EVALUATING SOURCE WATER PROTECTION STRATEGIES: A SOFT COMPUTING APPROACH

by

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ABSTRACT

Source water protection is an important step in the implementation of a multi-barrier approach that ensures delivery of safe drinking water cost effectively. However, implementing source water protection strategies can be a challenging task due to technical and administrative issues. Currently many decision support tools are available that mainly use complex mathematical formulations. These tools require large data sets to conduct the analysis, which make their use very limited. A simple soft-computing model is proposed in this research that can estimate and predict a reduction in the pollutant loads based on selected source water protection strategies that include storm water management ponds, vegetated filter strips, and pollution control by agricultural practice. The proposed model uses an export coefficient approach and number of animals to calculate the pollutant loads generated from different land uses (e.g., agricultural lands, forests, roads, livestock, and pasture). A surrogate measure, water quality index, is used for the water assessment after the pollutant loads are discharged into the source water. To demonstrate the proof of concept of the proposed model, a Page Creek Case Study in Clayburn Watershed (British Columbia, Canada) was conducted. The results show that rapid urban development and improperly managed agricultural area have the most adverse effects on the source water quality. On the other hand, forests were found to be the best land use around the source water that ensures acceptable drinking water quality with a minimal requirement for treatment. The proposed model can help decision-makers at different levels of government (Federal/ Provincial/ Municipal) to make informed decisions related to land use, resource allocation and capital investment.

PREFACE

A version of Chapters 2 and 3 in this thesis has been accepted (November 2010) in *Environmental Reviews* as a journal article titled “Reviewing Source Water Protection Strategies: A Conceptual Model for Water Quality Assessment (Islam *et al*., 2010)”. The paper was written by Nilufar Islam under the supervision of Dr. Rehan Sadiq and Dr. Manuel Rodriguez. A journal article based on Page Creek Case Study (Chapter 4) is under preparation. One conference paper (CSCE 2010) is published and one (BCWWA 2011) is under progress from this research.

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ABBREVIATIONS

ANN	Artificial neural networks
B. Fen	Barbed fencing
BMPs	Best management practices
BOD_5	5 day biochemical oxygen demand
CC	Cover crop
CCME-WQI	Canadian Council of Ministers of the Environment Water Quality Index
CE	Complex equation
CR	Crop rotation
CSO	Combined sewer overflow
CSS	Combined sewer systems
CSTR	Continuous stirred-tank reactor
DBD	Dry bulk density
DO	Dissolved oxygen
E. Coli	*Escherichia coli*
EC	Export coefficient
EMC	Event mean concentration
ER	Evidential reasoning
FC	Faecal coliforms
FCA	Fuzzy clustering analysis
Fen	Fencing
FIS	Fuzzy inference system
FMT	Fuzzy measures theorem
FRBM	Fuzzy rule-based model
FSE	Fuzzy synthetic evaluation
GIS	Geographical Information System
GPS	Global Positioning System
HACCP	Hazard Analysis Critical Control Points
LID	Low impact development
MIMO	Multiple-inputs-multiple-outputs
MISO	Multiple-inputs-single-output

MUSLE	Modified universal soil loss equation
NH_3-N	Ammonia nitrogen
NH_4-N	Ammonium nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NPS	Nonpoint pollution sources
NRCS	Natural Ressources Conservation Service
NSF-WQI	National Sanitation Foundation water quality index
OWA	Ordered weighted averaging
O-WQI	Oregon water quality index
Pb	Lead
PCAP	Pollution control by agricultural practice
PO_4	Phosphates
PPS	Point pollution sources
RT	Retention time
S	Summer
SISO	Single-input-single-output
SRC	Small and rural communities
SWC	Soil water content
SWM	Storm water management
SWP	Source water protection
TC	Total coliforms
TDS	Total dissolved solids
Temp	Temperature
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorous
TS	Toxic substance
TSK	Takagi-Sugeno-Kang
TSS	Total suspended solids

USLE	Universal soil loss equation
V. Fen	Vegetated fencing
VFS	Vegetated filter strips
W	Winter
WQI	Water quality index
WQP	Water quality parameter
WWT	waste water treatment

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Dedicated to my parents

1. INTRODUCTION

1.1 Background

The United Nations General Assembly asserted that safe and clean drinking water and sanitation is a fundamental human right. The grand challenges of engineering for the 21st century included: ‘providing access to the clean water’ among the top priorities. The protection of water supplies is a priority and an integral part of Canada’s Science & Technology Strategy as well. Advancement in technology and knowledge has improved accessibility to safe drinking water, however increasing urbanization, industrialization and emerging environmental issues are making water protection more challenging in the future. Information on the quality of source waters and associated risks to the human health is imperative to make informed decisions in prioritizing available resources. Sources of water for large cities like Toronto, Ottawa and Vancouver are comparatively well managed and adequate treatment is generally available to ensure ‘reduced risk’ to the consumers’ health. However for small and rural communities (SRC), achieving the same level of reduced risk under limited information and budgeting constraints is taxing.

