 20 μg/L was found to cost 800 $/yr for the installation of vegetation management practices at sources 2 and 3 to reduce pollutant concentrations.

Evaluation of GA Operators

The operators described for selection, recombination, and creation of new generation are evaluated to determine the best GA makeup and population size to ensure reliable model results.

Initiation

For this example, random population was created using a random generating number function. The population size needed to ensure reliable results is determined in the comparison of the operators reviewed.

Selection

Four selection operators are compared: the roulette wheel selection, tournament selection, random selection, and remainder stochastic sampling without replacement selection. Other operators used in these runs are uniform crossover for recombination, ChildRepWeak for creating new population, and sharing.

The roulette selection and remainder stochastic selection methods did very poorly in this analysis while the other random selection and tournament selection did comparably well. The tournament size did not appear to greatly affect the tournament selection reliability. Tournament selection appeared to be the most efficient selection operator as shown in Figure 3-8. This result concurs with some of the results reported in the literature (Goldberg and Deb, 1991). The tournament selection will be used in the watershed management model.

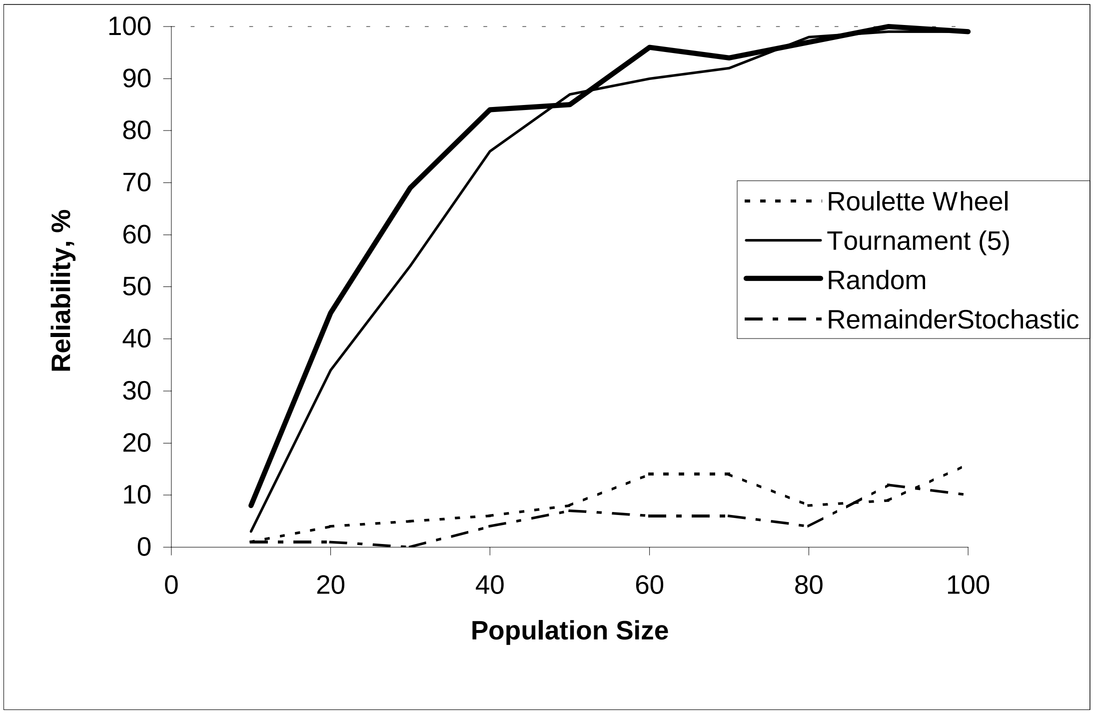

Figure 3-8: GA reliability for selection operators

Recombination

Two recombination operators are compared: single-point crossover and uniform crossover, both with crossover probability of 0.5. Other operators used are tournament selection, ChildRepWeak for creating new population, and sharing to improve reliability. Comparison results are presented in Figure 3-9. These results clearly show that the uniform crossover operator outperforms the single-point crossover.

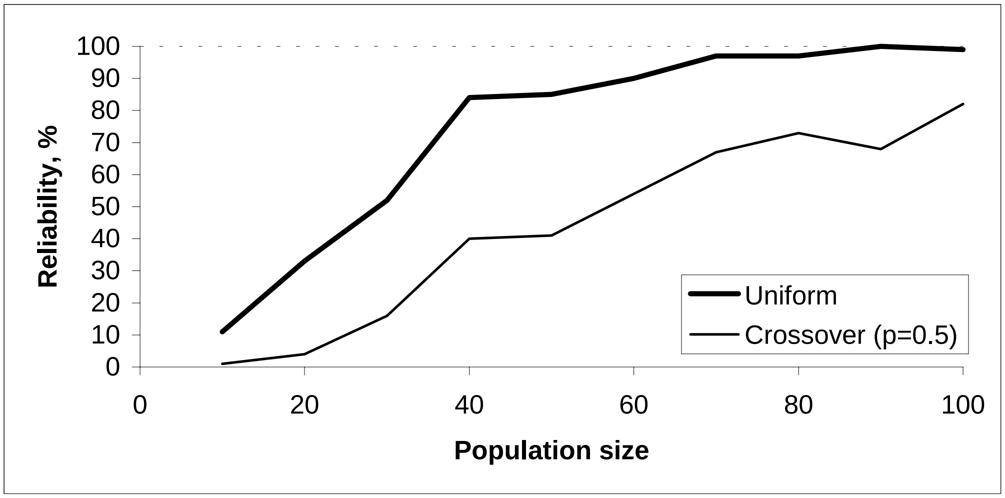

Figure 3-9: GA reliability for recombination operators

Creating New Populations

Choosing whether offspring are suitable to replace their parents in the new population is important in obtaining reliable solutions. Rapid replacement of weak members of the population could lead to a premature convergence. On the other hand, random replacement can lead to an inefficient search. Four operators are compared: replacement, WeakParent, ChildRepWeak, and restricted tournament. Other operators used in the GA are tournament selection, uniform crossover, and sharing. Comparison results are presented in Figure 3-10. ChildRepWeak outperforms all other operators and will be used in the GA model.

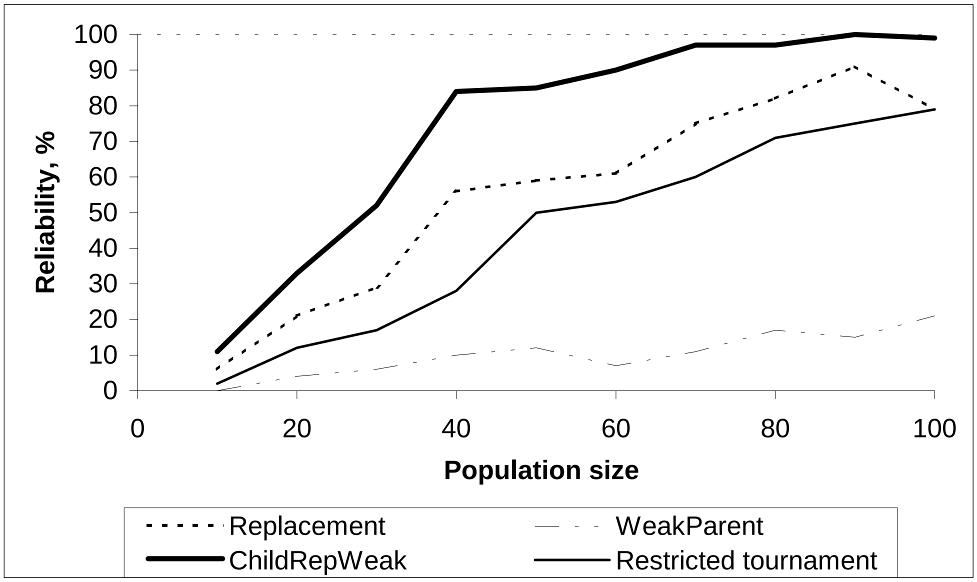

Figure 3-10: GA reliability for new population operators

Other Operators

In addition to the operators used for selection and recombination, other operators were compared in efforts to improve the algorithm's reliability. A comparison of sharing and elitism is shown in Figure 3-11. Model results suggest that the inclusion of these two operators does not change model reliability significantly.

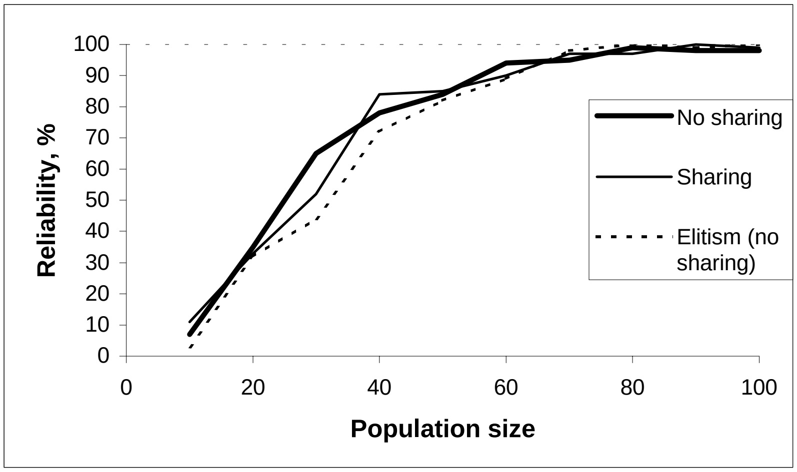

Figure 3-11: The effects of elitism and sharing on GA reliability

Population Size

Population size proved to be the most important factor in reliably obtaining a global solution as can be seen in Figure 3-8 through Figure 3-11. Small population sizes did not provide enough information from which solutions can be developed and as a result tended to converge too soon to a local optimum rather then the global optimal solution. On the other hand, large population sizes provided more samplings of the solution space and ensured a more diverse initial population.

Genetic Algorithm Final Structure

Based on the comparisons of operators, the Watershed Management GA optimization model will be run with the following components:

(1) Population size of 100 individuals randomly selected.

(2) Selection using a tournament operator

(3) Recombination and creation of new population using uniform crossover and replacement of weak individuals with offspring.

(4) Use sharing.

Conclusions

The development of the GA based optimization model presented in this chapter clearly illustrates how sensitive model reliability is to the structure of the algorithm and operators selection. It is therefore important to carefully develop GA and consider the effects of problem formulation and operators to ensure the development of a reliable model.

Notwithstanding, some of the comparison results documented in this chapter are in agreement with results reported in the literature and therefore should be strongly considered in GA development. Particularly, uniform crossover and tournament selection, both found to be superior to other operators, were shown to work well in preserving genotypic diversity and balancing exploration and exploitation well towards finding a reliable solution.

The formulation as presented in this chapter does not fully represent the complex relationships between the watershed and its receiving waters and can be solved with enumeration. Yet, the application of genetic algorithms to stormwater quality management can become invaluable as the problem formulation becomes more complex, in efforts to improve the representation of the watershed and its receiving waters.

Future Research

Most research reported in the literature on the effects of GA operators has been based on empirical testing tailored to specific problem formulations (GA environment). Additional research on the effectiveness of GA operators based on probability theory could improve the operator selection process. Furthermore, the optimization of GA operators can be incorporated into the GA formulation to balance exploration and exploitation in response to the changing solution landscaped explored by the GA.

4 STORMWATER MANAGEMENT WITH UNCERTAINTY, VARIABILITY, AND DIFFERENT OBJECTIVE FUNCTIONS

"What we call results are beginnings." Ralph Waldo Emerson (1803-82) American writer, philosopher

The most common approach to address stormwater quality management is to select SWQ-MPs based on reported removal efficiencies and costs. Yet, the characteristics of the receiving water (hydrology, pollution levels), the watershed (level of pollution generated), and the selected SWQ-MP (removal efficiency) can be highly variable and influence the observed outcome of stormwater management. In this chapter, the GA based watershed optimization model described in Chapter 3 is used to study how these factors might influence SWQ-MP selection and furthermore, how these factors might be considered and incorporated into the stormwater quality management planning process.

This chapter is organized in four sections. The first section expands the watershed model formulation to explicitly account for three of the four evaluation methods described in Chapter 2: chemical/physical evaluation, biological evaluation, and cost effectiveness. The second section presents model results of a cost-effectiveness analysis for a fictitious watershed based on two evaluation criteria: water quality standards and eutrophication limits. The importance of considering watershed, receiving water, and SWQ-MPs characteristics are explored in this section with cost effectiveness analysis. The third section of the chapter explores the importance of considering uncertainty in the watershed, receiving water, and SWQ-MPs and how these uncertainties can be incorporated into management decisions. The last section of the chapter provides a summary and conclusions based on the model results and identifies important factors that should be considered to ensure a reliable and economically efficient stormwater quality management program.

Model Reformulation

Though four evaluation approaches for stormwater quality management were presented in Chapter 2, only three approaches were applied to the watershed GA based optimization model. The cost-effectiveness evaluation is used in conjunction with the chemical/physical and biological process evaluations to develop economically efficient stormwater management program for a watershed. The watershed model is reformulated to account for water quality standards and eutrophication limits constraints as described below.

Concentration Standards

In developing management practices to meet regulatory standards' both the costs of SWQ-MPs and the desired concentration standards are considered. Equation (4-1) is the fitness function used to evaluate possible stormwater management alternatives. The fitness function is used to develop a tradeoff curve between management cost and concentration standards to demonstrate the effect of increasingly stringent regulations on capital costs spent on management practices.

$$\begin{aligned} &\min \quad CC_{SWQ-MP} \\ &S.T. \quad C_{RW} \le C_{STD} \end{aligned} \tag{4-1}$$

Where:

$CC_{SWQ\text{-}MP}$ = Capital cost of SWQ-MP, \$/yr.

C_{RW} = Receiving water pollutant concentration with SWQ-MP, mg/L.

C_{STD} = Pollutant concentration regulatory standard, mg/L.

Eutrophication Limits

The model considers eutrophication as an example of a biological process evaluation for receiving waters. Eutrophication levels are determined based on the combined effect of nitrogen and phosphorus generated by the watershed on the receiving water using the stoichiometric equation (4-2) (Novotny and Olem, 1994).

$$C_{106}H_{180}O_{45}N_{16}P + 53\frac{1}{4}H_2O \rightarrow 47\frac{1}{8}CO_2 + 58\frac{7}{8}CH_4 + 16NH_3 + H_3PO_4 \tag{4-2}$$

Table 4-1: Chemical atomic weight used for concentration calculations

Chemical	***Atomic weight***
H	1
C	12
N	14
O	16
P	31
$C_{106}H_{180}O_{45}N_{16}P + 154O_2$	2427

Based on this stoichiometric relationship, the ratio of nitrogen to phosphorus required for productivity is 7.22. The limiting nutrient controls the level of productivity and eutrophication in the receiving waters. Since SWQ-MPs' nitrogen and phosphorus removal efficiencies vary, optimal management choices will vary based on the nutrients' combined effect. The fitness function therefore depends on change in productivity rather than the pollutant concentrations and is represented by equation (4-3). The objective function value is the minimized total capital cost with a constraint requiring eutrophication levels to be below a specified desired level.

$$\begin{aligned} &\min \quad CC_{SWQ-MP} \\ &S.T. \quad C_N R_N \le E_{\text{limit}}, \qquad \text{for } \mathrm{R}_{N/P} \le 7.22 \\ &\qquad\quad C_P R_P \le E_{\text{limit}}, \qquad \text{for } \mathrm{R}_{N/P} > 7.22 \end{aligned} \tag{4-3}$$

Where:

C_N: Nitrogen concentration in receiving water, mg/L.

R_N: Molar ratio of algae to nitrogen, 10.83.

$\mathrm{R}_{\mathrm{N/P}}$: Ratio of nitrogen concentration and phosphorus concentration ($\mathrm{C_N/C_P}$) in the receiving water. For $\mathrm{R}_{\mathrm{N/P}}$ greater than 7.22, phosphorus is the limiting nutrient and for $\mathrm{R}_{\mathrm{N/P}}$ less than 7.22, nitrogen is the limiting nutrient.

C_P: Phosphorus concentration in receiving water, mg/L.

R_P: Molar ratio of algae to phosphorus, 78.29.

E_{limit}: Specified desired eutrophication level, mg/L

Unlike the synergetic effect of nitrogen and phosphorus in which the nutrients depend on each other to impair water quality, pollutants such as toxic metals may have compounding effects on receiving water quality and beneficial uses. In this evaluation, the combined effect of nutrients is considered through eutrophication. Other processes could easily be substituted for or added to the eutrophication process and applied to the model.

Example Application

Receiving Water Description

An example application is based on a completely mixed pond with a volume of 8.3 Acre-ft and no natural (background) pollution. For this analysis nitrogen is considered the primary pollutant in the concentration standard evaluation and both nitrogen and phosphorus are considered in the eutrophication limit evaluation. A range of concentration standards (0.2 to 2 mg/L) and eutrophication limits (2 to 20 mg/L) are considered in the development of a tradeoff relationship between the evaluations' criteria and the costs of the selected SWQ-MPs. Receiving water concentration of pollutants are calculated based on a simple mass balance as shown in equation (4-4) and watershed transport mechanisms or sediment-water interactions are ignored.

$$C_{rw} = \frac{C_{rw} Q_{rw} + \sum_{s=1}^{S} C_s Q_s}{Q_{rw} + \sum_{s=1}^{S} Q_s} \qquad (4\text{-}4)$$

Where

C_{rw}: Receiving water pollutant concentration

Q_{rw}: Receiving water flow

C_s: Source pollutant concentration

Q_s: Source flow

Watershed Description

Four tributary sources contribute flow and pollution to the pond from four zoning types: residential, commercial, industrial, and other (landscaped areas such as parks and golf course) as shown schematically in Figure 4-1 and summarized in Table 4-2. Pollution generated at each source is estimated using EPA's SWMM data (USEPA, 1976) and annual precipitation of 50 in. Commercial and industrial areas generate the highest nutrient concentrations while the fourth zoning category, other, produces relatively little nutrient concentrations.

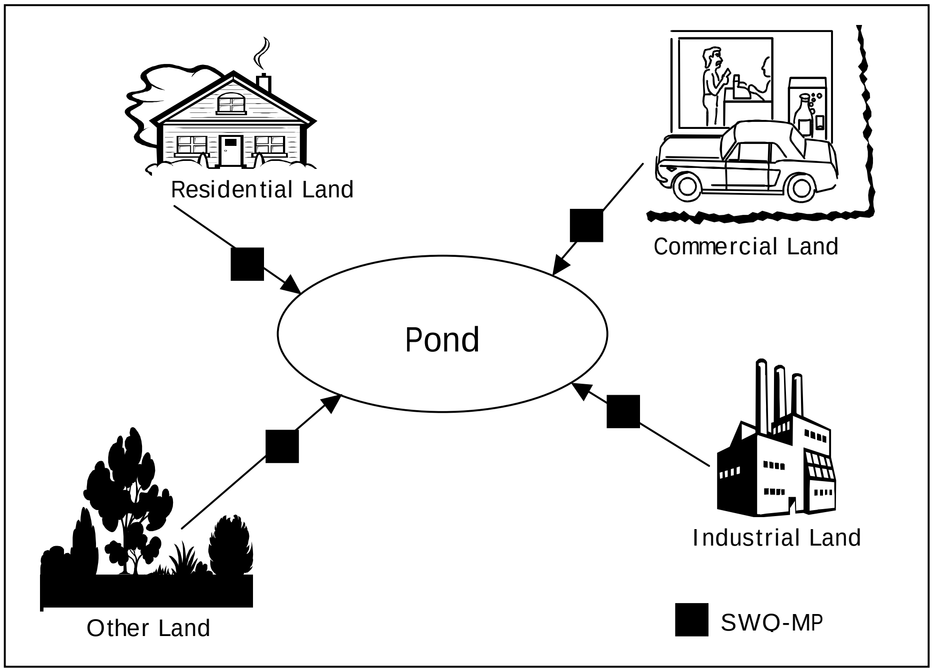

Figure 4-1: Example watershed with four tributary polluting sources

Table 4-2: Zoning types in example watershed

Zoning Type	Area (Acres)	Nitrogen Conc. (μg/L)	Phosphorus Conc. (μg/L)
Residential	1000	1,750	449
Commercial	1000	4,175	1,068
Industrial	1000	3,942	1,003
Other (Landscape)	1000	164	12

SWQ-MP Description

SWQ-MPs ranging from preventive source control measures to corrective measures can be used to protect receiving water quality. For this analysis, SWQ-MP costs are assumed to increase exponentially with removal efficiency. Seven levels of SWQ-MP were considered in the model. Table 4-3 lists the seven management levels, their costs, and their removal efficiencies for nitrogen and phosphorus. The seven levels of SWQ-MPs considered in this analysis vary in their removal efficiencies and include screening, vegetated systems such as filter strips and grass swales, infiltration basins, sedimentation basins, detention ponds, and disinfection treatment (removal efficiencies and costs shown in the tables are assumed for the analysis and are not based on field data).