The goal of source water protection (SWP) is to protect against potential pollution or resuscitate contaminated water if economically viable. A watershed may consist of diverse systems such as terrestrial, freshwater and ecosystems and that makes SWP a challenging task. Though source water generally refers to both ground and surface waters, the main focus of this research is on the later. Strategies for SWP refer to watershed-based protection of the water at the source. A watershed is a catchment area that drains into a common water source point, e.g., Lake Winnipeg is fed by a watershed that consists of four provinces in Canada and two U.S. states (Postel and Thompson, 2005).

A modern water supply system ensures the delivery of high quality water to homes, industries, agricultural lands, essential facilities (such as hospitals, schools) and recreational facilities. Strategies for SWP organize activities in the watershed to minimize undesirable effects that result in a poor water quality. Generally, it is very difficult to restore or substitute the polluted source waters and if the source water quality is compromised, water treatment often becomes prohibitively expensive (Wilsenach *et al*., 2003). In some cases, the high variability in the quality of source water (e.g., due to seasonal variability or land use change) increases the challenges for water treatment at affordable costs (Curriero *et al*., 2001). Protecting water at the source is always a preferred option (preventive action) as compared to subsequent expensive water treatment technologies (mainly corrective actions).

Small and rural communities (SRC) are generally incapable of providing sophisticated treatment plants due to lack of financial resources and trained staff (Timmer *et al*., 2007). Properly executed SWP strategies coupled with conventional water treatment can be an effective way of ensuring safe drinking water supplies not only true for SRC but also for larger municipalities. For example, Catskill/ Delaware watershed (USA) that supplies 90% of the New York drinking water, enhanced source water protection was provided. The city spent $1.5 billion for implementing enhanced SWP strategies for Catskill/ Delaware watershed which approximately saved $3.5 billion to the city by avoiding the cost of advanced water treatment (Garcia, 2004).

According to WHO (1993), SWP is found to be a cost effective way to ensure safe drinking water. This is due to the fact that effective SWP can result in not only less treatment cost but also lower microbial re-growth and reduced formation of disinfection by-products (DBPs are formed when disinfectant reacts with the naturally occurring organic matter) in the distribution networks (Ivey *et al.*, 2006; Krewski *et al.*, 2004). The Bonn Charter of Safe Drinking Water (2004) provides a generic framework for an effective management of water quality from source to tap that can be linked to WHO guidelines for drinking water. It emphasizes the need for proactive management of drinking water supplies. The Charter is generic enough to support approaches and methodologies such as a multi-barrier approach, Hazard Analysis Critical Control Points (HACCP) framework (Hulebak and Schlosser, 2002) and total water quality management. Multi-barrier approach has been recommended all over the world for the protection of drinking water supplies in various stages that includes: source water protection, water treatment, regular water quality in the distribution network and ensuring desirable free residual disinfectant. After the Walkerton enquiry, a multi-barrier approach has been recommended in Canada to ensure safe drinking water from source to tap (O'Connor, 2002).

Numerous studies have reported the benefits of SWP in terms of reduction of contaminants in receiving water bodies (Arora *et al.*, 2003; Bliss *et al.*, 2009; Borin *et al.*, 2010; Dietz, 2007; Hsieh and Davis, 2005; Hathaway *et al.*, 2009; Muthanna *et al.*, 2007; Scholz and Grabowlecki, 2007; Patty *et al.,* 1997; USEPA, 2000). The impacts and benefits of SWP can be linked to three dimensions of sustainability (a triple bottom line) social, economical and environmental. SWP is a complex and time consuming process. In most cases, various ministries at the Federal, Provincial/ Territorial and Municipal levels should coordinate to make SWP programs effective and efficient.