Table 4-3: SWQ-MP options

SWQ-MP Level	Cost ($)	% Removal (Nitrogen)	% Removal (Phosphorus)
Level I	15	10	10
Level II	30	20	20
Level III	75	40	40
Level IV	200	60	60
Level V	350	70	70
Level VI	550	80	80
Level VII	900	90	90

Model Results

The selection of SWQ-MPs for this watershed example is based on a single event with unvarying conditions. Since annual precipitation is assumed to be constant, runoff and pollutant concentrations generated in the watershed are constant as well. Model results were used to compare management decisions based on water quality standards and eutrophication limits as well as to identify the important factors that affect management decisions.

Comparison of Concentration Standard vs. Eutrophication Limit Results

The optimization model was used to develop two tradeoff curves. A tradeoff curve was developed for concentration standards and SWQ-MP cost and for eutrophication level and SWQ-MP cost. Figure 4-2 and Figure 4-3 show the tradeoff curves for the case study assuming annual precipitation of 50-in. These two tradeoff curves can be compared to determine the applicability of concentration standards in restoring or protecting desired eutrophication levels in the receiving waters. For example, a stormwater quality management plan to meet a nitrogen concentration standard of 1 mg/L at a cost of $345/yr will yield a eutrophication level of 10.5 mg/L. Comparing results from both evaluation methods can help determine if the concentration standard has been set appropriately to protect receiving water uses that are affected by eutrophication. If sufficient data has been gathered and receiving water processes are properly modeled, water quality standards can be set more judiciously to provide the appropriate level of treatment in the watershed to protect receiving water quality and aquatic life based on the model results.

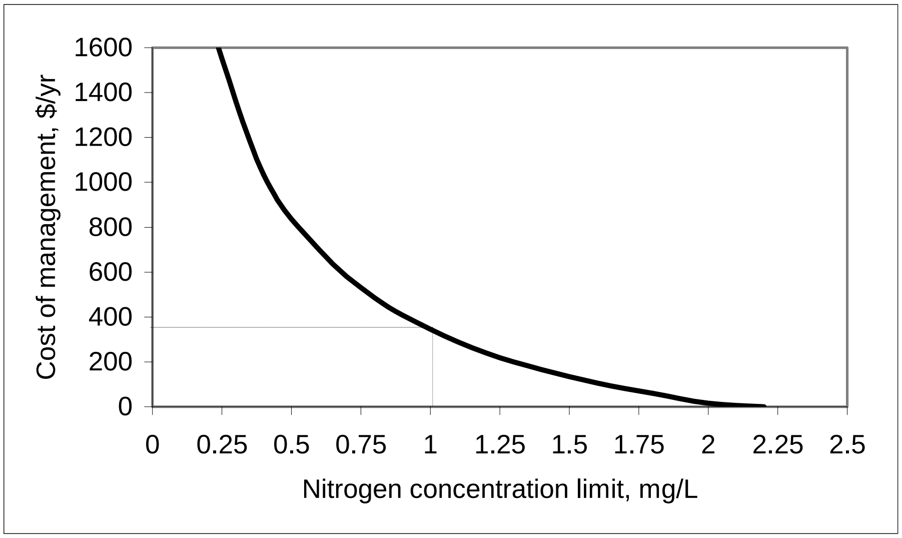

Figure 4-2: Tradeoff curve for concentration standards and SWQ-MP cost

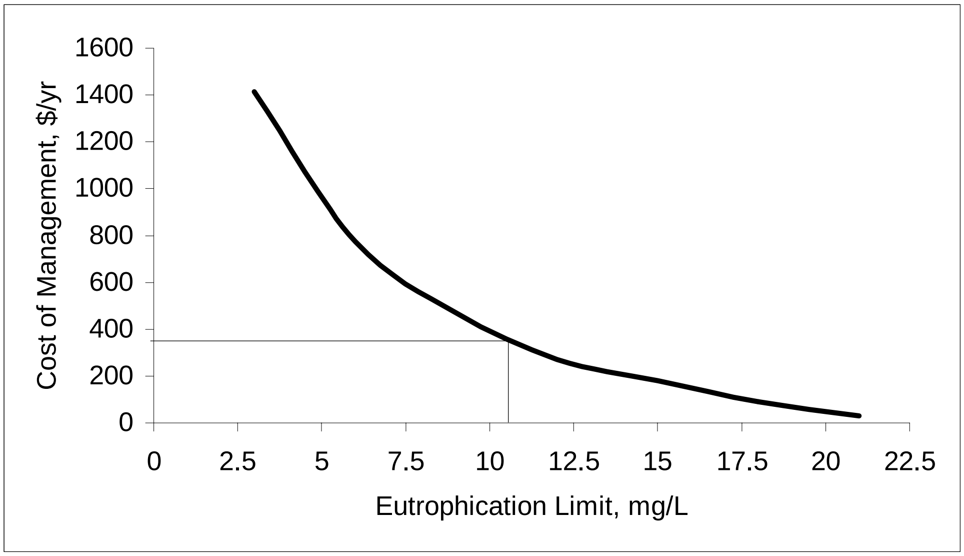

Figure 4-3: Tradeoff curve for eutrophication limits and SWQ-MP cost

Importance of Concentration Standard

The selection and cost of preferred stormwater quality management are very sensitive to the desired water quality standards, as can be seen from Figure 4-4. For example, given annual precipitation of 50-in, SWQ-MP cost to meet regulatory standard of 0.6 mgN/L will cost $715/yr instead of $180/yr if the regulatory standard was set higher at 1.4 mgN/L. This high difference in SWQ-MP cost to meet the regulatory standard demonstrates the importance of setting water quality standards appropriately and in some cases may justify spending resources on monitoring and gathering data to better set these standards.

The application of SWQ-MPs to meet stringent concentration limits are distributed in the watershed based on the relative contribution of the different zones in the watershed to the receiving water. Management is first directed towards controlling pollution from the industrial zone, which contributes the most pollution, and then applied to commercial and residential zones. Since landscaped areas are assumed to contribute relatively little loading, they do not require mitigation.

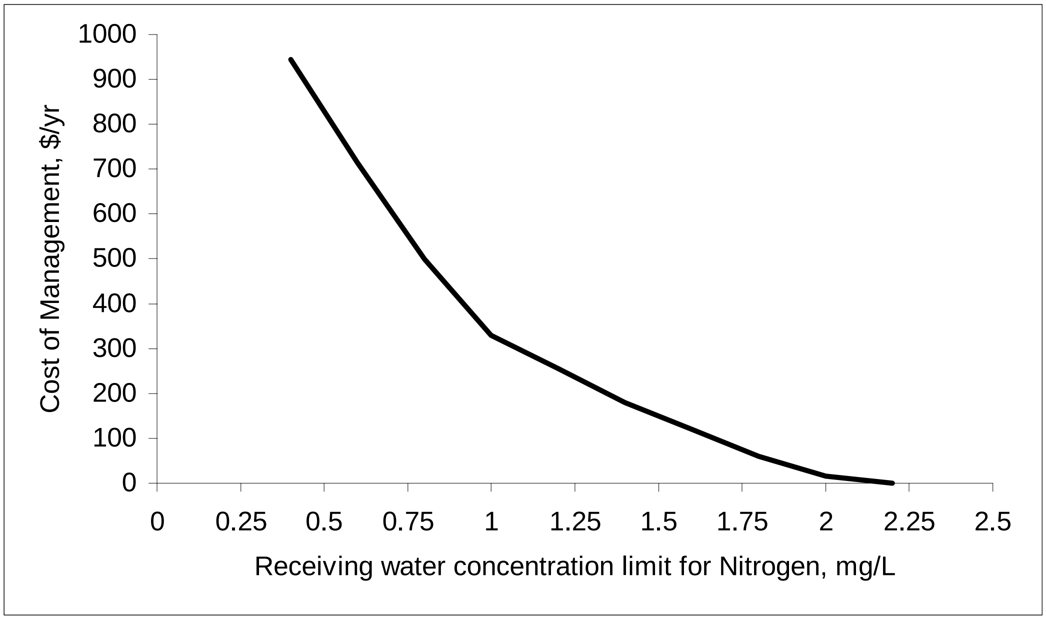

Figure 4-4: The effect of concentration standard on management choices (Precipitation = 50 in/yr)

Importance of Precipitation and Source Pollution

Figure 4-5 can be used to evaluate the importance of correctly representing precipitation, the main factor in estimating pollution concentration generated in the watershed. Based on the example's results, it appears that the selection of economically efficient management is not very sensitive to high precipitation levels but may be affected by misrepresentation when precipitation levels are below 30 in/yr and pollution levels are significantly higher. With precipitation levels above 30 in/yr, water concentration ranges between 2.0 and 2.1 mgN/L whereas for precipitation of 10 in/yr receiving water concentration is approximately 2.8 mgN/L requiring additional SWQ-MPs to meet water quality standards.

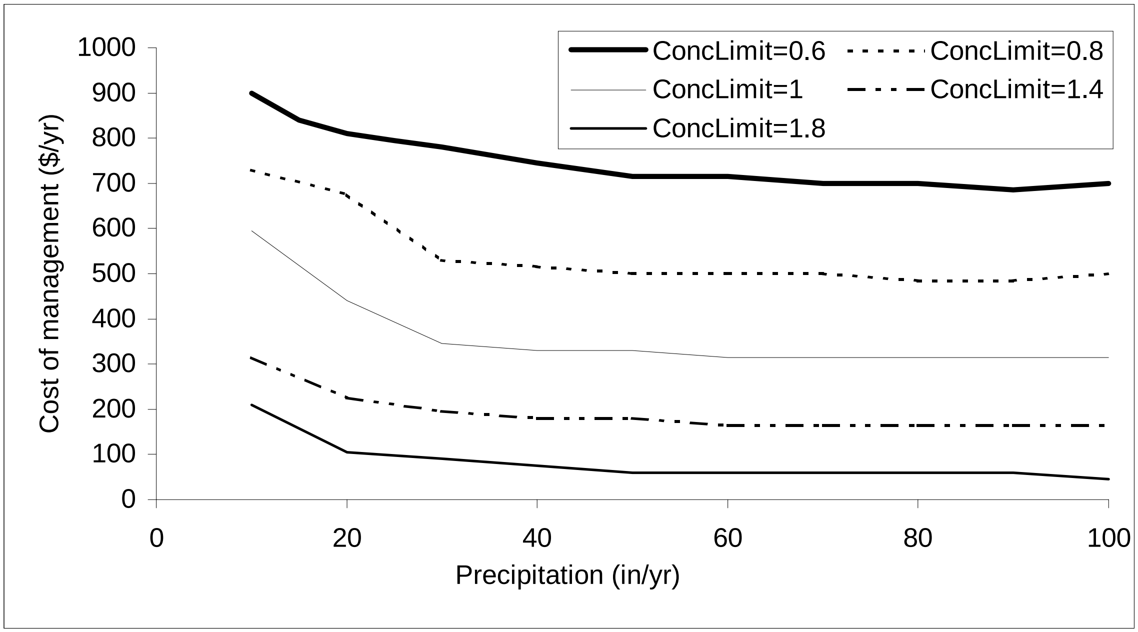

Figure 4-5: SWQ-MP cost for varying nitrogen concentration limits and precipitation

Importance of Initial Receiving Water Quality

The selection of SWQ-MPs is not very sensitive to the initial receiving water quality as can be seen in Figure 4-6. Stormwater quality management for receiving waters with concentrations within a range of 2.2 mg/L will remain the same. More significant variations in receiving water concentration will lead to additional SWQ-MP in the industrial and commercial areas as expected. Each step in Figure 4-6 represents the addition of one management practice on one of the land uses.

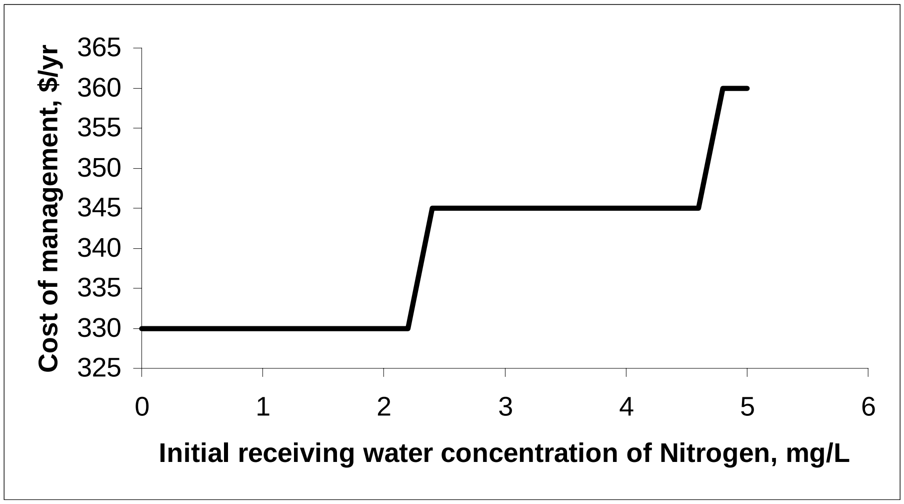

Figure 4-6: The effect of initial receiving water concentration on SWQ-MP selection

Importance of Watershed Zoning and Land Uses

Some research in stormwater quality management has focused on the effect of urbanization and vegetative management on receiving water quality. The effects of zoning changes from undeveloped pervious lands to urbanized impervious areas and vice versa can be studied with the watershed model. In addition, the willingness to pay for vegetative management can be estimated. For the watershed example presented, a tradeoff between industrial (the most polluting zone in the watershed) and landscaped (the least polluting zone in the watershed) areas was developed to determine the willingness to pay for a land use change and is shown in Figure 4-7. Increasing the landscaped area by 40%, from 1000 to 1400 acres (and reducing industrial zoning to 600 acres), will reduce the pollution load generated in the watershed by 6.3% (from 2.07 mgN/L to 1.94 mgN/L) and save \$60/yr in stormwater management cost (\$0.15/yr-acre of converted land use). Since SWQ-MPs choices provide much better removal efficiencies (Level IV at a cost of \$200/yr provides 60% removal), zoning change does not appear to be cost effective for this example. Land use can be incorporated to this analysis explicitly by considering land use changes as a set of management alternatives and the cost of converting a particular land use to vegetative land use (loss of revenues).

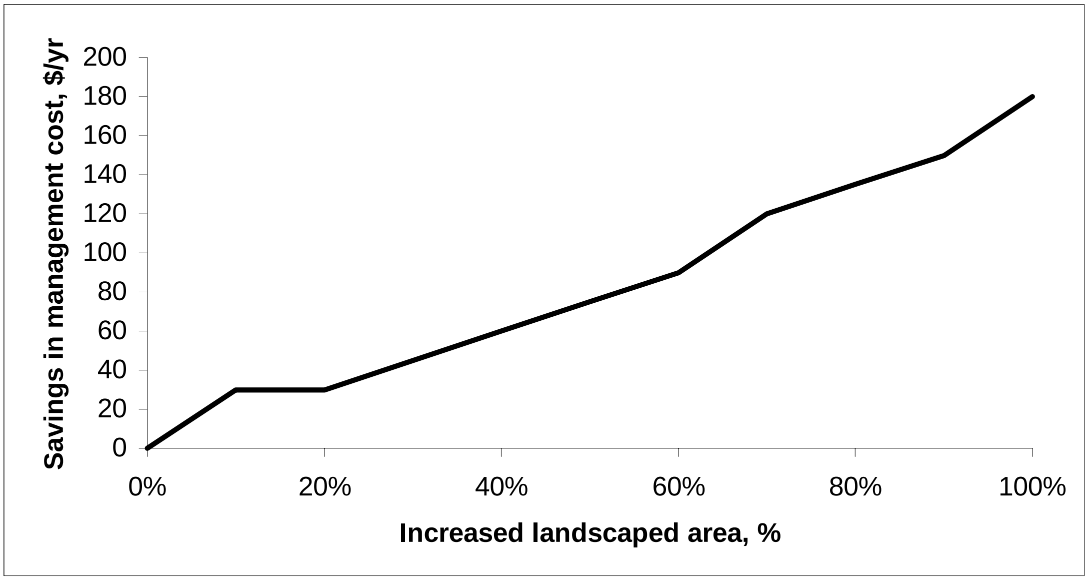

Figure 4-7: The benefit of replacing commercial land with landscaped land

Consideration of Uncertainty in Management Planning

Though most urban watershed management models used to evaluate management effectiveness are based on deterministic and single event representations, both the watershed and the receiving water are subject to fluctuations in pollutant concentration due to the variability in precipitation, pollution generation, and the effectiveness of the SWQ-MP used. Some agricultural runoff models have attempted to account for these variabilities and uncertainties (Yulianti et al, 1999) with Monte Carlo optimizations and sensitivity analyses.

Model Formulation with Monte Carlo Optimization

To account for variability in the watershed, receiving water, and SWQ-MPs, the model was reformulated by adding a Monte Carlo optimization component (Loughlin and Ranjithan, 1997). The objective function below is a stochastic optimization, one-stage decision process based on a variety of single events, as presented in the previous sections.

Objective Function

Cost effectiveness remains the optimization objective in developing stormwater quality management. The cost function is expanded to include a penalty for variance from the constraint. The mean total cost is represented as the sum of the cost of all SWQ-MPs applied in the watershed and the average penalty of not meeting the desired water quality objective as represented by equation (4-5).

$$\text{Min} \quad \frac{\sum_{r=1}^{R}\left(\sum_{s=1}^{S}\sum_{mp=1}^{MP} CC_{s,mp} + P_r\right)}{R} \tag{4-5}$$

Where:

$CC_{s,mp}$ = Capital cost of management practice (mp) at source (s).

r = Index for the number of Monte Carlo realizations, total R

s = Index for the number of sources, total S

mp = Index for the number of available management alternatives, total MP

P_r = Penalty of exceeding desired water quality. See equation (4-6).

If receiving water pollution concentration exceeds the water quality standards within a specified range (β), a penalty as a function of the difference between receiving water concentration and water quality standard is calculated. If receiving water quality concentration exceeds this range, a significantly higher fixed penalty (γ) is applied to discourage unacceptable levels of pollutant concentration. The penalty as a function of receiving water concentration and water quality limit is illustrated in Figure 4-8 and is calculated based on equation (4-6). For the watershed example, the acceptable range of variance from the water quality standard β, is 5 %, α equals \$8, and the maximum penalty of incompliance, γ is \$1,000,000.

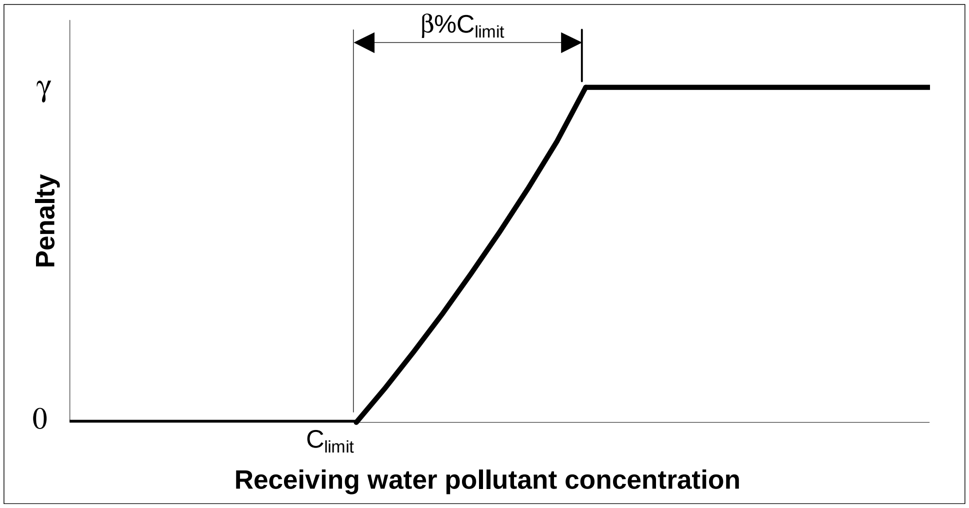

Figure 4-8: Penalty of exceeding water quality standards

$$P_r = \alpha e^{\beta \Delta c} \quad \text{for} \quad 0 < \Delta c \le 0.05 C_{\text{limit}}$$
$$P_r = \gamma \quad \text{for} \quad \Delta c > 0.05 C_{\text{limit}} \tag{4-6}$$

where

P_r: Penalty of not meeting water quality standard.

α: Cost of exceeding concentration limit within acceptable range, $.

β: Range of allowable exceedance, %

γ: Cost of exceeding acceptable water quality range.

Δc: The difference between receiving water concentration and water quality standard. (C_{rw}-C_{limit})

C_{limit}: Water quality limit.

Monte Carlo Optimization

The number of Monte Carlo (MC) realizations can greatly affect model results. Loughlin and Ranjithan (1997) explored the use of Monte Carlo optimization in genetic algorithm fitness functions to account for variability and uncertainty in the problem's key parameters. Loughlin and Ranjithan (1997) found the number of realizations, the configuration of the Monte Carlo optimization in the genetic algorithms, and the different representation of probabilities to be important factors in obtaining reliable results where reliability is defined as no change in model results with increased number of Monte Carlo realizations. The number of Monte Carlo realizations incorporated into the model can significantly affect the additional number of calculations required and therefore should be selected prudently.

In selecting the number of Monte Carlo realizations to be applied in the model, two scenarios are compared: incorporating Monte Carlo optimization at the generation level and the chromosome level. Introducing MC optimization at each generation allows the population at each generation to be evaluated based on the same realizations. Performing MC optimization for each chromosome at each generation generates unique realizations as basis for evaluation for each member of the population at each generation. The number of calculations required at the chromosome levels is twice that at the generation level. The number of calculations added due to Monte Carlo optimization includes the creation of realizations and the fitness calculations and is shown as Equation (4-7) (for Generation level) and equation (4-8) (for chromosome level). The number of calculations is directly proportional to the number of Monte Carlo realizations as shown in Figure 4-9.

$$N=MC*GEN*(P+1) \tag{4-7}$$

$$N=2*MC*GEN*P \tag{4-8}$$

Where:

N = Number of calculations

MC = Number of Monte Carlo Realizations

GEN= Number of generations

P = Population size

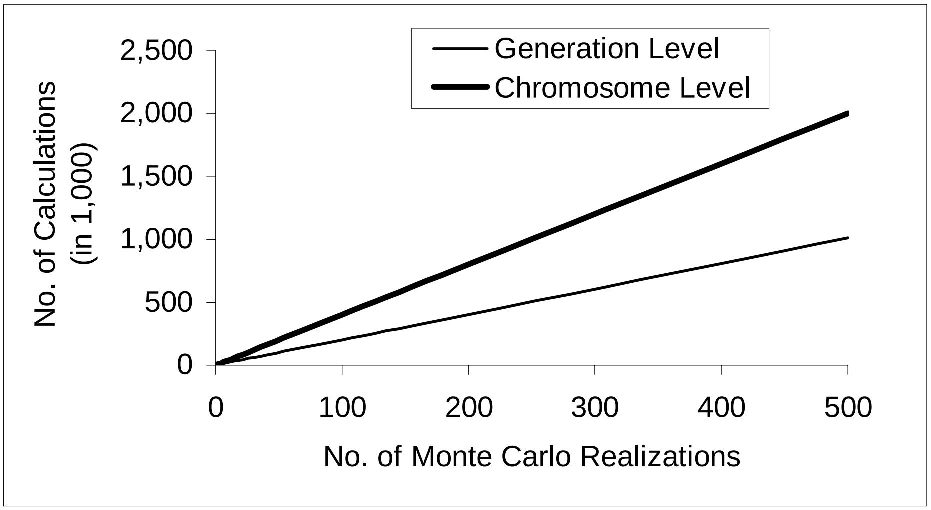

Figure 4-9: The effect of Monte Carlo optimization on number of calculations

For this watershed example, MC optimization was introduced at the generation level to reduce the number of calculations with the same random generator seed. With some variability, model results appeared to be fairly stable for runs with more than 75 MC realizations as can be seen from Figure 4-10. Based on these results, 100 MC realizations are used in the model to develop stormwater quality management with uncertainty.

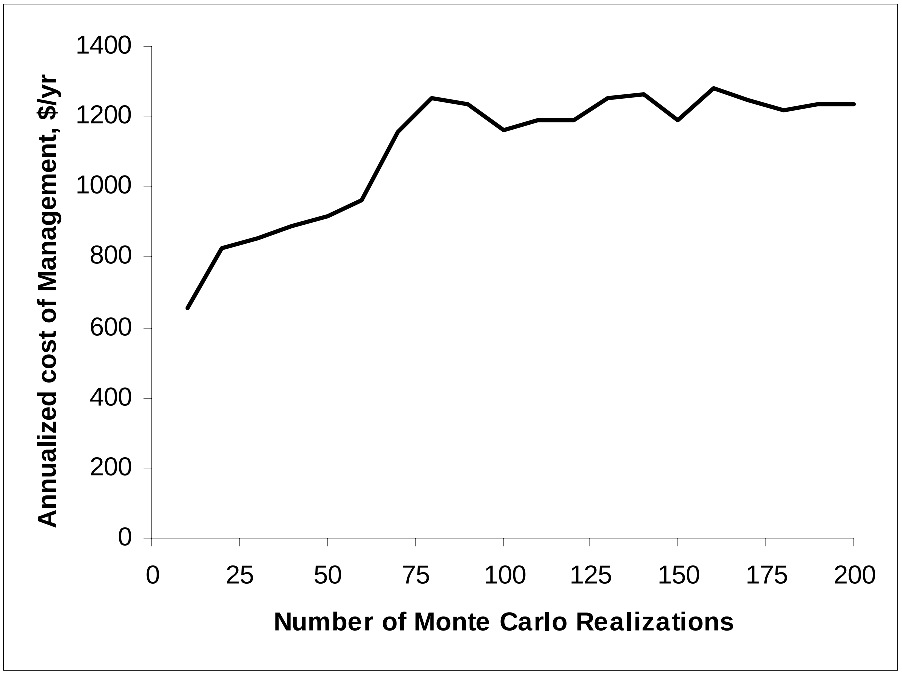

Figure 4-10: The effect of MC realizations on model reliability

Model Results with MC Optimization

Results from the deterministic single event runs are compared in this section to the results based on MC optimization.

Effect of Uncertainty in Precipitation (Loading from Watershed)

Stormwater quality management results from single event with an average annual precipitation of 25-in were compared to results with MC optimization having the same average precipitation and a uniform probability distribution function with a range between 0-in and 50-in. As shown in Figure 4-11, the single-event model results, not accounting for uncertainty in precipitation underestimated the management required for meeting water quality standards significantly. With single event modeling, management was selected to remove 55 % of pollutants compared with 82 % when precipitation uncertainty was considered.

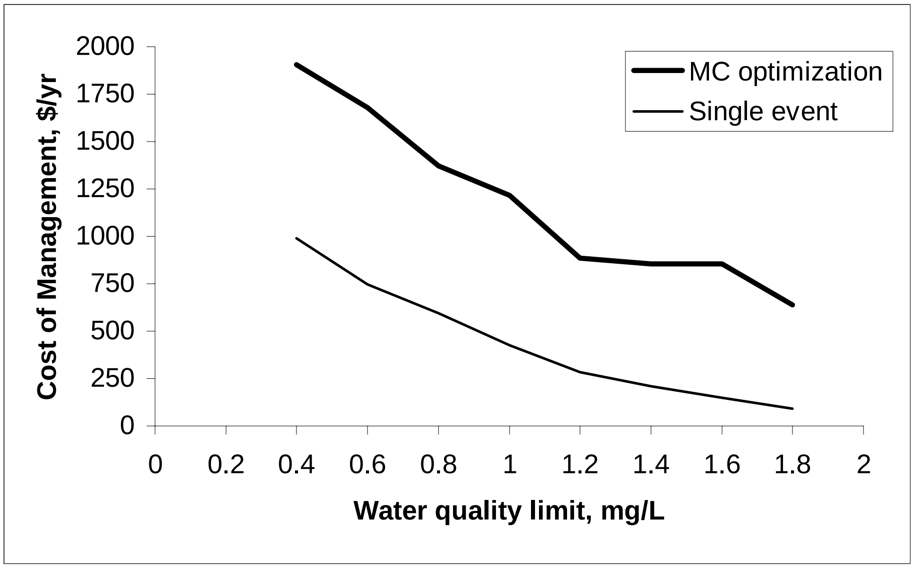

Figure 4-11: Cost of management for varying water quality limits (Average annual precipitation = 25-in)

Effect of Uncertainty in SWQ-MP Removal Efficiency

For the deterministic single-event runs, removal efficiencies of SWQ-MPs were assumed to be known and constant. Yet, SWQ-MPs' efficiencies tend to degrade with time and are not always known with certainty at time of implementation. As shown in Figure 4-12, the cost of SWQ-MP increases when uncertainty is assumed especially for water quality standards of low concentrations. The difference in management choice and cost is particularly acute for low water quality limits where it is harder to meet regulatory requirements. The increase in cost and the selection of more efficient SWQ-MPs compensate for the degradation of SWQ-MP effectiveness over time.

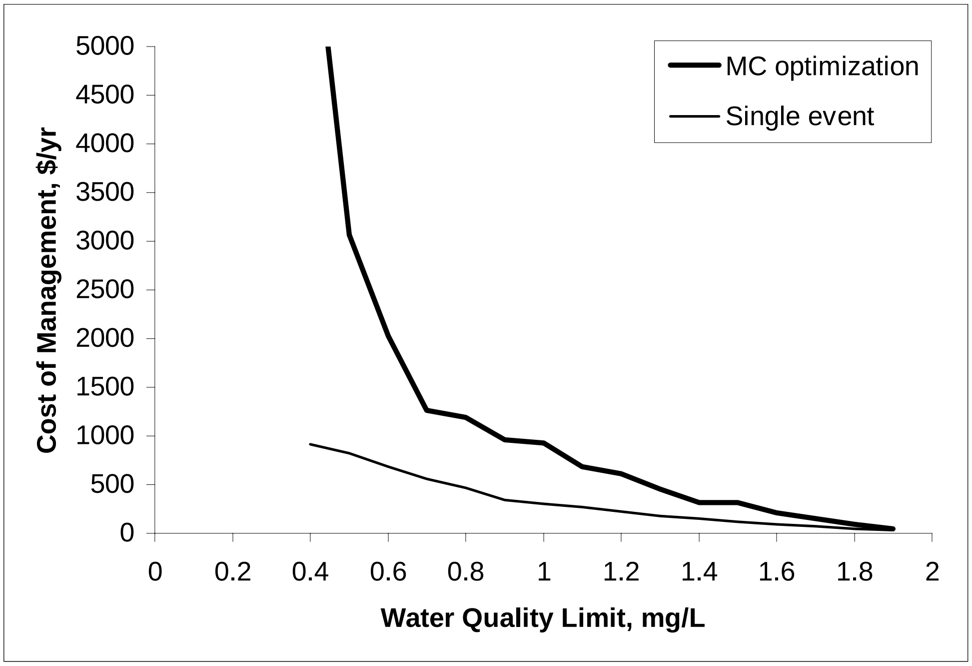

Figure 4-12: The effect of variable SWQ-MP efficiency on watershed management cost

Effect of Receiving Water Quality Variability

Since initial receiving water quality did not seem to be critical for the development of stormwater quality management under single event representation, it is unlikely that uncertainty in receiving water quality will have a significant effect. This assumption is supported by model results as shown in Figure 4-13. Figure 4-13 compares management choices to meet a 1 mgN/L water quality standard based on a single event model and a MC optimization model. Results shown in the figure for the MC optimization appear lower than single event results because the MC optimization model assumes that the receiving water concentration varies between 0 and the maximum concentration modeled under the single event condition. For example, single event model results for receiving water concentration of 1.8 mgN/L are compared to MC optimization model results for receiving water concentration varying between 0 and 1.8 mgN/L and therefore the MC optimization model appears to underestimate management costs ($315/yr compared to $330/yr). Nonetheless, management choices are very similar and applied to the same sources under both modeling conditions.

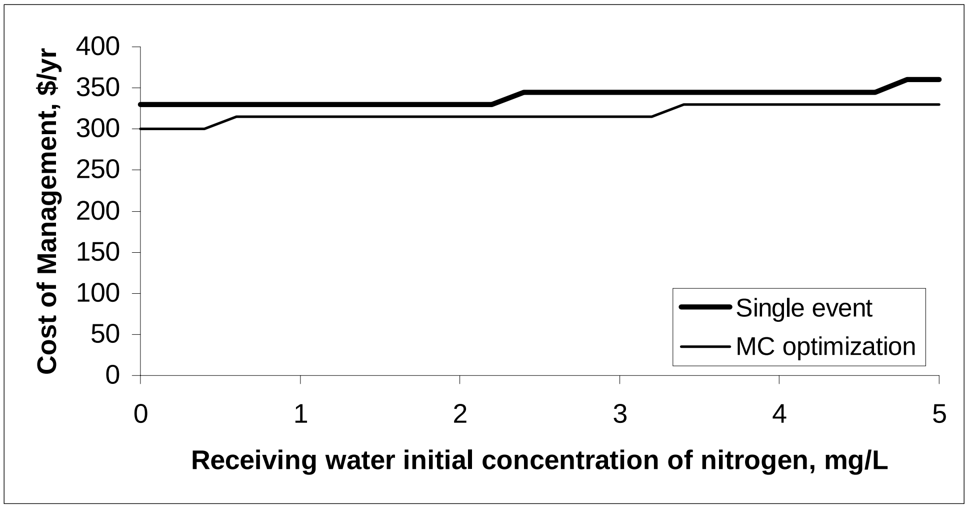

Figure 4-13: The effect of receiving water initial concentration variability on model results

Summary of Results

This chapter outlines a process of analyzing the importance of watershed, receiving waters, and SWQ-MPs characteristics representation in developing a stormwater quality management plan. For the watershed presented, the most important consideration in developing stormwater quality management is the desired water quality needed to protect receiving water beneficial uses. It is therefore important to judiciously set water quality standards prior to management selection. Precipitation and level of pollution generated in tributary sources to the receiving waters are important only at very high pollution levels. The initial water quality condition of the receiving water does not appear to be important in setting stormwater quality management throughout the watershed and zoning considerations appear to have minor effect on receiving waters in comparison to available management practices. Though these results are limited to the management practices evaluated in this example, replacing impervious areas with vegetation should be carefully weighed against other available management practices. Considering uncertainty is most important for the identification of pollution levels generated in the contributing watershed and the removal efficiency of the SWQ-MP evaluated. The importance of considering watershed, receiving water, and SWQ-MPs characteristics in the management planning phase is summarized in Table 4-4.

Table 4-4: Factors affecting stormwater quality management planning

Consideration factor	Single event evaluation	Consideration of variability
Constraint limits	Important	Important
Level of watershed pollution	Important only at very high levels (low precipitation)	Important
Receiving water initial concentration	Not significant within a range of 2.2 mg/L	Not important
Zoning distribution	Not important	-
Removal efficiency	Important	Important

Conclusions

The chapter presents the process of developing a model to represent the watershed, receiving waters, and SWQ-MPs for stormwater quality management planning. Though the example watershed presented is simplistic, it illustrates the need to consider variability and the relationships between the watershed, its receiving waters and polluting sources, as well as the available SWQ-MPs options when developing a stormwater quality management plan. Some characteristics of the watershed, receiving waters, or SWQ-MPs may have great affect on the resulting management plan and therefore resources should be invested to carefully represent them in the evaluation process. On the other hand, the management plan may not be very sensitive to other characteristics and therefore simple modeling will be sufficient for their representation. This example also illustrates the importance of considering variability and uncertainty; in some cases, ignoring variability and uncertainty in the model representation can lead to underestimating the cost of management needed to ensure compliance with concentration standards or desired water quality.

The following conclusions can be made based on the watershed example presented and its applicability to other watershed planning efforts.

1. Since the desired water quality in the receiving water largely dictates the level of management that should be applied to the watershed, it is important to focus resources on improving the process of identifying the appropriate level of water quality to ensure protection of receiving water beneficial uses.

2. In setting the desired water quality based on beneficial uses, it may be important to consider the benefits of protecting beneficial uses since they drive the cost of management.

3. Monitoring in the watershed prior to developing watershed management plan should focus on highly polluting sources. In addition, the transport mechanism from these sources to the receiving waters should be studied to better understand the impact of these highly polluting sources prior to selecting management alternatives.

4. Understanding SWQ-MPs' effectiveness is critical to a cost effective stormwater quality management plan. Monitoring and studies to better represent SWQ-MP effectiveness and degradation with time can be useful for developing economically efficient management and savings of resources in the long-term.

Future Research

The model and the watershed example present an oversimplified representation of the challenges of stormwater quality management. Based on the results presented in this chapter and the identification of important parameters for management consideration, the following studies and research are suggested to help in the process of stormwater quality management planning.

- The model presented is based on a simple mass balance ignoring the effects of sources based on their relative proximity to the receiving water and pollution transport mechanism. Since considering highly polluting sources is critical to the management selection process, it is important to improve our understanding of how the sources affect the receiving water individually.

- The model presented is based on a single event representation of the watershed. It may be important to consider the long-term effect of management in cases where toxicity and biota recovery are the driving evaluation criteria.

- Understanding the effectiveness of SWQ-MPs is critical to developing stormwater quality management appropriately. More research is needed to understand particularly how SWQ-MPs perform over time.

5 ANALYTICS OF MAINTENANCE AND STORMWATER QUALITY MANAGEMENT

"You can never step into the same river; for new waters are always flowing on to you."
Heraclitus (fl. 500 BC) Greek philosopher

The effectiveness of stormwater quality management practices (SWQ-MP) in providing adequate runoff control and water quality benefits depends on the SWQ-MP's operating and structural conditions. SWQ-MPs that remove pollutants require periodic maintenance and cleaning to preserve removal efficiencies. Maintenance problems such as weed growth have been observed with vegetative SWQ-MP such as swales and wetlands. Clogging, ponding, sedimentation and erosion, and debris accumulation are the most common problems associated with residence ponds and infiltration basins. In a survey of 258 SWQ-MP facilities in Maryland, Lindsey et al (1992) found that one third of the facilities were not functioning as designed and the remaining two thirds of the facilities required some maintenance to restore pollutant removal efficiency. In addition, Lindsey et al (1992) found that over a period of four years (from 1986 to 1990), SWQ-MP facilities degraded and required additional maintenance to restore removal efficiency.