Increasing population, rapid urbanization and industrialization increase the likelihood of water contamination through both point pollution sources (PPS) (e.g., municipal and industrial discharges) and nonpoint pollution sources (NPS) (e.g., agricultural runoff and storm water). In United States, PPS have been regulated since 1970 (Ernst, 2004), however the physical and regulatory controls of NPS is much more challenging because of the pollution load distribution (Meixler and Bain, 2010). In addition, source water quality is under increasing pressure due to the impacts of climate change and due to rapidly changing land use (IPCC, 2007). SWP has been practiced for the past 125 years in North America, e.g., the Cedar River in Seattle (Washington) was taken into protection in 1896 after a large fire outbreak which destroyed the whole eco-system (Ernst, 2004). Around the world, various SWP strategies have been implemented. Two major categories for SWP strategies include implementing activities allowing low impact development (LID) (henceforth we refer it as storm water management) and adopting best management practices (BMPs) (management of industrial, municipal and agricultural areas).
Water quality is a vague concept which depends on numbers parameters and the intended use of water. Many studies have reported diverse methods for quality assessment of surface waters (e.g., Banerjee and Srivastava, 2009; Dojlido *et al.,* 1994; Jonnalagadda and Mhere, 2001; Lermontov *et al*., 2009; Rajankar *et al*., 2009; Ramakrishnaiah *et al.,* 2009; Sedeno-Diaz and Lopez-Lopez, 2007; Suratman *et al*., 2009). These studies proposed certain water quality parameters to derive a water quality index (WQI). The water quality index (WQI) for the assessment of water quality at the source after reduction in pollutant loads has never been linked to any human effort (implementation of SWP strategies).

Decision support tools can be very useful to make informed decisions related to the selection of source water and implementing SWP strategies that can improve the quality of the water at the source. However, the development of a decision support tool requires an understanding about the impacts of SWP strategies on water quality and the related regulatory regimes. A number of watershed models provide a process for the calculation of pollutant loads based on land use (

Bingner *et al.,* 2001; Bjorneberg, 1999; Borah *et al.,* 2002; Bottcher, 1998; Chen *et al.,* 2003; Chiew and McMahon, 1999; Downer and Ogden, 2002; EMRL, 1998; HSPF, 1985; Irvine *et al.,* 1993; Neitsch *et al.,* 2001; Ovbiebo and She,1995; Pitt, 1993; Roesner *et al.,* 1988; Skaggs, 1980; Sydelko *et al.,* 2000; Walker, 1997; Williams *et al.,* 1983; Woolhiser *et al.,* 1990; Young *et al.,* 1987). These models are based on complex mass balance and empirical relationships (e.g., universal soil loss equation). These models predict the reduction in pollutant loads based on different land use, however, the impact on water quality at the source is generally not estimated. There is a pressing need for linking reduction in the pollution loads to the quantitative assessment of source water quality for informed decision-making.

To calculate pollutants loads, export coefficients (land use based pollutant export to the source water) and number of animals' calculations (Lahlou *et al.,* 1998; Palmstrom and Walker, 1990; USACE-HEC, 1977) provide a much simpler approach that can be easily integrated with water quality assessment calculations. The developed decision support tool based on this research addresses the limitations of existing tools and provides a framework for water quality assessment at the source. Soft computing-based formulations have been used to develop decision support tools (Chang *et al*., 2001; Chen *et al*., 2010; Dahiya *et al*., 2007; Francisque *et al*., 2009; Hajkowicz and Collins, 2007; Icaga, 2007; Kuoa *et al.,* 2007; Lu and Lo, 2002; Liou *et al*., 2003**;** Li *et al*., 2009; Ocampo-Duque *et al*., 2006; Rankovic *et al.,* 2010; Sadiq *et al*., 2006; Sadiq *et al*., 2007; Spinella *et al*., 2008; Singh *et al*., 2009; Yeon *et al.,* 2008) which can handle uncertainty and vagueness in the data.

1.2 Research Objectives

Overall objective of this thesis is to develop a model (decision support tool) which can predict the reduction in pollutant loads by implementing selected SWP strategies and subsequently predict the improvement in surface water quality based on reduced pollutant loads.

Specific objectives of this research are to:

i) review existing regulations for source water protection in various parts of the world with a special focus on Canada and the USA, and study state-of-the-art source water protection (SWP) strategies to deal with non-point pollution sources

ii) investigate mathematical formulations to develop a water quality index (WQI) for water quality assessment at the source *iii)* develop a conceptual framework that can relate reduction in pollutant loads with the improvement in WQI, and

iv) apply the developed model to a case study and demonstrate a proof-of-concept for the proposed approach.

1.3 Thesis Organization

This thesis is organized in five chapters. The first chapter provides background and objectives of this research. Chapter 2 presents a detailed literature review for the related topics that includes: (a) source water quality; (b) potential impacts of land use on water quality; (c) water quality regulations for source water; (d) source water protection strategies; and (e) existing watershed models used for estimating pollutants loads. Chapter 3 provides the steps for model development based on the proposed conceptual framework. Chapter 4 discusses a case study of a small creek in British Columbia using the developed model. Finally, Chapter 5 provides the conclusions and makes recommendations for future research.

2. LITERATURE REVIEW

2.1 Pollution Sources

Microorganisms, nutrients, heavy metals, organic and toxic substances can be found in natural water bodies. Surface waters are generally vulnerable to microbial contamination that may lead to devastating consequences if the water is used for drinking without proper treatment. Undesirable levels of organic matter and nutrients provide a favorable environment for rapid microbial growth in surface waters (Carreiro-Silva *et al*., 2009). A comprehensive assessment of these pollutants and mechanisms by which they reach source water requires an implementation of SWP strategies to ensure high quality water at the source.

The pollutants entering into receiving water bodies from a number of point and non-point pollution sources can adversely affect human wellbeing as well as ecosystem health. For example, the release of nutrients (e.g., phosphorus, nitrogen) from agricultural sources can lead to the growth of toxic algal blooms (Bechmann *et al*., 2009; Hickey and Gibbs, 2009) and can cause eutrophic conditions which impact the biological and chemical quality of water (Schoumans and Chardon, 2003). Similarly, heavy metals such as lead, mercury and arsenic may ingress into the source waters through industrial discharges, runoff and spills (Zakir *et al*., 2009). If the water is not properly treated before consumption, the exposure to lead and mercury may have severe consequences for the consumers (Howard, 2002). Arsenic is a proven human carcinogen and exposure to high levels may lead to skin cancer (Otles and Cagindi, 2010). Most pesticides contain a number of toxic substances which can adversely affect human health (Zhang *et al*., 2010). Harmful pesticides (e.g., atrazine, diazinon) can enter into source water not only from agricultural lands but also from runoffs from gardens and parks (Wittmer *et al*., 2010).

After a heavy rainfall or snowfall event, the runoff from agricultural and urban lands can contaminate source waters. Untreated municipal discharges or improper diversion of wastewater from the municipal sources can cause contamination of surface waters. In addition, if a wastewater treatment plant is not working effectively the toxic substances can contaminate source waters. Combined sewer systems (CSS) designed to carry wastewater from industrial, domestic and commercial sources with storm water (snowmelt/ rain water) can also be a source of pollution. In case of excess water (during heavy rains), the wastewater beyond the capacity of the treatment plant may be released as combined sewer overflow (CSO). Approximately 43 million people in 1,100 communities in the USA are served by a CSS (USEPA, 1995). The pollutant load depends on the land use. For example, forests, agricultural land, farms (livestock), pasture/forage, residential, industrial, commercial areas and roads generate diverse types and the amounts of pollutant loads.

The export coefficient (EC) concept is widely used for deriving the potential pollutant loads based on soil erosion and runoff (Amatya *et al*., 2004; Beaulac and Reckhow, 1982; Bourne *et al*., 2002; Ding *et al*., 2010; Dodd *et al*., 1992; Easton *et al*., 2009; Kay *et al*., 2008; Line *et al*., 2002; Loehr *et al*., 1989; McFarland and Hauck, 2001; Prepas *et al*., 2001; Rast and Lee, 1983; Reckhow *et al*., 1980; Shrestha *et al*., 2008; Veiga and Dziedzic, 2010). It describes the amount of pollutant or a specific parameter that can be related to water quality (e.g., total suspended solids, total nitrogen, and total phosphorous). Table 2.1 provides export coefficients for different land uses expressed in kg/ha/yr (i.e., flux units), except for coliforms which are described by colony forming unit/ha/yr (CFU/ha/yr). A large variability in the EC values for water quality parameter can be noticed. For example, Prepas *et al*. (2001) and Reckhow *et al*. (1980) provided EC values for TSS that varied significantly in case of runoffs from forests. The difference in topography and precipitation is the main reason behind this variation. However, the EC approach is found to be very effective in calculating pollutant transport amount from different land uses. Table 2.2 provides average pollutant concentrations (mg/l) for different land uses. This table describes pollutant concentration (either an average or average ± standard deviation) variability for the same land use. It should be noted that the concentration depends not only on the runoff quantity but also on the type of pollutant. Therefore, the reported land use concentration or sometimes expert judgment can be used to estimate the pollutant loads.