Stormwater management decisions largely depend on reported SWQ-MP removal efficiencies. Therefore, to sustain desired water quality effects and budget long-term costs, maintenance should be incorporated into management decisions in SWQ-MP selection. In addition, existing facilities should be maintained in economically efficient manner to ensure that water quality goals are achieved and maintained. This chapter proposes an economic method to optimally schedule maintenance that can be either incorporated into the development of stormwater management plans to aid in the selection of economically efficient management practices or used to preserve existing facilities to protect receiving water quality and beneficial uses.

Maintenance Scheduling

Maintenance is critical for sustaining most forms of industrial and public infrastructure. Three typical goals are generally sought in developing maintenance schedules: (a) reliability improvement, (b) reduction in maintenance cost, and (c) improving net benefits. Much research has been done on maintenance scheduling under different contexts using a multitude of decision support systems and optimization methods (Dekker and Scarf, 1998).

Van Noortwijk et al (1992) developed an expert judgment component to help determine the optimal maintenance interval with the objective of minimizing the total mean cost of failures and preventive maintenance activities for a production plant. Lund (1990) developed a cost minimization function for dredging schedule to maintain minimum clearance in navigation channels while accounting for variabilities in sedimentation rates. Mauney and Schmidt (1997) presented a decision analysis to maximize the net present value by selecting maintenance action timing within budget constraint for a chemical facility. The analysis incorporated reliability with the use of a Weibull probability distribution for component failure. Nesbitt et al (1992) used a semi-Markov formulation for pavement maintenance selection. The authors assumed four maintenance categories: preventive, repair, rehabilitation, and reconstruction and five pavement ratings. A semi-Markov formulation was used to determine the optimal maintenance strategy for each condition while minimizing the discounted life cycle of the maintenance cost. Liu et al

(1997) used a genetic algorithm to develop a maintenance strategy for bridge deck repair based on four maintenance strategies (routine, repair, rehabilitation, and replacement). The algorithm assumed that each maintenance strategy is appropriate for specific deck deterioration scenarios. The objective of the optimization model was to minimize the sum of maintenance cost and penalty cost (representing deterioration level).

Development of SWQ-MP Facilities Maintenance Schedule

Generally, stormwater quality management facilities are cleaned and repaired in response to loss of removal efficiency (full detention ponds, overgrown vegetation) and in some cases to avoid nuisance and health problems created by unmaintained facilities. In developing a facility maintenance schedule, several factors may need to be considered (Tan and Kramer, 1997). These factors include removal efficiency of SWQ-MPs, variability of pollutant loading, receiving water impacts, cause and rates of degradation, maintenance objectives, effectiveness of maintenance, and scheduling constraints.

Removal Efficiency of SWQ-MP Facilities

Pollutant removal efficiencies vary with the type of management and the pollutants that are removed. Moreover, monitoring and research reveal a wide range of efficiencies for specific SWQ-MPs depending on size, location, and storm characteristics. This variability is well demonstrated by Table 5-1 that lists common SWQ-MPs and their range of removal efficiency for nitrogen, phosphorus, and total suspended solids.

Table 5-1: Removal efficiencies for common SWQ-MPs

SWQ-MP	Average removal efficiency, %[1]		
	Nitrogen	Phosphorus	Total Suspended Solids
Filter strips	20-60	20-60	20-80
Infiltration basins	60-70	65-75	85-99
Sand filters	35	40	85
Sedimentation basins	30	35	60-80
Wet residence ponds	35-80	12-90	32-99
Wetlands	20-85	40-80	75-93

[1] Removal efficiencies reported in this table are based on a literature review on BMPs efficiencies. Currier et al (1998). Highway Stormwater Quality Management Practices for Lake Tahoe. University of California, Davis.

Variability of Pollutant Loading

Storm characteristics, land use, and area imperviousness may all contribute to variability in pollutant loading. Therefore, it may be difficult to predict the rate SWQ-MP is degrading. Infrequent storms may carry high pollutant load spikes that significantly affect the SWQ-MP whereas smaller frequent storms may not have much effect. This loading variability will affect how fast the SWQ-MP will degrade and the benefit of removing higher pollutant loading before reaching the receiving waters.

Receiving Water Impacts

Accumulation of pollutants in receiving waters depends largely on its hydrology and residence time. Residence time is defined as the average time required for an incoming parcel of water to leave a body of water. For well-mixed receiving waters, residence time will affect a pollutant’s impact on aquatic biota and toxic bioaccumulation. Receiving waters with insignificant residence time such as streams may not accumulate significant amounts of sediments and pollution due to flushing and the hydrologic nature of the receiving waters. However, many receiving waters, such as lakes and wetlands, have long residence times that result in pollutant accumulation. The accumulation of pollutants in receiving waters with residence time is shown in Figure 5-1.

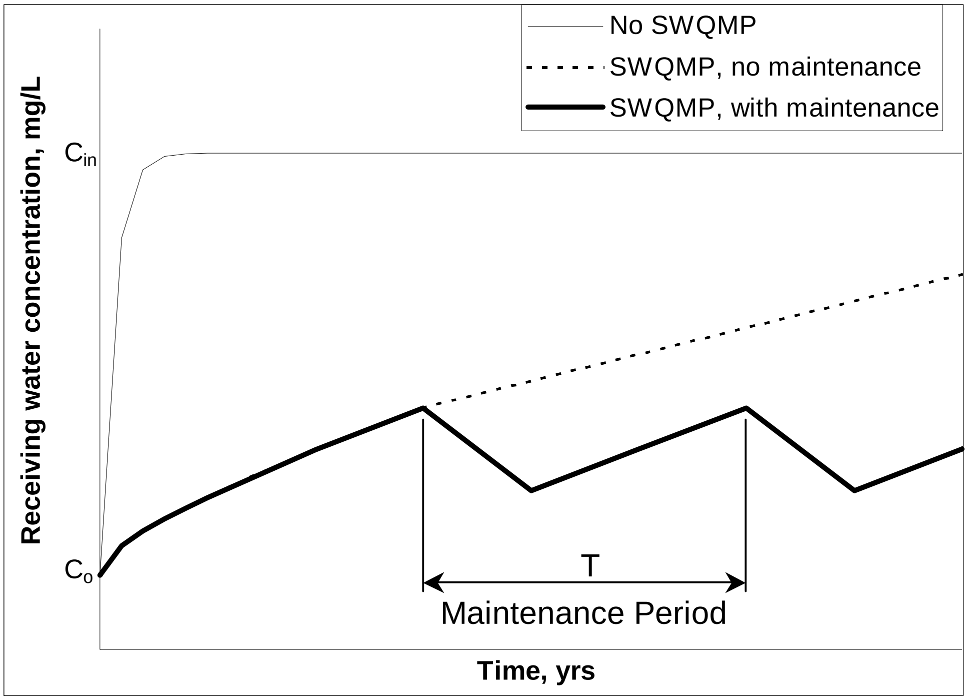

Figure 5-1: Accumulation of pollutants with time

Cause and Rate of Degradation

Several types of degradation may reduce SWQ-MP removal efficiency. Degradation may occur sporadically, linearly, or exponentially making it difficult to predict the SWQ-MP long-term effectiveness. For example, the degradation of a detention basin, a commonly used SWQ-MP, may be due to sediment accumulation, weed growth, and structural deterioration. These types of degradations may require different types of response and maintenance.

Degradation is generally assumed to be a function of time. Yet, in addition to aging, degradation may be a function of storm history in terms of intensity, duration, and frequency and the variety and quantities of pollutants or sediments generated in the contributing watershed area. Efficiencies of facilities designed to remove sediments can be easily compared to accumulation of sediments in reservoirs where sediments trapped are a function of the reservoir capacity and total inflow; sediment accumulation in the reservoirs fluctuates greatly, reflecting changes in inflow while decreasing reservoir capacity (Linsley et al, 1992).

The load of solids washed-off by stormwater has been estimated by Sartor et el. (1972) using the simple first-order removal concept in Equation (5-1).

$$\frac{dP}{dt} = -k_u r P \tag{5-1}$$

where:

r = rainfall intensity, mm/hr

k_u = a constant called 'urban washoff coefficient' that depends on street surface characteristics. k_u ranges between 10 um to 1mm. Commonly given the value of 0.19 (Novotny and Olem, 1994).

P = amount of solids remaining on the surface, g/m-curb

t = time, hr

By integrating this relationship, Equation (5-2) represents pollutant removed by a storm event:

$$P_t = AP_o\left(1-\exp\left(-k_u rt\right)\right), \text{ g/m-curb} \tag{5-2}$$

where $A = 0.057 + 0.04\left(r^{1.1}\right)$, the availability factor that accounts for the nonheterogeneous makeup of particles and the variability in the travel distances of the dust and dirt particles. The maximum value for A is 1 (HEC, 1975).

Based on this simplified relationship, storms with higher rainfall intensities tend to remove a higher fraction of accumulated sediments and generate higher quantities of sediments and pollutants. As shown in Figure 5-2, for a specific case, increasing storm intensities removes a higher fraction of the accumulated sediments up to a storm intensity of 18 mm/hr where the availability factor A approaches 1. Storm intensities that exceed 18 mm/hr remove most of the accumulated sediments. Though it can be assumed from this relationship that higher storm intensities increase degradation of SWQ-MP removal efficiencies, the stochastic nature of storm events and their frequency makes it difficult to estimate removal efficiency degradation.

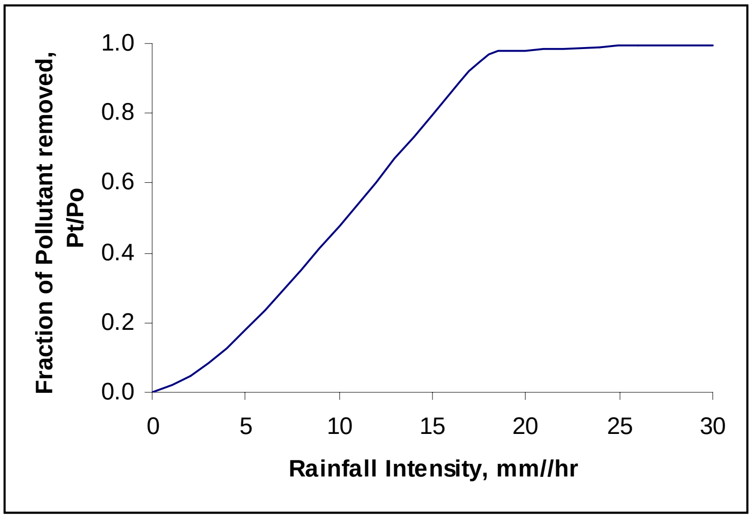

Figure 5-2: Rainfall intensity effect on pollutant removal (P_o = 30 g/m-curb, t =1 hr, and k_u = 0.19)

Maintenance Objectives

The main objectives in maintenance scheduling are economic or cost performance based, represented either as net benefits or minimized cost for maintaining some level of receiving water quality or removal efficiency. Unscheduled maintenance activities also may be performed in response to safety, aesthetics concerns, or performance following severe storm events.

Effectiveness of Maintenance

Maintenance usually is assumed to completely restore the efficiency of a SWQ-MP. However, in some cases it may be impossible to restore a SWQ-MP to its original maximum efficiency. Limited access and SWQ-MP physical characteristics may limit debris and sediment removal, mowing, and repair. Incorrect use of maintenance equipment may result in less than complete recovery of SWQ-MP effectiveness. Street sweeping is a maintenance practice intended to remove suspended solids as a SWQ-MP; yet due to incorrect operation of the sweepers, only a small fraction of the debris and suspended solids actually are removed (based on conversation with LAPW- Stormwater Division personnel).

Scheduling Constraints

Scheduling may be limited to particular periods during the year due to restricting weather, service demands, or environmental constraints. Maintenance may not be feasible during rainy or winter seasons when SWQ-MPs are most needed to protect receiving waters. Protection of habitat and aquatic life (spawning season, migration season) also may restrict scheduling.

Maintenance Scheduling

Maintenance scheduling can be important both in the stormwater management planning stages and once SWQ-MPs are in operation. Considering maintenance scheduling as part of the planning process can help illuminate tradeoffs between capital cost and maintenance costs of facilities and long-term facility performance and financial demands. For example, deep detention basins may incur higher capital costs than shallow basins but may need less frequent maintenance, thereby reducing long-term costs. In selecting management practices with known removal efficiencies and degradation rates, it may be important to consider higher removal efficiencies as a safety measure given efficiency degradation and the maintenance costs associated with preserving design efficiencies. For existing facilities, developing maintenance schedules will help preserve desired SWQ-MP efficiency and receiving water quality.

Though periodic maintenance of SWQ-MPs can increase their effectiveness and environmental benefits, too frequent maintenance can lead to inefficient use of financial resources while sporadic maintenance can result in receiving water degradation. Presented here is a method to select the time period between maintenance events based on the cost and effectiveness of the SWQ-MP and the benefit realized from protecting a receiving water and its uses. Given a fixed installation cost (capital cost), the net benefit of a particular SWQ-MP can be estimated as the difference between the discounted accumulated annual benefits and the maintenance cost over period T, the length of time between maintenance events for a long operation and maintenance scheduling horizon. Annual benefits are assumed to be correlated with pollution concentration in the water; lower concentration levels have less effect on the receiving water's beneficial uses and increase annual benefits (Kalman et al., in press). The objective of maximizing the net benefit of a SWQ-MP can be obtained by selecting the optimal period, T^*, between maintenance events.

Several assumptions are made to simplify the analysis. It is assumed that the rate of efficiency degradation is constant (efficiency degrades exponentially with time); maintaining a facility incurs a fixed cost at the time of maintenance regardless of the period between maintenance events; maintenance is not constrained by time of year and provides complete recovery of removal efficiencies; and pollutant loading is constant each year making this formulation deterministic.

The effect of receiving water residence time on facility maintenance scheduling is considered as well, since residence time affects pollution accumulation in the receiving water. Receiving waters with less residence time will accumulate less pollution but are more responsive to transient pollution episodes. With very long residence times, pollutants accumulated in receiving waters may need to be removed, flushed, or treated periodically to preserve long-term water quality irrespective of SWQ-MP maintenance.

Formulation

The following sections describe the variables affecting maintenance scheduling and how they are incorporated into the net benefit optimization formulation. The cost of maintenance is compared to its benefits over indefinitely long periods of time where benefits depend on the receiving water value and the relationship between beneficial uses and water quality. The complete derivation of the formulation is provided in Appendix 3.

Removal Efficiency

As previously discussed, removal efficiencies of SWQ-MPs degrade over time at a rate that depends on the nature of pollutants removed and storm characteristics. A schematic representation of the change in removal efficiency over time, assuming exponential degradation, is shown in Figure 5-3. Periodic maintenance (every T years) is assumed to restore the removal efficiency to its original capacity (E^o).

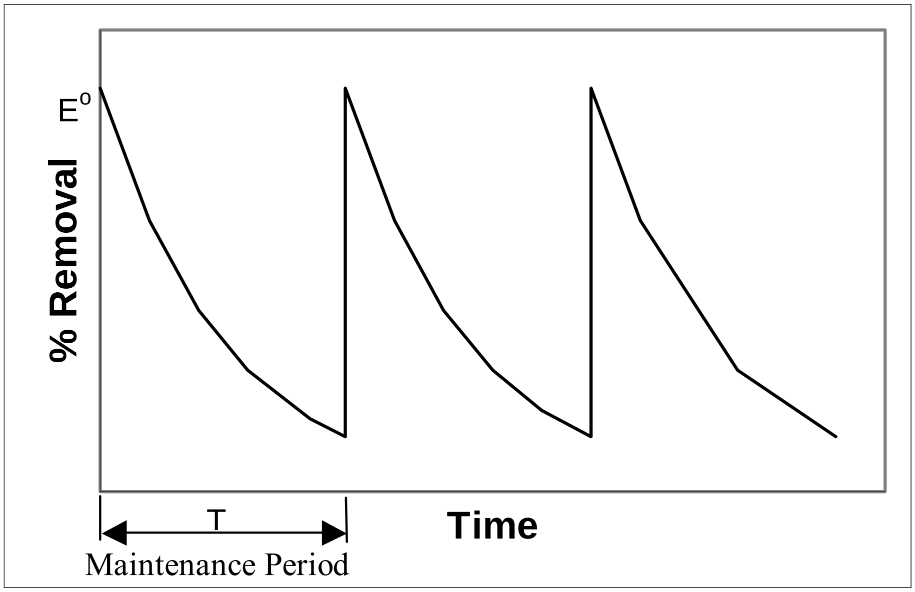

Figure 5-3: Degradation or SWQ-MP removal efficiency over time with periodic maintenance

This simplified representation of removal efficiency degradation can be expressed in terms of maximum efficiency and degradation rate due to accumulation of pollutants in a SWQ-MP as represented by equation (5-3).

$$E(t) = E^{o} e^{-kt} \qquad (5\text{-}3)$$

where:

$E(t)$ = Pollutant removal efficiency, a function of time, fraction

E^{o} = Maximum initial removal efficiency, fraction

k = Rate of efficiency degradation, 1/t

Since in many cases degradation is due to accumulation of sediments and pollutants, SWQ-MPs with high removal efficiency will potentially degrade faster than SWQ-MPs with low removal efficiency. For example, a residence basin that removes 50% of the runoff sediments will fill up twice as fast as a residence basin with 25% removal efficiency given equal capacities.

Management Benefits

The benefit gained from installing and maintaining a SWQ-MP depends on the value of the receiving water (determined by its beneficial uses) and the pollutant concentration. Benefits are assumed to be directly correlated to receiving water quality as shown in Figure 5-4. In Figure 5-4, V_{rw} represents the highest receiving water value achievable with pristine water quality. C_{max} corresponds to the concentration threshold that represents loss of all receiving water benefits. As removal efficiency decreases, more pollutants will be discharged into the receiving water, thereby decreasing the quality and value of the receiving water. The decrease in benefit with time due to decreasing removal efficiency is shown in

Figure 5-5. At the end of each period T, there will be a cost (M) associated with maintaining the SWQ-MP and restoring the value of the receiving water.

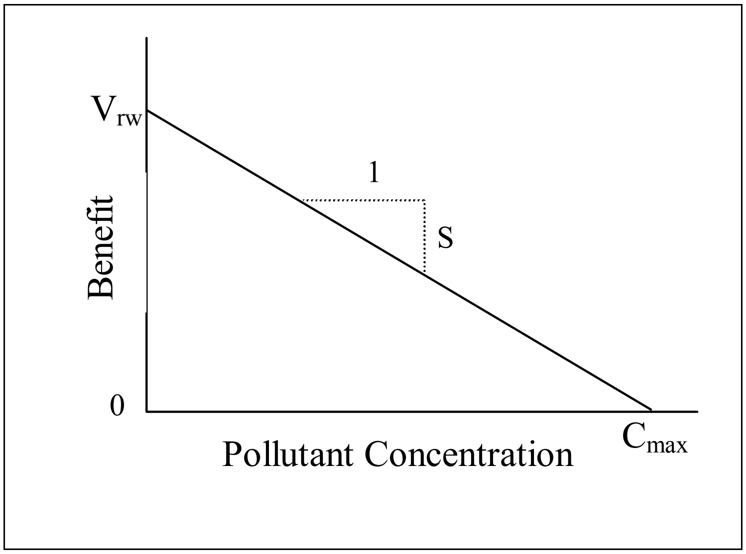

Figure 5-4: Relationship between benefits and receiving water pollutant concentration

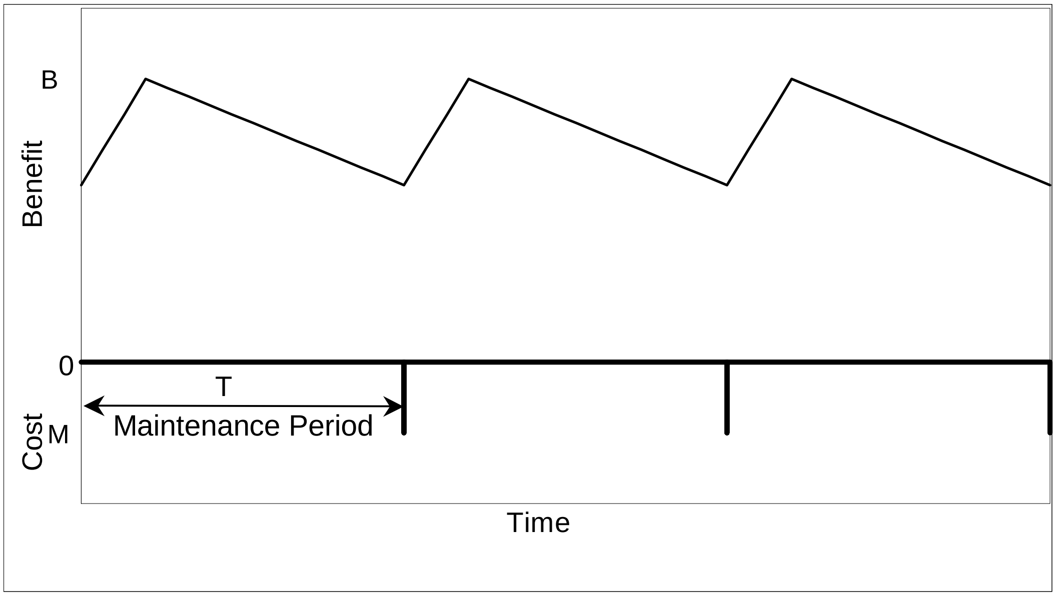

Figure 5-5: Benefits and costs of SWQ-MP

The benefits of SWQ-MP depend on the level of pollution in the receiving water and can be represented with equation (5-4):

$$BEN = S\Delta C(t) \tag{5-4}$$

Where:

BEN = total annual benefits of receiving water, \$/t

$S = -V_{rw}/C_{max}$

V_{rw}: Unimpaired value of the receiving water, \$/t

C_{max}: Pollutant concentration where no benefits are attained, μg/L

$\Delta C(t)=C(t)_{NoSWQ\text{-}MP}-C(t)_{w/SWQ\text{-}MP}$

Receiving Water Concentration

A simplified mass balance is used to describe pollutant concentration in receiving waters affected by one polluting source. For simplicity, pollutant exchange between the water and sediments is neglected though it is recognized that sediment loading can significantly affect pollutant accumulation and availability. The simplified mass balance equation for the receiving water is represented by equation (5-5).

$$C(t)V = C(t-\Delta t)V + C_{in}Q_{in}\Delta t - C_{out}Q_{out}\Delta t \pm (L_{sed}) \tag{5-5}$$

Where:

$C(t)$: Receiving water concentration at time t, μg/L

V: Volume of receiving water (assumed to be constant), L

C_{in}: Inflow concentration, μg/L

Q_{in}: Inflow, L/t

C_{out}: Outflow concentration, μg/L

Q_{out}: Outflow, L/t

L_{sed}: Sediment loading (neglected in analysis), μg

Assuming that inflow and outflow are the same, based on this mass balance the change in pollutant concentration in a receiving water over time can be represented by equation (5-6):

$$\frac{dC}{dt} = \frac{C_{in}(t)}{R_i} - \frac{C(t)}{R_o} \tag{5-6}$$

Where:

R_o: Residence time, Ratio of V/Q_{out}, t

R_i: Residence time, Ratio of V/Q_{in}, t

For receiving waters with equal inflow and outflow this relationship can be rewritten as: $\frac{dC}{dt} = \frac{C_{in}(t) - C(t)}{R}$.

Solving differential equation (5-6) yields an expression for C(t) as represented by equation (5-7) (Complete derivation appears in Appendix 3).

$$C(t) = C_{in}\left(\frac{R_o}{R_i}\right)\left(1 - \frac{E^o e^{-tk}}{1 - R_o k} - e^{-\frac{t}{R^o}} + \frac{E^o e^{-\frac{t}{R_o}}}{1 - R_o k}\right) + Pe^{-\frac{t}{R_o}} \tag{5-7}$$

Where:

k: Removal efficiency degradation rate, 1/t

E^o: Maximum removal efficiency rate, %/100

P: Initial receiving water concentration, μg/L

t: Time since last maintenance, t

The change in concentration due to SWQ-MP can be represented by equation (5-8).

$$\Delta C(t) = C_{in} \frac{R_o}{R_i} \left(\frac{E^o}{1 - R^o k} \right) \left(e^{-tk} - e^{-\frac{t}{R_o}} \right) \tag{5-8}$$

Management Practice Maintenance Cost

The cost of maintaining the SWQ-MP may vary with time depending on the amount of pollutant that has accumulated over time. The cost of maintenance may include mobilization of equipment, maintenance (such as mowing) time, and offsite disposal of material removed. Though maintenance costs might increase as the period between maintenance events increases, for simplification, the cost of a maintenance event, *M* is assumed to be constant and has a present value represented by Equation (5-9).

$$\text{Maintenance} = Me^{-rT}\text{, \$} \tag{5-9}$$

Present Value of Net Benefit

The present value net benefit of maintenance every T years over a long scheduling horizon, *NT*, where *N* is the number of maintenance events, is represented by equation (5-10).

$$PVNB(T) = \sum_{n=0}^{N} NB(T) e^{-rTn} \tag{5-10}$$

For an infinite scheduling horizon ($NT = \infty$), this summation converges as represented by equation (5-11) (Theusen and Fabrycky, 1984).

$$PVNB(T) = \frac{NB(T)}{1 - e^{-rT}} \tag{5-11}$$

The present value of net benefits can be calculated as the accumulated benefits realized from the SWQ-MP between maintenance events less the cost of maintaining the SWQ-MP at the end of the period. The present value of net benefit is represented by equation (5-12):

$$PVNB = \frac{\int_{t=0}^{T} S\Delta C(t) e^{-rt}\, dt - Me^{-rT}}{(1 - e^{-rT})} \tag{5-12}$$

where:

r: Discount rate, 1/t

M: Maintenance cost, $

T: Maintenance period, t

The relationship between the present value net benefit and the period between maintenance is shown in Figure 5-6.

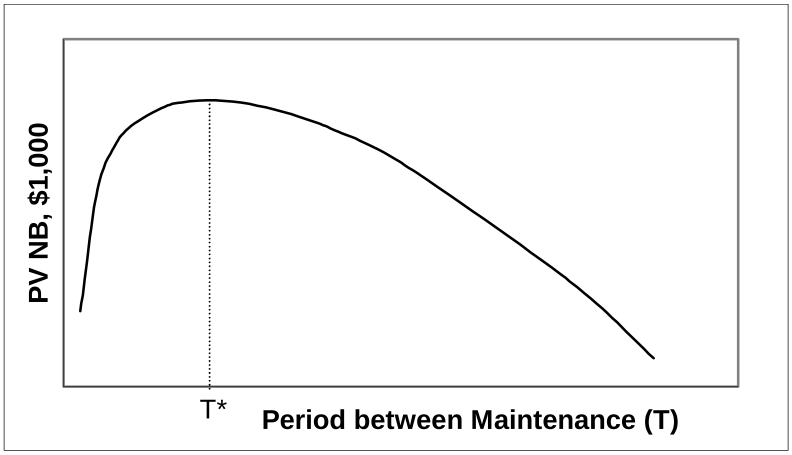

Figure 5-6: The relationship between PVNB and T, the maintenance period

Substituting equation (5-8) into equation (5-12) and completing the integration yields the PVNB relationship in equation (5-13):

$$PVNB = \frac{B\left(\frac{-e^{-T(k+r)}}{k+r} + \frac{1}{k+r} + \frac{e^{-T(\frac{1}{R_o}+r)}}{\frac{1}{R_o}+r} - \frac{1}{\frac{1}{R_o}+r}\right) - Me^{-rT}}{(1-e^{-rT})} \tag{5-13}$$

$$B = SC_{in}\left(\frac{R_o}{R_i}\right)\left(\frac{E^o}{1-R_o k}\right) \tag{5-14}$$

By calculus, the first order condition for maximizing the present value of net benefit yields equation (5-15). This relationship assumes that inflow and outflow are nearly equal.

$$\frac{B_{\max}}{rM} = \frac{\left(1 - R_o k\right)}{\left(\frac{rR_o}{1 + rR_o}\right)\left(e^{-T^*\left(\frac{1}{R_o}+r\right)} - 1\right) - \left(\frac{r}{k + r}\right)\left(e^{-T^*(k+r)} - 1\right) + \left(e^{-\frac{T^*}{R_o}} + e^{-T^* k}\right)\left(1 + e^{-T^* r}\right)} \tag{5-15}$$

Where

$B_{\max} = SC_{in}E^{o}$, Maximum benefit of SWQ-MP

This relationship can be rewritten with four dimensionless variables representing (a) the ratio of maximum annual benefits to annualized maintenance cost (economic ratio, β), (b) maintenance period (τ), (c) degradation rate (κ), and (d) residence time (ρ). The dimensionless form of equation (5-15) is represented by equation (5-16).

$$\beta = \frac{\left(1 - \kappa\rho\right)}{\left(\frac{\rho}{1 - \rho}\right)\left(e^{-\tau^*\left(\frac{1}{\rho}+1\right)} - 1\right) - \left(\frac{1}{\kappa + 1}\right)\left(e^{-\tau^*(\kappa+1)} - 1\right) + \left(e^{-\frac{\tau^*}{\rho}} - e^{-\tau^* \kappa}\right)\left(1 - e^{-\tau^*}\right)} \tag{5-16}$$

Where:

$\beta = B_{max}/rM$, dimensionless economic ratio

$\tau^* = rT$, dimensionless optimal maintenance period

$\kappa = k/r$, dimensionless degradation rate

$\rho = rR_o$, dimensionless residence time

Results

Maintenance Schedule for Existing Facilities

Using the dimensionless representation of the relationship between economic ratio, maintenance period, degradation rate, and residence time, several conclusions can be made about scheduling maintenance efficiently for existing facilities.

Economic Ratio (β)

As shown in Figure 5-7, maintenance period of SWQ-MP depends on the receiving water’s Economic ratio, the ratio of its annual maximum benefit to the annualized cost of a maintenance event. As the ratio increases, representing either higher receiving water values or lower maintenance cost, the frequency of maintenance increases as well (τ^* becomes smaller). Also, the faster the SWQ-MP degrades, the more frequently maintenance should be performed to protect receiving water values. As can be seen from Figure 5-7 and Figure 5-8, a minimum ratio is required to make the SWQ-MP economically efficient. This is particularly important in developing SWQ-MP plans since these results suggest that for receiving waters with low value or management practices with high maintenance costs, it may not be economically efficient to install SWQ-MP. The minimum economic ratio required also depends on the receiving water hydrology represented as residence time. The higher the receiving water’s residence time, representing higher pollutant accumulation, the higher the economic ratio must be to warrant SWQ-MP installation.

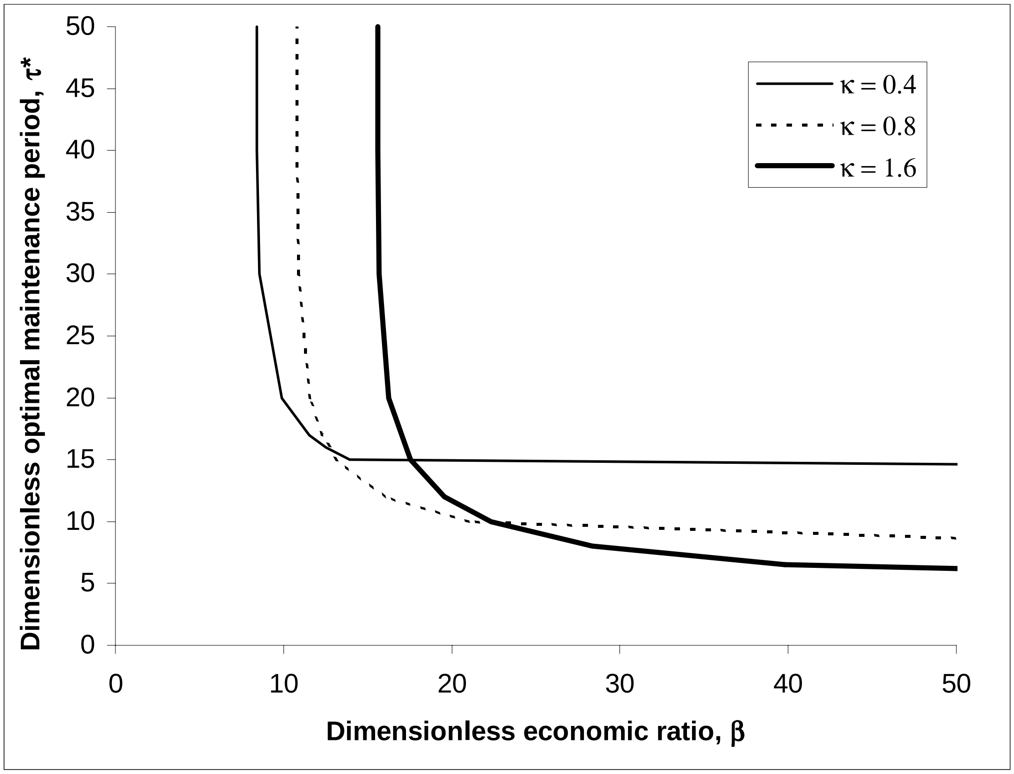

Figure 5-7:Maintenance scheduling based on Economic ratio (ρ=5)

For example, given SWQ-MP with degradation rate of 3.2 percent per year and assuming a high economic ratio and 4 % real interest rate, the optimal maintenance period is approximately 1 yr and 5 months. The optimal maintenance period can be calculated from Figure 5-7 where $\kappa = 0.032/0.04 = 0.8$ yields approximately $\tau^* = 11$ for high economic ratios. From τ^*, the optimal maintenance period can be calculated as $\tau/r = 11/0.04 = 275$ days or approximately 9 months. Figure 5-8 can be used to estimate the minimum economic ratio needed to establish efficient maintenance schedule for different receiving water conditions. For example, the maintenance of SWQ-MP with degradation rate of 3.2 %/yr ($\kappa = 0.8$ for 4 % interest rate) and constant maintenance cost installed for protecting a receiving water with residence time of 125 days ($\rho = 5$) will be economically efficient only if the economic ratio is higher than 10.8 whereas if the same SWQ-MP were to be applied to a receiving water with residence time twice as long (250 days or ρ = 10), the economic ratio needed for economically efficient maintenance is 19.8.

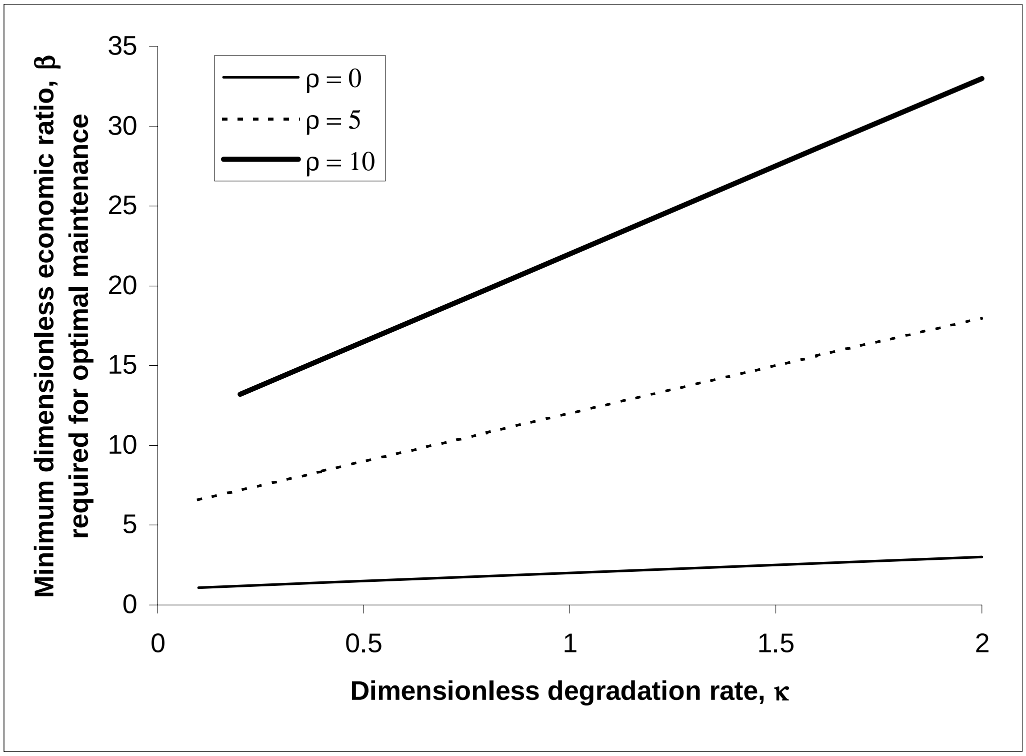

Figure 5-8: Minimum economic ratio required for maintenance for varying degradation rates

Residence Time

Similar SWQ-MPs applied to different receiving waters with varying residence times will merit different maintenance schedules as shown in Figure 5-9. Receiving waters with long residence time are less affected by incoming pollutant sources and therefore frequent SWQ-MP maintenance is not critical to maintain a specified economic ratio. For receiving waters with very long residence time, where pollutants accumulate in the water and sediment, it may not be economically efficient to maintain and therefore install

SWQ-MP. For example, for a receiving water with residence time of 250 days ($\rho = 10$ based on interest rate of 4 %/yr) and specified beneficial value, maintenance period will increase from 385 days to 530 days ($\tau^* = 15.4$ to 21.2) as the economic ratio, β decreases due to increasing maintenance cost from 50 to 30.