To protect source water from pollutant loads various SWP strategies can be used. Selecting a suitable SWP strategy is a key for reducing the amount of pollutants and improving water quality at the source. Next section provides an overview of guidelines and regulatory regimes that directly or indirectly impacts source water quality and help in decision-making related to the selection of SWP strategies.

Table 2.1: Export coefficient (kg/ha/yr) for different land uses

Reference	Place	TSS	TN	TP	FC	TC
Forests						
Bourne *et al.* (2002)	Manitoba, Canada	-	0.2-3.9	0.01-0.4	-	-
Dodd *et al.* (1992)	Albemarle Pamlico, USA	-	0.70-3.8	0.09-0.2	-	-
Loehr *et al.* (1989)	NS	-	1-6	0.007-0.9	-	-
Prepas *et al.* (2001)	Boreal plain, Western Canada	20.86	0.6	0.04	-	-
Reckhow *et al.* (1980)	NS	253	1.4-6.3	0.02-0.8	-	-
Kay *et al.* (2008)	UK	-	-	-	$8.8E+07^{a}$	$3.4E+08^{a}$
Agricultural						
Bourne *et al.* (2002)	Manitoba, Canada	-	0.3-6.7	0.03-1	-	-
Dodd *et al.* (1992)	Albemarle Pamlico, USA	-	5-14	0.6-2	-	-
Loehr *et al.* (1989)	NS	-	2-80	0.06-3	-	-
Rast and Lee (1983)	North America	-	5	0.5	-	-
Reckhow *et al.* (1980)	NS	-	2-80	0.3-19	-	-
Reckhow *et al.* (1980)	NS	-	1-7.8	0.1-3	-	-
Livestock						
Reckhow *et al.* (1980)	NS	-	680~7980	21~790	-	-
Loehr *et al.* (1989)	NS	-	100~1600	10~620	-	-
Pasture/Forage						
Bourne *et al.* (2002)	Manitoba, Canada	-	0.17-4.3	0.02-0.5	-	-
Loehr *et al.* (1989)	NS	-	3-14	0.05-0.6	-	-
Urban (residential)						
Loehr *et al.* (1989)	NS	-	5-7	0.8-2	-	-
Urban (industrial and commercial)						
Loehr *et al.* (1989)	NS	-	2-14	0.4-4	-	-
Reckhow *et al.* (1980)	NS	870	2.3	8	-	-
Kay *et al.* (2008)	NS	-	-	-	$3.6E+09^{a}$	$1.1E+10^{a}$

a-Unit in CFU/ha/hr ; NS - not specific; TSS- Total suspended solid; TN- Total nitrogen; TP- Total phosphorous; FC- Faecal coliform; TC-Total coliform; CFU-Colony forming unit

Table 2.2: Typical concentrations (mg/l) in runoffs from different land uses

Reference	Land use	TSS	BOD_5	TN	TP	FC	TC	Pb
Boller *et al*. (2007)	Roads	100±60	-	2±1	0.3±0.1	-	-	0.02±0.01
Gotvajn and Zagorc-Koncan (2009)	Roads	-	1.2	.4	0.04	-	-	-
Resource Management Factsheet (1994)	Agricultural	75	40	26	-	200[a]	-	-
Poudel *et al*. (2010)	Agricultural	1800 ± 550	7 ± 0.60	5 ± 0.70	0.40 ± 0.04	-	-	-
Poudel and Jeong (2009)	Agricultural	680 ±200	7±2	2 ±0.4	0.50±0.10	-	-	-
Udeigwe *et al*. (2010)	Agricultural	1600	6.2	4.8	0.7			
Poudel *et al*. (2010)	Residential	80±20	5± 0.3	3 ± 0.2	0.6 ± 0.03	-	-	-
Poudel and Jeong (2009)	Residential	30 ±10	4±0.6	2 ±0.3	0.5 ±0.10	-	-	-
Lopez *et al*. (2006)	Municipal	5	29	13	2.4	40	149	-

a- Unit in CFU/l, mean±Standard deviation, TSS- Total suspended solid; BOD_5- 5 day biochemical oxygen demand; TN-total nitrogen, TP-total phosphorous; FC- Faecal coliform; TC- total coliform; Pb- lead