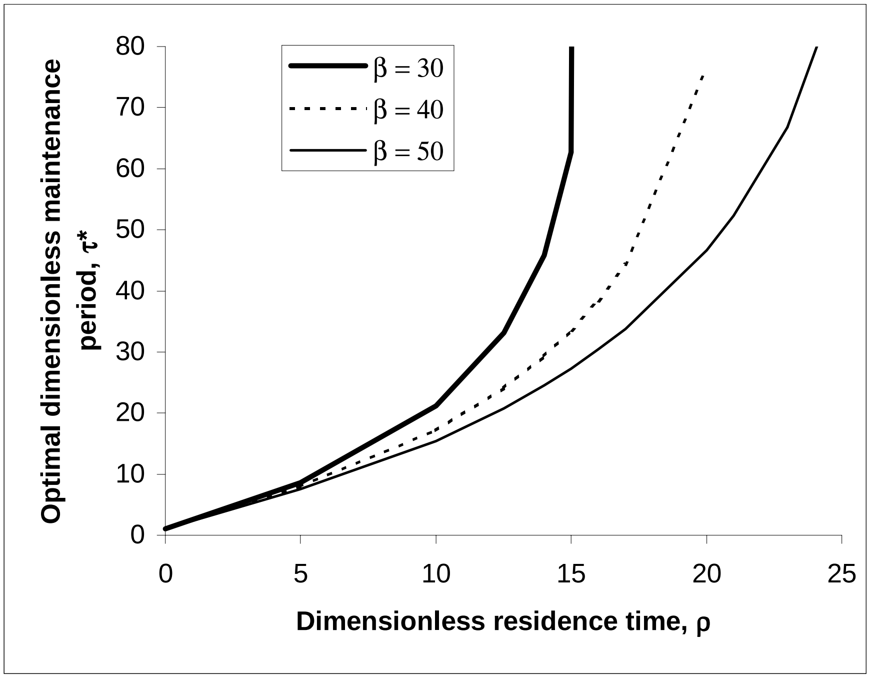

Figure 5-9: The effect of residence time on maintenance schedule, $\kappa = 0.8$

Degradation Rate

SWQ-MP's degradation rate affects the maintenance schedule as shown in Figure 5-10, particularly for receiving waters with low economic ratios. A high degradation rate reduces the receiving water value and SWQ-MP benefits thereby making SWQ-MP maintenance and ultimately installation less optimal. Therefore, the higher the degradation rate the less likely maintenance will be economically efficient, and less frequently maintenance will be scheduled. For receiving waters with a high economic ratio, low degradation rate represents very slow decrease in receiving water value and therefore maintenance may not be needed frequently to protect receiving water benefits.

For example, a SWQ-MP with a fixed degradation rate of 3.2 %/yr ($\kappa = 0.8$ with a 4 %/yr interest rate) and fixed maintenance cost will be maintained every fourteen months ($\tau^* = 17.23$) if installed at a receiving water with high beneficial value (high economic ratio of 40), but only every 3 years and 10 months ($\tau^* = 56.45$) if applied to a receiving water with low beneficial value (low economic ratio of 20).

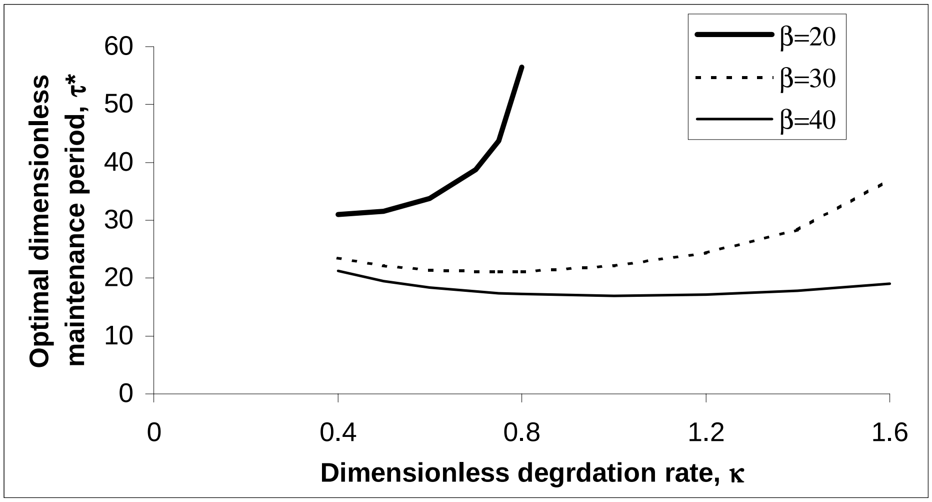

Figure 5-10: The effect of degradation rate on maintenance schedule, ρ= 10

Receiving Waters with Insignificant Residence Time

Receiving waters with insignificant residence time (such as streams) may not accumulate significant amounts of sediments and pollution due to flushing and the hydrologic nature of the receiving waters. As residence time approaches zero, equation (5-15) for the optimal maintenance period becomes equation (5-17).

$$\frac{B_{\max}}{rM} = \frac{-1}{\left(\frac{r}{k+r}\right)\left(e^{-T^*(k+r)}-1\right)+e^{-T^*k}\left(1+e^{-T^*r}\right)} \tag{5-17}$$

Equation (5-17) can be rewritten in dimensionless form with three variables: economic ratio, maintenance period, and degradation rate as shown with equation (5-18).

$$\beta = \frac{-1}{\left(\frac{1}{\kappa+1}\right)\left(e^{-\tau^*(\kappa+1)}-1\right)+e^{-\tau^*\kappa}\left(1+e^{-\tau^*}\right)} \tag{5-18}$$

With negligible residence time, optimal maintenance of SWQ-MP to protect receiving waters is most affected by the SWQ-MP removal efficiency and its degradation rate. For SWQ-MP with degradation rate, k, maintenance will become less frequent with decreasing economic ratios, until a minimum economic ratio is reached where maintenance is not economically efficient. Increases in degradation rate, k for SWQ-MPs represents faster loss of receiving water value and decrease in economic ratio and therefore leads to scheduling of maintenance at decreasing rates.

Integration of Maintenance Schedule into the Stormwater Planning Process

The maintenance schedule model can be used to develop a tradeoff relationship between SWQ-MP capital expenditures and long-term maintenance cost and aid in selecting the most economically efficient facilities during the planning phase. Assuming that SWQ-MP efficiency is correlated to capital cost, higher removal efficiencies will have higher annualized capital costs as shown in Figure 5-11.

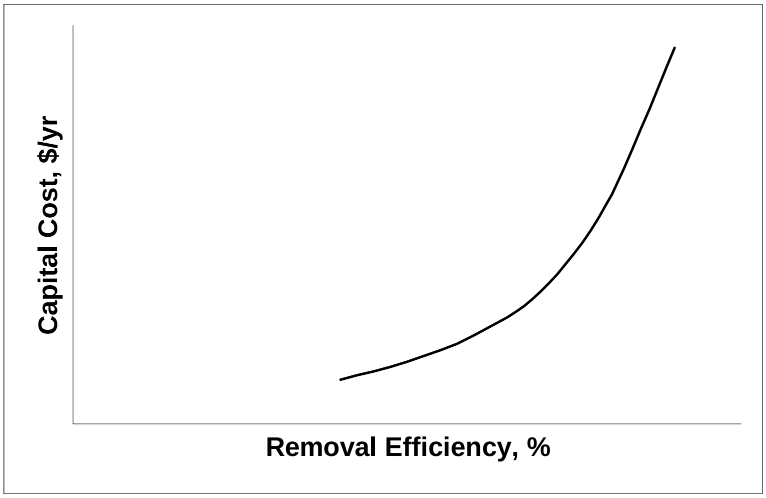

Figure 5-11: Relationship between removal efficiency and capital cost of SWQ-MPs

The model can be used to estimate the economically efficient total annualized cost (capital cost and maintenance cost) and help determine the appropriate level of total funding that should be allocated to stormwater management. The net present value net benefit can be calculated as the difference between the annualized benefits of implementing and maintaining SWQ-MPs (as previously calculated) and the annualized capital cost as represented by equation (5-19).

$$NPVNB = \frac{NB(T, E^o)}{1 - e^{-rt}} - C(E^o) \qquad (5\text{-}19)$$

where

$NB(T,E^o) =$ Net benefit of SWQ-MP given maintenance period, T and maximum removal efficiency, E^o.

$C(E^o) =$ Cost of SWQ-MP with maximum removal efficiency, E^o.

Equation (5-19) can be optimized by calculus by obtaining first order partial differential equations (5-20) and (5-21) with respect to two variables: maintenance period, T and maximum removal efficiency, E^o.

$$\frac{\partial NPVNB}{\partial E^o} = 0 \tag{5-20}$$

$$\frac{\partial NPVNB}{\partial T} = 0 \tag{5-21}$$

The tradeoff between annualized costs, annualized benefits, and removal efficiencies of SWQ-MPs can be evaluated for a receiving water with specified initial concentration and maximum beneficial value as shown in Figure 5-12. For calculations represented in Figure 5-12, receiving water initial concentration is assumed to be 200 μg/L, maximum value of receiving water is $5,000/yr, and maximum level of pollution is 400 μg/L. As shown in Figure 5-12, for the scenario presented, net benefit is positive for SWQ-MPs with removal efficiencies greater than approximately 75%, corresponding to the lowest total annualized costs. The maximum net benefit is observed with SWQ-MP with 80% removal efficiency. As can be observed with this example, consideration of capital costs alone is inadequate for SWQ-MPs selection and results in underestimating the true cost of SWQ-MPs. All costs and the benefits must be considered to ensure an economically efficient SWQ-MPs selection.

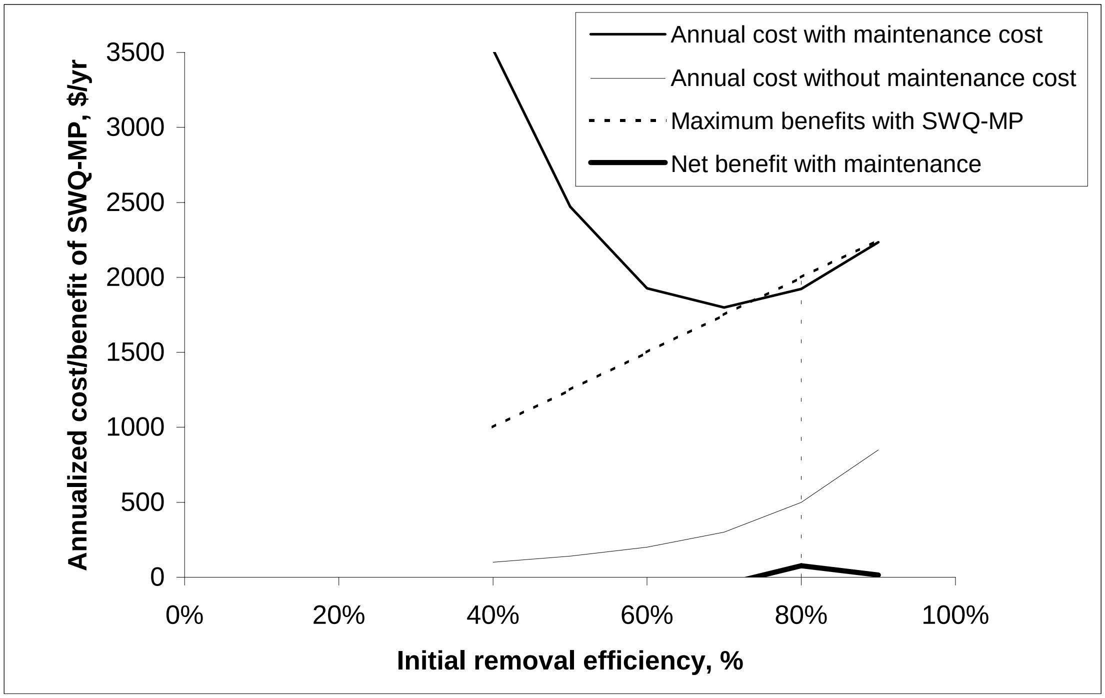

Figure 5-12: Total cost of SWQ-MP for varying levels of SWQ-MP removal efficiencies

Conclusions

The economic aspects of maintaining SWQ-MP to protect receiving water quality, a function of maintenance cost, receiving water maximum value, maximum SWQ-MP removal efficiency, and maximum concentration of pollutant in incoming source, are important in scheduling SWQ-MP maintenance. Yet, the most important considerations in developing maintenance schedules are the rate at which SWQ-MP efficiency degrades over time and the hydrologic residence time of the receiving waters. Table 5-2 provides a summary of the effect of the variables considered in this analysis on scheduling SWQ-MP maintenance.

Table 5-2: Maintenance scheduling considerations

Characteristics	Optimal maintenance period, T^*
Cost of Maintenance	Directly correlated
Removal efficiency	Inversely correlated
Efficiency degradation rate	High k - inversely correlated, Low k - directly correlated
Level of incoming pollution	Directly correlated
Value of receiving water	Directly correlated
Residence time	Directly correlated

These findings suggest that more information and monitoring may be important to understanding how efficiency decreases with time and use, and ultimately, how maintenance should be scheduled optimally. When evaluating stormwater management options, in addition to the traditional evaluation of SWQ-MP based on maximum removal efficiency, evaluation should include consideration of the efficiency degradation and resultant maintenance costs. Since receiving water hydrology appears to play a major role in developing an optimal maintenance schedule, careful study of the water hydrology is needed to understand the effect of implementing both SWQ-MP and maintenance.

It is important to consider SWQ-MP scheduling as part of the selection and management of SWQ-MP in a watershed. In cases where selected SWQ-MPs degrade too fast or maintenance is too costly, it may be prudent to select other SWQ-MPs that over the long term will better protect receiving water quality. For receiving waters with low value it may not be cost efficient to apply SWQ-MPs and resources may be better used to protect receiving waters with higher values.

Future Research

Maintenance scheduling can be critical for efficient stormwater quality management and can benefit from further research to better understand and represent the receiving water pollution mechanism by incorporating pollutant transfer between the water and the underlying sediments. In addition, the representation of the economic ratio can benefit from better representation of maintenance costs and benefits. Maintenance costs can be better accounted for by introducing cost variability with respect to time between scheduled maintenance events. Benefit representation can be improved by developing better relationships between the pollutants and their effects on receiving waters' beneficial uses.

6 CONCLUSIONS

"Life is the art of drawing sufficient conclusions from insufficient premises."
Samuel Butler (1612-80) English poet, author

Though stormwater runoff abatement has been extensively researched and developed for flood protection and flow attenuation, attention to runoff water quality issues has lagged. Since the 1970s, runoff quality models such as STORM and SWMM have been developed to aid in identifying pollutants and estimating levels of pollution generated by stormwater runoff. Much of the available research deals with agricultural and rural environments. Available research on stormwater runoff quality management in urban areas is generally limited to attempts in identifying and quantifying relevant pollutants and developing design guidelines for specific structural management alternatives. In this dissertation, an attempt was made to use existing research on pollutant accumulation and distribution in urban settings and assess existing evaluation methods for stormwater quality management to protect and enhance water quality in receiving waters that are affected by urban runoff.

Based on the research presented in this dissertation, several general observations and conclusions can be made about the development process for stormwater quality management programs in terms of evaluation methods used for planning, modeling efforts, and the importance of the watershed, receiving waters, and SWQ-MP characteristics.

Evaluation Methods for Stormwater Quality Management Planning

Four types of evaluation methods were reviewed and compared: physical-chemical standards, biological processes, ecological, and economics. The data and knowledge gained with each type of evaluation method creates interdependence between the four different methods. The economic analysis depends on the appropriate chemical-physical, biological, and ecological representations of the receiving water. The ecological evaluation depends on correctly describing chemical and physical properties of the receiving water and the interaction between these properties and the biota in the receiving waters. Therefore, in considering the level of evaluation used for stormwater quality management, planners should consider data requirements and availability, monitoring, and level of detail in watershed and receiving water representation and weigh them against the potential improvements in water quality, water quality benefits, and beneficial uses with SWQ-MPs. Based on the review of evaluation methods, the following general conclusions are offered:

- Evaluation by chemical-physical standards is best used when the primary goal of stormwater quality management is meeting regulatory requirements. Yet, this evaluation will ensure protection of receiving water quality and beneficial uses only if standards are set using more demanding and difficult biological and ecological evaluations.

- The biological and ecological evaluations are best used to address specific water quality problems such as eutrophication, toxicity, or specific species' population protection. Assuming sufficient data are available, these two evaluation methods would help develop management plans that provide adequate protection of receiving water beneficial uses.

- The economic evaluation is best used to identify appropriate allocation of limited resources to address the most critical receiving water quality issues regionally rather than address specific receiving water quality issues.

- Regardless of the evaluation method used, appropriate selection of SWQ-MPs and their distribution in the watershed largely depends on the availability of data and ability to monitor the performance of management practices and water quality once management is implemented.

Stormwater Quality Management Model Development

Genetic algorithms were explored to optimize watershed water quality management. Genetic algorithms are particularly appropriate since the mathematical representations of the watershed and the receiving water pollutant concentration are non-linear due to the nature of the relationship between pollutant sources, receiving water quality, and effect of management on water quality. In addition, genetic algorithms are well suited for problems with large solution spaces.

Numerous operators for selection and regeneration have been well documented at varying degrees of reliability for the development of genetic algorithms based optimization models. For large problems, it is important to tailor the genetic algorithm to the problem and not assume generic forms of GA. Moreover, the selected population size was found to be the most critical aspect in ensuring reliable model results. In selecting a population size the tradeoff between obtaining reliable results and the number of calculations (which increases substantially with population size) must be taken into consideration. Limiting population size leads to insufficient breadth and possibly results in local optima.

GA optimization was found to be very useful in its application to watershed management. The main strength of GA based optimization is the ease in which the model can be modified to address different evaluation methods and expanded to improve the representation of the watershed and pollution in the receiving water. The model can easily be modified to include a more detailed simulation of pollution generation in the watershed, mixing in the receiving waters, and chemical and biological processes such as eutrophication.

Monte Carlo simulation is introduced in the model to evaluate the importance of variability in selecting SWQ-MPs. The number of Monte Carlo realizations can greatly affect management results. Increased number of realizations will improve model reliability at a high calculation cost. It is therefore important to estimate the number of Monte Carlo realizations necessary for reliable model results.

Comparison of Evaluation Methods

Since data requirements are the most important consideration in the evaluation of stormwater quality management, it is critical to understand how the watershed representation, receiving water quality, and SWQ-MPs efficiency affect the selection process. Based on the modeling results, some conclusions can be made for the example watershed examined. It should be noted that these results are specific to the example presented and are based on simplified representation of pollution transport and mixing and therefore should be considered with caution.

- Based on SWMM representation of relative contribution of pollution from four zoning types (industrial, commercial, residential, and other (landscaped)), industrial and commercial zones contribute the most pollution per unit area to the receiving water. Therefore, stormwater quality management is particularly important in these critical areas.

- Precipitation is the main watershed characteristic to affect pollutant concentration. The more precipitation a watershed exhibits the less nutrient concentration will be discharged into the receiving water, most likely due to dilution effects. Areas with high precipitation levels will probably require less mitigation than areas with low precipitation. This can be applied to evaluating management needs at different seasons of the year where precipitation levels vary greatly.

- The water quality limit assigned to receiving water has great effect on the choice of management options. Stringent limits require the implementation of additional SWQ-MPs. It is therefore important to consider the processes and the aquatic life to be protected to ensure that the water quality limit selected represents correctly the desired protection of beneficial uses of the receiving water.

- Variability in precipitation and SWQ-MP removal efficiency uncertainties are important considerations in developing stormwater quality management plans particularly when striving to meet stringent water quality standards. It is therefore important to obtain precipitation data and evaluate SWQ-MPs judiciously to avoid the implementation of SWQ-MPs that are insensitive to these variabilities.

Importance of Maintenance

Generally, stormwater quality management plans do not address monitoring and maintenance issues. Maintenance is performed in response to reported SWQ-MPs malfunction or health hazards. Since SWQ-MPs degrade over time, it is important to consider maintenance as part of the management plan to ensure that receiving water quality is protected adequately. Maintenance scheduling should ideally be part of the planning process to ensure that high maintenance SWQ-MPs are avoided, more economically efficient stormwater management programs are developed, and that receiving water quality meets the planning expectations.

- The most important considerations in developing maintenance schedules are the rate at which SWQ-MP efficiency degrades over time and the hydrology of the receiving waters (represented by its residence time). Therefore, it may be important to spend some resources on understanding the effectiveness of SWQ-MPs and improve understanding of the receiving water hydrology and mixing patterns.

- Since some receiving waters may not have sufficiently high benefits to warrant maintenance, it may not be cost effective to develop management practices to protect receiving water for a short duration. Instead, limited resources should be used to protect and enhance receiving waters with highly valued beneficial uses.