2.2 SWP Regulations

Regulatory regimes related to source water protection are very common in Canada, e.g., Ontario (e.g., Clean Water Act, 2006a, 2006b), Alberta (e.g., Environmental Protection and Enhancement Act, 1993a, 1993b) and British Columbia (Ecological Reserve Act, 1975; Environmental Management Act, 2004a, 2004b). In other parts of the world such as the USA (e.g., State Source Water Assessment and Protection Programs, 1997; USEPA, 2001a-h), Australia and the European Union (Drinking Water Directive, 1980) also have promulgated regulatory frameworks for source water protection. Generally, SWP regulations directly or indirectly affect water quality at the source. These regulations help to control or eliminate potential hazards through effective implementation of selected SWP strategies. These strategies are related to the land use, storm water management, agriculture, farming (livestock), vehicle spills, roads, and municipal and industrial wastewater management. Figure 2.1 provides a schematic relating potential hazards to different management strategies. Landfill management is related more to groundwater however, a landfill in close proximity to the surface source water can also be a hazard that may lead to microbial and chemical pollution (Yu *et al*., 2010).

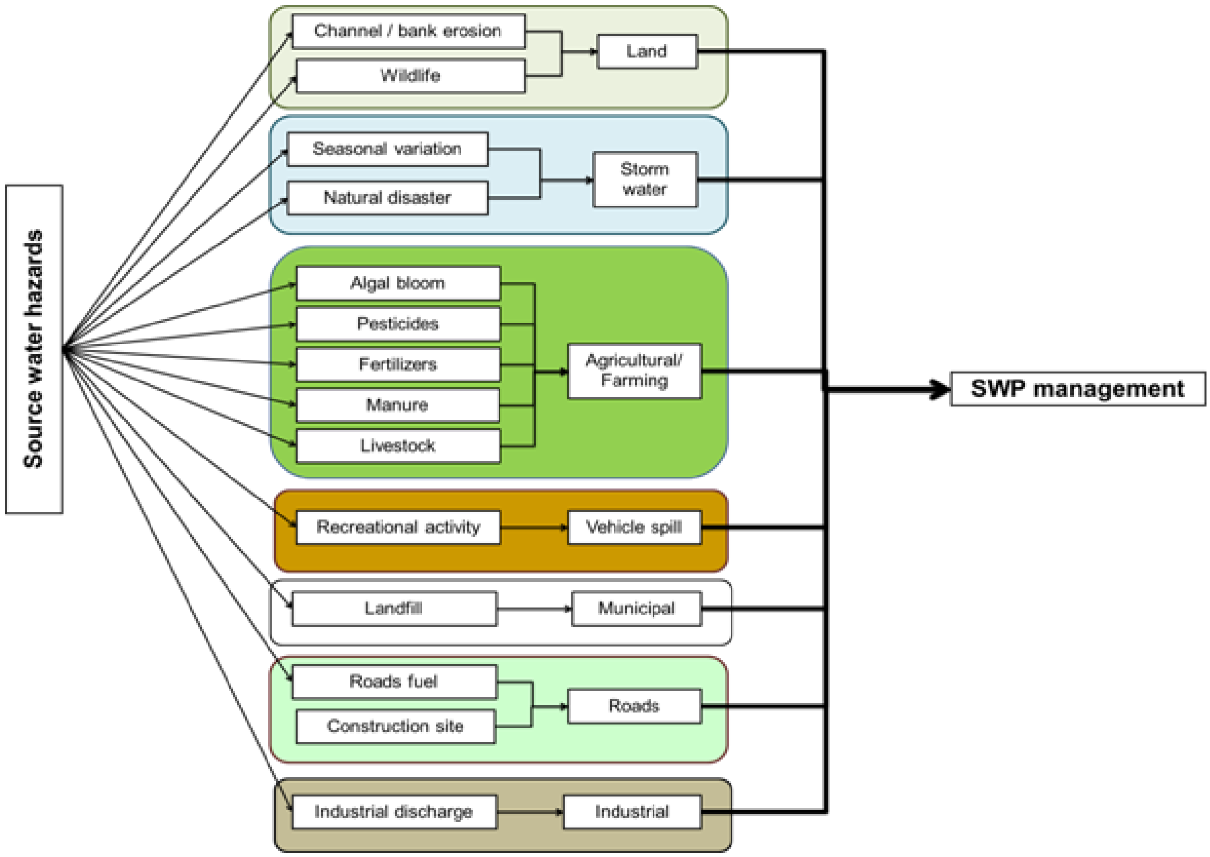


Figure 2.1: Common source water hazards and SWP management

2.2.1 Canadian regulations

Canada has roughly 9% of the world's fresh surface water (Can. Gov 2001). More than 85% of Canadians are supplied with drinking water from surface water (Davies and Mazumder, 2003). Surface waters can be affected by PPS and NPS and can lead to significant health-related risks if the water is not or poorly treated before consumption. Environment Canada (2001) has reported roughly 90,000 illnesses and 90 deaths due to unsafe drinking water each year. Especially, the *E. coli* outbreak in Walkerton (Ontario), *Cryptosporidium* outbreaks in North Battleford (Saskatchewan) and British Columbia (BC) have made drinking water one of the major health concerns in Canada in recent years (Krewski *et al*., 2004). Appendix A lists various regulations that may directly or indirectly influence source water protection in Ontario (ON), Alberta (AB), and British Columbia (BC).

Ontario (ON): In the recent past, a few serious incidences related to water outbreaks have been reported in Ontario. For instance in 2000, more than 2,300 people suffered gastroenteritis, 65 were hospitalized and 27 were affected by haemolytic uraemic syndrome during the Walkerton E. coli outbreak (Hrudey *et al*., 2003). More tragically, seven among those affected died (OMAG, 2002). After a long judicial investigation, the court concluded and recommended to reduce these types of incidences in the future through enhanced protection of source waters and training of technical staff.

In Ontario, source water protection is part of the watershed management program and has been clearly mentioned in the regulatory framework. Ontario regulations 288/07 and 287/07 under the Clean Water Act (2006a, 2006b) describe the role of a source water protection committee (298 members) and also list numerous protected source waters. Public involvement and participation are highly encouraged under the Ontario regulation 385/08 (Clean Water Act, 2006b) for effective SWP. Appendix A shows various recommended SWP strategies and many setback rules to comply with specific regulations.