REFERENCES

1. Abbott, M.B., Bathurst, J.C., Cunge, J.A, O'Connell, P.E. & Rasmussen, J. (1986). "An Introduction to the European Hydrological System. Systeme Hydrologique Europeen, "SHE", 1: History and Philosophy of a physically based, distributed modeling system." *Journal of Hydrology,* 87, pp. 45-59

2. Adams, William J., R.A. Kimerle, J.W. Jr. Barnett (1992). "Sediment Quality and Aquatic Life Assessment." *Environmental Science and Technology,* 26(10) pp. 1864-1876.

3. Alley, W.M., Dawdy, D.R., and J.C. Schaake, Jr (1980). "Parametric Deterministic Urban Watershed Model" *Journal of Hyd. Division of ASCE,* 106 pp. 679-690.

4. Angermeier, Paul L. and J.R. Karr (1994). "Biological Integrity versus Biological Diversity as Policy Directives: Protecting Biotic Resources." *BioScience*, 44(10) pp. 690-697.

5. Back, Thomas and F. Hoffmeister (1991). "Extended Selection Mechanisms in Genetic Algorithms". In *Proceedings of the Fourth International Conference on Genetic Algorithms*. R.K. Belew and L.B.Booker (Ed.) pp. 92-99.

6. Bagachi, S, S. Uckun, Y. Miyabe, and K. Kawamura (1991). "Exploring Problem-Specific Recombination Operators for Job Shop Scheduling." In *Proceedings of the Fourth International Conference on Genetic Algorithms*. R.K. Belew and L.B.Booker (Ed) pp 10-17.

7. Balch, G.C. and R.D. Evans (1999). "A Recirculating Flow-through System for Toxicity Testing with Stream-dwelling Aquatic Benthic Invertebrates." *Aquatic Toxicology,* 45(4) pp. 241-251.

8. Barbier, Edward B, Joanne C Burgess, and Carl Folke (1994), *Paradise Lost? The Ecological Economics of Biodiversity.* Earthscan Publication Ltd., London.

9. Baron, David S. (1995). "Water Quality Standards for Rivers and lakes: Emerging Issues." *Arizona State Law Journal,* 27(2) pp. 559-596.

10. Bartlett, Geoff (1995). "Genie: A First G.A." In *Practical Handbook of Genetic Algorithms. Applications Volume I.* Lance Chambers (Ed.) pp 31-56.

11. Behera, Pradeep Kumar, F. Papa, and B.J. Adams (1999). "Optimization of Regional Storm-Water Management Systems." *Journal of Water Resources Planning and Management*, 125(2) pp. 107-

12. Blickle, Tobias and Lothar Thiele (1995). "A Mathematical Analysis of Tournament Selection." In *Proceedings of the Sixth International Conference on Genetic Algorithms*. L.J. Eshelman (Ed.) pp. 9-16.

13. Bramlette, Mark F (1991). "Initialization, Mutation, and Selection Methods in Genetic Algorithms for Function Optimization." In *Proceedings of the Fourth International Conference on Genetic Algorithms*. R.K. Belew and L.B.Booker (Ed.) pp. 100-107.

14. Brown, S.A., S.M. Stein, and J.C. Warner (1996). *Urban Drainage Design Manual. Hydraulic Engineering Circular No. 22*. Publication no. FHWA-SA-96-078.

15. Cavicchio, D.J. (1970). *Adaptive Search using Simulated Evolution*, (Doctoral dissertation, University of Michigan).

16. Chang, Ni-Bin, C.B. Wen, and S.L. Wu (1995). "Optimal Management of Environmental and Land Resources in a Reservoir Watershed by Multiobjective Programming." *Journal of Environmental management*, 44 pp. 145-161.

17. Chao-Hsien, Yeh and J.W. Labadie (1997). "Multiobjective watershed-level planning of storm water detention systems." *Journal of water resources planning and management*, 123(6) pp. 336-343.

18. Chen, Carl W., J. Herr, L. Ziemelis, R.A. Goldstein, and L. Lomsted (1999). "Decision Support System for Total Maximum Daily Load." *Journal of Environmental Engineering,* 125(7) pp. 653-659.

19. CRWQCB (1995), *Water Quality Control Plan, San Francisco Bay Basin*. http://www.swrcb.ca.gov/~RWQCB2

20. Davis, Lawrence (1991a). "What is a Genetic Algorithm?" In *The Handbook of Genetic Algorithms*. L. Davis (Ed.) pp. 1-22. Van Nostrand Reinhold, New York .

21. Davis, Lawrence (1991b). "Parameterizing a Genetic Algorithm." In *The Handbook of Genetic Algorithms*. L. Davis (Ed.) pp. 91-97. Van Nostrand Reinhold, New York.

22. De Ceballos, B.S.O., A. Konig, and J.F. De Oliveira (1998). "Dam Reservoir Eutrophication: A Simplified Technique for a Fast Diagnosis of Environmental Degradation." *Water Research,* 32(11) pp. 3477-3483.

23. De Jong, K.A. (1975). *An Analysis of the Behavior of a Class of Genetic Adaptive Systems.*

24. Dekker, Rommert and Philip A. Scarf (1998). "On the Impact of Optimization Models in Maintenance Decision Making: the State of the Art." *Reliability Engineering and System Safety,* 60(2) pp. 111-119.

25. DEQ (The Division of Environmental Quality), Twin Falls Regional Office, Idaho (1997). The Middle Snake River Watershed Management Plan: Phase 1 TMDL, Total Phosphorus. http://www.magiclink.com/WEB/TMDL

26. Dorn, Jason, S. Ranjithan, S. Liehr, and R.C. Borden (1995). "A Genetic Algorithm Approach to Water Supply Watershed Management." In *Computing in Civil Engineering 2* pp 971-978. ASCE, New York, NY.

27. Eshelman, Larry J. and J.D. Schaffer (1993). "Crossover's Niche." In *Proceedings of the Fifth International Conference on Genetic Algorithms*. S. Forrest (Ed.) pp. 9-14.

28. Everett, (1995). In *Practical Handbook of GA Applications, Volume I.* L. Chambers (Ed.) pp. 16-.

29. Falkenauer, Emanuel (1998). *Genetic Algorithms and Grouping Problems*. John Wiley and Sons, NY NY. Pp 220.

30. Feldman, A.D. (1995). "HEC-1 Flood Hydrograph Package." In *Computer Models of Watershed Hydrology*. V.P. Singh (Ed.). Water Resources publications, Highlands Ranch

31. Fore, Leska S., J.R. Karr, and L.L. Conquest (1994). "Statistical Properties of an Index of Biological Integrity Used to Evaluate Water Resources." *Canada Journal of Fish Aquatic Science,* 51 pp. 1077-1087.

32. Goldberg, David E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley Publishing Company, Inc. Reading, Massachusetts.

33. Goldberg, David E. and K. Deb (1991). "A Comparative Analysis of Selection Schemes Used in Genetic Algorithms." In *Foundations of Genetic Algorithms*. Bruce M. Spatz (Ed.) pp. 69-93. Morgan Kaufmann Publishers, Inc, San Mateo, CA.

34. Goldberg, David E., D. Kalyanmoy, and J.H. Clark (1993). "Accounting for Noise in the Sizing of Populations." In *Foundation of Genetic Algorithms 2*. L. Darrell Whitley (Ed.) pp 127-140. Morgan Kaufmann Publishers, Inc. San Mateo, CA.

35. Greene, R.G. and J.F. Cruise (1995). "Urban Watershed Modeling Using Geographic Information System." *Journal of Water Resources Planning and Management*, 121(4) pp. 318-325.

36. Hancock, Peter J.B. (1995). "Selection Methods for Evolutionary Algorithms." In *Practical Handbook of Genetic Algorithms. New Frontiers volume II.* Lance Chambers (Ed.) pp. 67-92. CRC Press, NY.

37. Hanley, Nick, Clive Spash, and Lorna Walker (1995), "Problems in Valuing the Benefits of Biodiversity Protection" *Environmental and Resource Economics*, 5 pp. 249-272.

38. Harig, Amy L. and M.B. Bain (1998). "Defining and Restoring Biological Integrity in Wilderness Lakes." *Ecological Applications,* 8(1) pp. 77-87.

39. Harik, Georges R. (1995). "Finding Multimodal Solutions Using Restricted Tournament Selection." In *Proceedings of the Sixth International Conference on Genetic Algorithms*. L.J. Eshelman (Ed.) pp 24-31.

40. Hession, W. Cully, D.E. Storm, C.T. Haan, K.H. Reckhow, and M.D. Smolen (1996). "Risk Analysis of Total Maximum Daily Loads in and Uncertain Environment Using EUTROMOD." *Journal of Lake and Reservoir Management,* 12(3) pp. 331-347.

41. Holland, John, H. (1992). *Adaptation in Natural and Artificial Systems*. MIT Press, Cambridge, MA.

42. Huber, W.C. and Dickinson, R.E. (1988). *Storm Water Management Model, Version 4: User's Manual*. Dept. of Enviro. Enginr. Sci., University of Florida, Gainesville, FL. EPA/600/3-88/001a. NTIS PB88-23664/AS.

43. Hydrologic Engineering Center (1975). *Urban Stormwater Runoff- STORM.* US Army Corps of Engineers, Davis, CA.

44. Jackson, Susan and W. Davis (1994). "Meeting the Goal of Biological Integrity in Water-Resource Programs in the US Environmental Protection Agency." *Journal of the North American Benthological Society,* 13(4) pp. 592-597.

45. Jorgensen, S.E. (1995). "State-of-the-Art Management Models for Lakes and Reservoirs." *Lakes and Reservoirs: Research and Management*, 1(2) pp. 79-88.

46. Kalman, Orit, J.R. Lund, D.K. Lew, and D.M. Larson (in press). "Benefit Cost Analysis of Stormwater Quality Improvements." *Environmental Management.*

47. Karr, James R. (1990). "Biological Integrity and the Goal of Environmental legislation: Lessons for Conservation Biology." *Conservation Biology*, 4(3) pp. 244-250.

48. Kobylinski, Edmund, A., G.L. Hunter, and E.A Quinlan (1993). "Implementing the New Water Quality Standards-Fitting the Puzzle Together." *Environmental Progress,* 12(3) pp. 169-174.

49. LeBlanc, Robert T., R.D. Brown, and J.E. FitzGibbon (1997). "Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams." *Journal of Environmental management*, 49 pp. 445-469.

50. Li, James, D. Weatherbe, D. Mack-Mumford, and M. D'Andrea (1997). "A Screening Tool for Stormwater Quality Management in Urbanized Areas: the City of Scarborough Case Study." *Water Quality Research Journal of Canada,* 32(1) pp. 37-52.

51. Li, J. Y. and D. Banting (1999). "A Stormwater Retrofit Plan for the Mimico Creek Watershed." *Water Science and Technology*, 39(12) pp. 133-140.

52. Lindsey, Ray, K., J.B. Franzini, D.L. Freyberg, and G. Tchobanoglous (1992). *Water Resources Engineering*. Fourth Edition. McGraw-Hill, Inc. New York. Pg. 203.

53. Lindsey, Greg, L. Roberts, and W. Page (1992), "Maintenance of Stormwater BMPS in Four Maryland Counties: A Status Report." *Journal of Soil and Water Conservation*, 47(5) pp. 417-422.

54. Lindsey, Greg, L. Roberts, and W. Page (1992), "Inspection and Maintenance of Infiltration Facilities." *Journal of Soil and Water Conservation*, 47(6) pp. 481-486.

55. Liu, Chunlu, A. Hammad, and Y. Itoh (1997). "Maintenance Strategy Optimization of Bridge Decks Using Genetic Algorithm." *Journal of Transportation Engineering*. 123(2), pp. 91-101.

56. Loughlin, Daniel H. and S.R. Ranjithan (1997). "Chance-Constrained Genetic Algorithms." In *Proceedings of the 7th International Conference on Genetic Algorithms*, Lansing, MI, 1997. pp. 369-376

57. Lund, Jay R. (1990). "Scheduling Maintenance Dredging on a Single Reach with Uncertainty." *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 116(2) pp. 211-231

58. Mahfoud, Samir W. (1995). "A Comparison of Parallel and Sequential Niching Methods." In *Proceedings of the Sixth International Conference on Genetic Algorithms*. L.J. Eshelman (Ed.) pp. 136-143. Morgan Kaufmann Publishers, Inc. San Francisco, CA.

59. Mapp HP, DJ Bernardo, GJ Sabbagh, S Geleata, and KB Watkins (1994). "Economic and Environmental Impacts of Limiting Nitrogen Use to Protect Water Quality- A Stochastic Analysis." *American Journal of Agricultural economics,* 76(4) pp. 889-903.

60. Mauney, David A. and Michael E.G. Schmidt (1997). "Fully Quantitative Predictive Maintenance/Inspection Planning Optimization for Chemical Process Plant Components." *Process Safety Progress,* 16(4) pp. 262-265.

61. McCarty, Lynn S. and D. MacKay (1993). "Enhancing Ecotoxicological Modeling and Assessment. (Critical Body Residue Method)." *Environmental Science and Technology,* 27(9) pp. 1719-1729.

62. Mitchell, Melanie (1998). *An Introduction to Genetic Algorithms*. A Bradford Book, The MIT Press Cambridge, Massachusetts.

63. Mumley, Thomas E. (1995). "Urban Runoff Pollution Prevention and Control Planning: San Francisco Bay Experiences." In *Seminar Publication. National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, county, and State Level*. March 30-April 2, 1993 Chicago, Illinois. EPA/625/R-95/003

64. National Research Council (1992). *Restoration of Aquatic Ecosystems*. National Academy Press, Washington, D.C.

65. Nesbitt, Dale M., G.A. Sparks, and R.D. Neudorf (1993). "A Semi-Markov Formulation of the Pavement Maintenance Optimization Problem." *Canadian Journal of Civil Engineering,* 20(3) pp. 436-477.

66. Newman, Peter J., S.C. Nixon, and Y.J. Rees (1994). "Surface Water Quality Monitoring, Classification, Biological Assessment and Standards." *Water Science and Technology,* 30(10) pp. 1-10.

67. Nix, Stephan J (1994). *Urban Stormwater Modeling and Simulation*. Lewis Publishers. Boca Raton, Florida.

68. Novotny, Vladimir and H. Olem (1994). *Water Quality. Prevention, Identification, and Management of Diffuse Pollution*. Van Nostrand Reinhold, New York. pp.1054.

69. Pickett, Paul J. (1997). "Pollutant Loading Capacity for the Black River, Chehalis River System, Washington." *Journal of the America Water Resources Association*, 33(2) pp. 465-480.

70. Polls, Irwin (1994). "How People in the Regulated Community View Biological Integrity." *Journal of the North American Benthological Society,* 13(4) pp. 598-604.

71. Porcella, Donald (1992). "Predicting Toxicity in Aquatic Ecosystems." *EPRI Journal,* 17(2) pp. 38-42.

72. Predeep, Kumar Behera, F. Papa, and B.J. Adams (1999). "Optimization of Regional Storm Water Management Systems." *JWRPM,* 125(2), pp. 107-113

73. Qiu, Zeyuan and T. Prato (1998). "Economic Evaluation of Riparian Buffers in an Agricultural Watershed." *Journal of the American Water Resources Association,* 34(4) pp. 877-890.

74. Roesner, Larry A. and A. C. Rowney (1996). "National Stormwater Quality Regulations and Standards." *Journal of Hydraulic Research,* 34(6) pp. 841-856.

75. Rosca, Justinian P. and D.H. Ballard (1995). "Causality in Genetic Programming." In *Proceedings of the Sixth International Conference on Genetic Algorithms*. Larry J. Eshelman (Ed.) pp. 256-263. Morgan Kaufmann Publishers, Inc. San Francisco CA.

76. Ryan (1995). *Practical Handbook of Genetic Algorithms Vol. I.* Lance Chambers (Ed.). Boca Raton: CRC Press.

77. Sartor, J.D. and G.B. Boyd (1972). *Water Pollution Aspects of Street Surface Contamination*. EPA R2-72-081, USEPA, Washington, DC.

78. Schaffer, David J. and L.J. Eshelman (1991). "On Crossover as an Evolutionarily Viable Strategy." In *Proceedings of the Fourth International Conference on Genetic Algorithms*. Belew, R.K. and Booker L.B. (Ed.) pp. 61-67. University of California, Sand Diego. July 13-16, 1991.

79. Schaffer, Eshelman, and Offutt (1991). *Foundations of Genetic Algorithms*. Gregory J.E. Rawlins (Ed.). San Mateo, Calif.: M. Kaufmann Publishers, c1991. 341 p.

80. Schleich, Joachim and D. White (1997). "Cost Minimization of Nutrient Reduction in Watershed Management Using Linear Programming." *Journal of the American Water Resources Association,* 33(1) pp. 135-142

81. Shamsi, Uzair M. (1994). "Storm-Water Management Implementation through Modeling and GIS." *Journal of Water Resources and Management,* 122(2) pp. 114-127.

82. Spash, C.L. and N. Hanley (1994), "Preferences, Information and Biodiversity Preservation" *Ecological Economics,* 94/1.

83. (SWRCB) State Water Resources Control Board, California Coastal Commission (1999, draft). *Nonpoint Source Program Strategy and Implementation Plan, Volume 1, 1998-2013.* http://www.swrcb.ca.gov/nps/planvol1.doc

84. Sun, Henglun, J. Houston, and J. Bergstrom (1996). "Economic Analysis of Best Management Practices in the Gum Creek Watershed Water Quality Program." *Journal of Soil and Water Conservation,* 51(3) pp. 176-180.

85. Spears, William M. and K.A. De Jong (1991). "On the Virtues of Parameterized Uniform Crossover." In *Proceedings of the Fourth International Conference on Genetic Algorithms*. R.K. Belew and L.B.Booker (Ed.) pp.230-236.

86. Takyi, Andrews K. and B.J. Lence (1996). "Chebyshev Model for Water-Quality Management." *Journal of Water Resources and Management*, 122(1) pp. 40-48.

87. Tan, Jonathan S. and Mark A. Kramer (1997). "A General Framework for Preventive Maintenance Optimization in Chemical Process Operations." *Computers Chem. Engineering,* 21(12) pp. 1451-1469.

88. Thomann, Robert V. and L.C. Linker (1998). "Contemporary Issues in Watershed and Water Quality Modeling for Eutrophication Control." *Water Science and Technology,* 37(3) pp. 93-102.

89. Thuesen, G.J. and W.J. Fabrycky (1984). *Engineering Economy*. Prentice-Hall, Englewood Cliffs, N.J.

90. Tilley, David R. and M.T. Brown (1998). "Wetland Networks for Stormwater Management in Subtropical Urban Watersheds." *Ecological Engineering*, 10 pp. 131-158.

91. Tyson, JM and V Foster (1995). "Valuing Environmental Benefits from River Quality Improvements." *Water Science and Technology,* 32(5-6) pp. 111-115.

92. USEPA (1975). *Stormwater Management Model: Level I- Preliminary Screening Procedures*. Environmental Protection Technology Series EPA-600/2-76-275.

93. USEPA (1991). Guidance for Water Quality-Based Decisions: The TMDL Process. EPA 440/4-91-001.

94. USEPA (1996). *TMDL Development Cost Estimates: Case Studies of 14 TMDLs*. EPA 841-R-96-001.

95. USEPA (1996). *Water Quality Analysis Simulation Program.* http://www.epa.gov/earth100/records/wasp.html

96. USEPA (1999). *Enhanced Stream Water Quality Model, Windows (QUAL2E)* http://www.epa.gov/ostwater/QUAL2E_WINDOWS/.

97. U.S. Soil Conservation Service (US SCS), 1986, *Urban Hydrology for Small Watersheds, Technical Release No 55 (TR-55)*. 2nd edition

98. Vanderkooij, L.A., D. Vandemeent, C.J. Vanleeuwen, W.A. Bruggeman (1991). "Deriving Quality Criteria for Water and Sediment from the Results of Aquatic Toxicity Tests and Product Standards- Application of the Equilibrium Partitioning Method." *Water Research,* 25(6) pp. 235-242.