Alberta (AB): Alberta promulgated many regulations that are indirectly related to source water protection. A few cases of high faecal coliforms (FC) levels have been reported in Oldman River and its tributaries in Southern-Alberta during the period of 1998-2000 (Hyland et al., 2003). Since 2007, water management programs have been implemented for province wide source water protection through land use planning. The main target of these programs is to establish a water policy and implement integrated water management. Proper education/ awareness and advanced storm water management have been promoted (Linking Source Water Protection to Land Use Planning in Alberta, 2008). Appendix A highlights SWP strategies such as the conservation of forests and wetlands and effective drainage design. In addition, some setback regulations from pollutant sources are also discussed.

British Columbia (BC): Since 1980, more than 28 waterborne disease outbreaks have been reported in BC. In most of the cases, proper implementation of multi-barrier approach was lacking (Christensen and Parfitt, 2003). Numerous regulations have been promulgated over time that indirectly affect source water; however there is a growing need for more stringent and direct regulations for source water protection in BC. The Water Act (2007) encompasses groundwater regulations such as flood proofing. However, no allusion of surface source waters is available in these acts. The land management to reduce impervious layer of soil for improved infiltration was also not properly addressed in the Environment and Land Use Act (1996). In the Environmental Management Act (2004a, 2007, 2008a), source water protection was not clearly defined. However, in the Ecological Reserve Act (1975) under B.C. Reg. 335 number of rivers, streams, and creeks have been mentioned to protect certain eco-systems. Many agricultural management acts have been promulgated in BC with SWP strategies such as forests, vegetative buffer (Appendix A). The control of vehicular spillage is also mentioned in the Environmental Management Act (2004b) with restriction on recreational dumping. However, the regulations in BC (Appendix A) discuss problems of surface source waters in a general context, but do not explicitly discuss the detailed strategies to protect or control them.

2.2.2 USA

The United States Environmental Protection Agency (USEPA) is responsible for source water protection, and suggests a number of strategies to protect source water quality. In many major cities of USA, such as Seattle, San Francisco, Boston and New York, source water protection has been encouraged since the early 1800s - well before the availability of sophisticated water treatment technologies (Ernst, 2004). Currently, source water protection programs have been integrated with the Safe Drinking Water Act (SDWA) (State Source Water Assessment and Protection Programs Final Guidance, 1997). Conservation vegetation, e.g., buffer strips, riparian vegetation and wetlands have been recommended as methods to protect source water (USEPA 2001a, 2001d, 2001e). The USEPA has also proposed a number of other strategies, such as crop rotation, cover crop, spot treatment, storm water detention ponds`, fencing, geo-textile or impervious cover use. The basic information related to these strategies has been provided in Appendix B.