99. Van Noortwijk, Jan M., R. Dekker, R.M. Cooke, T.A. Mazzuchi (1992). "Expert Judgment in Maintenance Optimization." *IEEE Transactions on Reliability,* 41(3) pp. 427-433.

100. Viessman, W. & Lewis, G.L., 1996, *Introduction to Hydrology*. 4th edition, Harper Collins.

101. Walker, D.J., BL Calkins, and JR. Hamilton (1993). "Marginal Cost Effectiveness Analysis for Agricultural Nonpoint Source Water Quality Control." *Journal of Soil and Water Conservation,* 48(4) pp. 368-372.

102. WRI, IUCN, UNEP (1992), *Global Biodiversity Strategy*, New York: World Resources Institute.

103. Yeh, Chao-Hsing and J.W. Labadie (1997). "Multiobjecitve Watershed-Level Planning of Storm Water Detention Systems." *Journal of Water Resources and Management*, 123(6) pp. 336-343.

104. Yulianti, J.S., B.J. Lence, G.V. Johnson, and A.K. Takyi (1999). "Non-point Source Water Quality Management Under Input Information Uncertainty." *Journal of Environmental Management*, 55(3) pp. 199-217.

APPENDIX 1: CALCULATIONS OF POLLUTION AND RUNOFF FROM URBAN SOURCES

(Based on EPA's SWMM model[2])

Infiltration = fn(population density)

$$I = 9.6PD_d^{(0.573-0.0391\log_{10} PD_d)}$$

where: I=Infiltration (%)

PD_d=Population density (Persons/Acre)

Depression storage = fn(Infiltration)

$$DS = 0.25 - 0.1875(I/100)$$

where: DS=Depression storage

Annual runoff = fn(Precipitation, infiltration, and depression storage)

$$AR = (0.15 + 0.75I/100)P - 5.234DS^{0.5957}, \text{ AR>=0}$$

where: AR=Annual runoff (inches/yr)

P =precipitation (inches/yr)

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[2] USEPA (1975). Stormwater Management Model: Level I- Preliminary Screening Procedures. Environmental Protection Technology Series EPA-600/2-76-275.

Runoff Volume = fn(annual runoff and area)

$V = AR(A)$, V>=0

where: V = Volume (inches-Acre/yr)

A = Area (Acre)

Pollutant loading for wet weather

$M = P\alpha f(PD_d)$

where: M=Pollutant loading (lb/Acre-yr)

α = Pollutant coefficient

$f(PD_d)$ = population density function

Land Use	***PO4***	***N***
Residential	0.0334	0.131
Commercial	0.0757	0.296
Industrial	0.0705	0.277
Other	0.00994	0.0605

Pollutant concentration

$C = \frac{Mk}{AR}$, C>=0

where: C = Pollutant concentration (mg/L-yr)

k = 4.4185 conversion factor

APPENDIX 2: MODEL CODE

1. PROJECT MODULE

Description: This module sets the GA model. The MAIN routine sets the file to which solutions are saved and the numbers of runs. The MAIN1 routine is the outline of the GA model. MAIN1 sets up the initial random populations and calls for the routines necessary to advance from one generation to the next. The following is a list of all routines in the module.

Routine Name	Routine Purpose
Selection of GA Operators and watershed Characteristics	
Watershed	Specifies the characteristics of the watershed including the number of sources affecting the receiving water, number of available management practices, the population size, and the number of generations to be produced. User can specify GA operators to be used in the model at the beginning of the run in the appropriate form.
Population management	
Aging	Ages the population to make room for a new population. The new population becomes the old population. New individuals are added to the new population in a separate routine.
Creation	Randomly generates the first generation.
Generation	Creates the new population by calling a procedure to select parents and a procedure to create the offspring.
Rejuvinate	Creates a new generation as a replica of the old generation
Flip	Determines randomly whether or not a parent will undergo crossover operation.
HeadLine	Creates the headline of the file where solutions are stored.
WriteSolution	Writes to a file the individuals and their fitness, and the solution for each generation.
Selection Operators (See Population class)	
Sharing	Creates sub-populations based on similar makeup and penalizes individuals within sub-populations to limit their selection.

	Recombination Operators
CrossGene	Crosses two parents to create two new offspring by randomly choosing to switch each gene on the chromosome string.
CrossOver	Randomly selects the breakpoint location on the chromosome and then creates two offspring by switching the parent chromosome segments.
	Replacement Operators
ChildRepWeak	Replaces the weakest in the population with the new offspring when creating a new population.
FitWeak	Searches through the population and identifies the strongest and weakest chromosomes. The weakest chromosome is then replaced with the strongest chromosome. This function increases the overall fitness of the population.
WeakParent	Compares the fitness of offspring and their parents. If the offspring have higher fitness they replace their parents otherwise they are discarded and the parents are added to the newly created population.

2. BMP CLASS/BMPS COLLECTION

In this module, all feasible management alternatives are identified with their respective costs and removal efficiencies.

3. CHROMOSOME CLASS

This module provides the representation of the solutions considered at each generation. The characteristics of the receiving water are calculated given the user's input data and the solution makeup.

Routine Name	Routine Purpose
Receiving Water Characteristics	
Productivity	Calculates the productivity in the receiving water given nutrients concentrations. Productivity is based on an N: P ratio of 7.22. Productivity is calculated as: Pconc*(2427/31) for P limiting Nconc*(2427/16*14) for N limiting
TotalProductivity/ WaterProductivity	Calculates receiving water productivity without/with stormwater management.
TotalNConc/TotalPConc	Calculates the receiving water concentration (N or P) prior to implementation of management at pollutant sources.
WaterNConc/ WaterPConc	Calculates the receiving water concentration (N or P) with stormwater management alternative
Evaluation of Solution String	
Fitness	Calculates the fitness of the alternative solution. Fitness can be based on either water quality or eutrophication (productivity) limits. The fitness is based on minimizing total cost of management. Total cost is the sum of implementation cost and penalties incurred when limits are not achieved.
Penalty	Calculates the penalty of exceeding water quality or eutrophication requirement. Penalty is a function of the difference between receiving water concentration and standards up to a specified limit. If this limit is exceeded, a high penalty is given.
WaterCost	Calculates the cost of implementing the solution
Solution String Management	
Replace	Replaces one individual with another
Add	Creates alternative management solutions

4. GENE CLASS

This class represents the choice of management practices at a specific source. The class provides the location and value of the gene within the chromosome (solution). This class includes the function Mutation that randomly mutates the gene to diversify the population.

5. POPULATION CLASS/POPULATIONS COLLECTION

In this class/collection, solutions are selected for the creation of new populations.

Routine Name	Routine Purpose
	Population Characteristics
Average	Calculates the average fitness of the generation.
SumFitness	Calculates the total fitness of the population.
Inferior	Identifies the weakest individual in the population.
Superior	Identifies the fittest individual in the population.
	Selection Operators
TournamentSelection	Chooses two individuals randomly and selects the fittest one to become parent for next generation.
RouletteSelection	Chooses individuals to become parents based on their fitness. The higher the fitness the higher the probability of selection.
RandomSelection	Randomly selects individuals to become parents for next generation.
RTSelection	Compares a child to a predetermined number of individuals randomly selected. If the fitness of the child exceeds the individual most similar to it, it is used in the next generation.

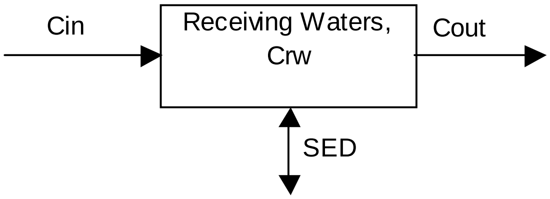
6. SOURCE CLASS/SOURCES COLLECTION

In this class/collection, all polluting sources are identified and their respective flows and pollutant concentrations are calculated. Flows and information on each source are specified by the user in an excel file 'RWInfo'. The values entered by the user can be verified in the dialog box presented at the beginning of each run.

Routine Name	Routine Purpose
	Source Information
Zone	Zoning for each source (four zoning are available) is specified by the user in the excel file 'RWInfo'.
Area	Area for each source (in Acres) is specified by the user in the excel file 'RWInfo'.
PD	Person density for each source (Persons/Acre) is specified by the user in the excel file 'RWInfo'.
Precip	Precipitation (inches) is specified by the user at the beginning of the run in the receiving water form. There is an option in the MAIN1 routine in the Project module to create random generation of precipitation.
Add	Add sources to the watershed management model
	Source Pollution Contribution
Runoff	Calculates the runoff volume (acre-ft/yr) for each source contributing flow to the receiving waters.
NConc/PConc	Calculates the N/P concentration in each source (mg/l)

APPENDIX 3: RECEIVING WATERS WITH RESIDENCE TIME

Receiving water pollutant concentration



Based on mass balance:

$$C_{rw}^{t} V_{rw}^{t} = C_{rw}^{t-\Delta t} V_{rw}^{t-\Delta t} + C_{in}^{t} Q_{in}^{t} \Delta t - C_{out}^{t} Q_{out}^{t} \Delta t \pm L_{sed}^{t} \tag{22}$$

Where:

C_{rw} = Pollutant concentration in receiving water

V_{rw} = Volume of receiving water

C_{in} = Pollutant concentration at incoming flow

Q_{in} = Flow from polluting source

C_{out} = Pollutant concentration at outlet

Q_{out} = Flow at outlet

Assumptions:

1. Ignore sediment load
2. Cout(t) = Crw(t)
3. Residence time, R=V/Q
4. Incoming pollutant concentration, $C_{in}^{t} = C_{in}^{t}\left(1 - E^{o} e^{-kt}\right)$
5. Receiving water initial concentration, $C_{rw}^{t=0} = P$

$$\frac{\Delta C_{rw}}{\Delta t} = \frac{C_{rw}^{t} - C_{rw}^{t-\Delta t}}{\Delta t} = \frac{C_{in}^{t}}{R_{in}} - \frac{C_{rw}^{t}}{R_{out}} \qquad \mathbf{(23)}$$

Using 1st order differential equation[3]:

$$y' + ay = g(x)$$

$$y' = \frac{\Delta C}{\Delta t}; \quad a = \frac{1}{R_o}; \quad y = C_{rw}(t); \quad g(x) = \frac{C_{in}(t)}{R_{in}}$$

$$\begin{aligned}
y &= e^{-ax}\int_x e^{at} g(t)dt + Ce^{-ax} \qquad (24)\\
&= e^{-\frac{t}{R_o}} \int_t e^{\frac{x}{R_o}} \frac{C_{in}\left(1 - E^o e^{-kx}\right)}{R_{in}} dx + ce^{-\frac{t}{R^o}}\\
&= e^{-\frac{t}{R_o}} \frac{C_{in}}{R_{in}} \int_t e^{\frac{x}{R_o}} - E^o e^{x\left(\frac{1}{R_o} - k\right)} dx + ce^{-\frac{t}{R^o}}\\
&= e^{-\frac{t}{R_o}} \frac{C_{in}}{R_{in}} \left(R_o e^{\frac{t}{R_o}} - \frac{E^o e^{t\left(\frac{1}{R_o} - k\right)}}{\left(\frac{1}{R_o} - k\right)} \right) + ce^{-\frac{t}{R^o}}\\
&= C_{in} \frac{R_o}{R_{in}} \left(1 - \frac{E^o e^{-tk}}{\left(1 - R_o k\right)} \right) + ce^{-\frac{t}{R^o}}\\
y(0) = P &= C_{in} \frac{R_o}{R_{in}} \left(1 - \frac{E^o}{\left(1 - R_o k\right)} \right) + c
\end{aligned}$$

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[3] Ref: Boyce, W.E. and R.C. DiPrima (1977). Elementary Differential Equations. 3rd Ed. John Wiley and Sons, NY pp.451

$$c = P - C_{in}\frac{R_o}{R_{in}}\left(1-\frac{E^o}{(1-R_o k)}\right) \tag{25}$$

Final representation of receiving water concentration as a function of time:

$$C_{rw}(t) = C_{in}\frac{R_o}{R_{in}}\left(1-\frac{E^o e^{-tk}}{(1-R_o k)} - e^{-\frac{t}{R_o}} + \frac{E^o e^{-\frac{t}{R_o}}}{(1-R_o k)}\right) + Pe^{-\frac{t}{R_o}} \tag{26}$$

<u>Benefits of SWQ-MP</u>

$$\Delta B = s\Delta C \tag{27}$$

$$s = \frac{V_{rw}}{C_{\max}}$$

$$\Delta C = C^t_{NoSWQ-MP} - C^t_{SWQ-MP}$$

Receiving water concentration without SWQ-MP (E^o=0)

$$C(t) = C_{in}\frac{R_o}{R_{in}}\left(1-e^{-\frac{t}{R_o}}\right) + Pe^{-\frac{t}{R_o}} \tag{28}$$

Change in receiving water concentration, ΔC

$$\Delta C(t) = C_{in}\frac{R_o}{R_{in}}\left(\frac{E^o e^{-tk}}{(1-R_o k)} + \frac{E^o e^{-\frac{t}{R_o}}}{(1-R_o k)}\right) \tag{29}$$

Change in benefits of receiving water with SWQ-MP, ΔB

$$\Delta B(t) = sC_{in}\frac{R_o}{R_{in}}\left(\frac{E^o e^{-tk}}{(1-R_o k)} + \frac{E^o e^{-\frac{t}{R_o}}}{(1-R_o k)}\right) \tag{30}$$

Net benefit as a function of benefits and maintenance cost

$$NB = \frac{TB - Me^{-rT}}{1 - e^{-rT}} \tag{31}$$

Total benefits for the period between maintenance, TB

$$\begin{aligned} TB &= \int_{t=0}^{T} sC_{in} \frac{R_o}{R_{in}} \frac{E^o}{(1 - R_o k)} \left(e^{-tk} + e^{-\frac{t}{R_o}} \right) e^{-rt} dt \\ &= \int_{t=0}^{T} sC_{in} \frac{R_o}{R_{in}} \frac{E^o}{(1 - R_o k)} \left(e^{-t(k+r)} + e^{-t\left(\frac{1}{R_o}+r\right)} \right) dt \\ &= sC_{in} \frac{R_o}{R_{in}} \frac{E^o}{(1 - R_o k)} \left(\frac{e^{-t(k+r)}}{-(k+r)} + \frac{e^{-t\left(\frac{1}{R_o}+r\right)}}{\frac{1}{R_o}+r} \right) \\ &= sC_{in} \frac{R_o}{R_{in}} \frac{E^o}{(1 - R_o k)} \left(\frac{e^{-T(k+r)}}{-(k+r)} + \frac{1}{(k+r)} + \frac{e^{-T\left(\frac{1}{R_o}+r\right)}}{\frac{1}{R_o}+r} - \frac{1}{\frac{1}{R_o}+r} \right) \end{aligned} \tag{32}$$

Let $B = sC_{in} \frac{R_o}{R_{in}} \frac{E^o}{(1 - R_o k)}$

Present value net benefit is:

$$PVNB = \frac{B\left(\frac{e^{-T(k+r)}}{-(k+r)} + \frac{1}{(k+r)} + \frac{e^{-T\left(\frac{1}{R_o}+r\right)}}{\frac{1}{R_o}+r} - \frac{1}{\frac{1}{R_o}+r} \right) - Me^{-rT}}{1 - e^{-rT}} \tag{33}$$

1st order condition is used to find optimal solution for PVNB

$$\frac{d\,\dfrac{e^{-T(k+r)}}{-(k+r)}}{dT}=e^{-T(k+r)}$$

$$\frac{d\,\dfrac{1}{(k+r)}}{dT}=0$$

$$\frac{d\,\dfrac{e^{-T\left(\frac{1}{R_o}+r\right)}}{\dfrac{1}{R_o}+r}}{dT}=e^{-T\left(\frac{1}{R_o}+r\right)}$$

$$\frac{d-\dfrac{1}{\dfrac{1}{R_o}+r}}{dT}=0$$

$$\frac{d-M^{e-rT}}{dT}=rMe^{-rT}$$

$$\frac{d\left(1-e^{-rT}\right)}{dT}=re^{-rT}$$

Using chain rule the 1st order derivative of PVNB is:

$$\frac{dPVNB}{dT}=0=\frac{\left(Be^{-T(k+r)}-Be^{-T(\frac{1}{R_o}-r)}+rMe^{-rT}\right)\left(1-e^{-rT}\right)-\left(\dfrac{-Be^{-T(k+r)}}{k+r}+\dfrac{B}{k+r}-\dfrac{Be^{-T(\frac{1}{R_o}-r)}}{\dfrac{1}{R_o}-r}-Me^{-rT}\right)\left(re^{-rT}\right)}{\left(1-e^{-rT}\right)^2} \tag{34}$$

$$\frac{rM}{B}+\frac{r}{\frac{1}{R_o}+r}-\frac{r}{k+r}=-e^{-T(k+r)}\left(\frac{r}{k+r}-1\right)+e^{-T\left(\frac{1}{R_o}+r\right)}\left(\frac{r}{\frac{1}{R_o}+r}-1\right)-e^{-Tk}+e^{-\frac{T}{R_o}} \tag{35}$$

Let $\frac{rM}{B}=\frac{rM}{B_{\max}}(1-R_ok)$ for $R_o=R_i$ and $B_{max}=SCE^o$. Substituting into equation (35) yields:

$$\frac{rM}{B_{\max}}=e^{-T\left(\frac{1}{R_o}+r\right)}\left(\frac{r}{(1-R_ok)\left(\frac{1}{R_o}+r\right)}-\frac{1}{(1-R_ok)}\right)+\frac{e^{-\frac{T}{R_o}}}{(1-R_ok)}-\frac{r}{(1-R_ok)\left(\frac{1}{R_o}+r\right)}-e^{-T(k+r)}\left(\frac{r}{(1-R_ok)\left(\frac{1}{R_o}+r\right)}-\frac{1}{(1-R_ok)}\right)-\frac{e^{-Tk}}{(1-R_ok)}+\frac{r}{(1-R_ok)(k+r)} \tag{36}$$

Manipulating equation (36) result in the dimensionless equation:

$$\frac{B_{\max}}{rM}=\frac{(1-R_ok)}{\left(\frac{rR_o}{1+rR_o}\right)\left(e^{-T(\frac{1}{Ro}+r)}-1\right)-\left(\frac{r}{k+r}\right)\left(e^{-T(k+r)}-1\right)+\left(e^{-\frac{T}{Ro}}+e^{-Tk}\right)\left(1-e^{-Tr}\right)} \tag{37}$$

Equation (37) can be rewritten with dimensionless variable for analysis:

Dimensionless variables:

$\beta=\frac{B_{\max}}{rM}$

$\tau=rT$

$\kappa=k/r$

$\rho=rR_o$

$$\beta=\frac{(1-\kappa\rho)}{\left(\frac{\rho}{1+\rho}\right)\left(e^{-\tau\left(\frac{1}{\rho}+\right)}-1\right)-\left(\frac{1}{\kappa+1}\right)\left(e^{-\tau(\kappa+1)}-1\right)+\left(e^{-\frac{\tau}{\rho}}-e^{-\tau\kappa}\right)\left(1-e^{-\tau}\right)} \tag{38}$$

For receiving waters with no residence time ρ = 0

$$\beta=\frac{1}{\left(1-e^{-\tau\kappa}\right)\left(-e^{-\tau}\right)-\left(\frac{1}{\kappa+1}\right)\left(e^{-\tau(\kappa+1)}-1\right)} \tag{39}$$