2.2.3 European Union

Kramer *et al*. (2001) reported more than 260,000 cases of gastrointestinal diseases per year in Europe. In most cases, the incidences of bacterial dysentery can easily be attributed to countries with lower standards of sanitation systems. Worldwide more than 325 parasitic protozoan outbreaks have been reported and of which around 28 percent were from European countries (Kourenti *et al*., 2007). The water quality regulations in European Union countries mainly emphasize treatment technologies, and there is much less emphasis on source water protection (New Drinking Water Directive, 1998). Surface water regulations were initiated with the 1975 Surface Water Directive and later were updated by the 1980 Drinking Water Directive 80/778/EEC (Drinking Water Directive, 1980). Regulations related to drinking water (New Drinking Water Directive, 1998), sources of harmful substances (Dangerous Substance Directive, 2006), nitrate (Nitrates Directive, 1991) and pesticides (Council Directive, 1991) also emphasize strict maintenance of a threshold value (guideline value) of the water quality parameters rather than focusing on protecting source water.

2.2.4 Australia

Australia is mainly a dry place but has variations, e.g., most of the areas have low rainfall while the coast of the eastern seaboard has high rainfall (ABS, 2000). The Murray-Darling River is the only major river which is under great pressure because of increasing agriculture (McKay and Moeller, 2000) that uses large quantities of pesticides and herbicides. Blue-green algae have been identified as a threat to surface waters all over Australia (Atech Group, 2000). In 1991, Australia faced tremendous *Cyanobacteria* blooms which affected more than 1,000 km of the Murray-Darling River and many rural water supplies (McKay and Moeller, 2000).

Australia has one of the most sophisticated water supply management systems which strictly follow the principles of multi-barrier approach with special emphasis on source water protection[1]. From source to tap, the Drinking Water Quality Guidelines in Australia are based on risk assessment approach (Australian Government, 2004). Sedimentation ponds, artificial wetlands, water infiltration (recharge), source controls, and public education are highly encouraged in Australia for effective source water protection (Davis and Birch, 2009). Australia has promulgated numerous regulations to protect surface waters from industrial and commercial

[1] http://www.water.wa.gov.au/Waterways+health/Drinking+water/default.aspx

sources of pollution for more than three decades, but it is still in the process of developing rules for dealing with nonpoint pollution sources (Davis and Birch, 2009). To make water management process more cost effective in Australia, the planning decisions are based on population density (Pigram, 1993).

2.3 Source Water Protection (SWP) Strategies

SWP strategies can directly or indirectly improve the water quality at the source by reducing the pollutant loads entering into source waters. Generally, there are two types of SWP strategies: 1) storm water management, and 2) physical barriers to protect source water contamination. Most of the existing regulations have been focussed on storm water management, and control excess runoff from heavy rainfall or snowfall. However, other strategies including crop rotation, cover crop, fencing, and buffer strip can also be effective for protecting source waters. Examples of indirect strategies are enforcing regulations, increasing public education (and awareness) and regular water quality monitoring. These indirect actions lead to an improvement of source water quality as they promote direct actions.

2.3.1 Storm water management

Storm water management (SWM) plays an important role in protecting source water from nonpoint pollution sources (NPS) which is also called low impact development (LID). Effective storm water management limit the untreated runoff (due to rainfall or snowmelt) or from the CSO entering into the source water. This can be achieved through specific arrangements by collecting runoff or CSO during excessive storm events.

Storm water can cause problems as it carries many pollutants in large quantities to source water. The main purpose of storm water management is to reduce the pollutant load either through controlling runoff entering into the receiving water bodies or providing desired water treatment before it is discharged into surface waters. For example, places used for storm water management are detention ponds that collect water and provide basic treatment naturally and allow the treated water to go into the source waters at a regulated lower rate. The treatment is naturally performed through processes like sedimentation (Hsieh and Davis, 2005; Hsieh *et al*., 2007a, 2007b; Hathaway *et al*., 2009; Scholz and Yazdi, 2009), adsorption (Hsieh and Davis, 2005; Hathaway *et al*., 2009; Muthanna *et al*., 2007), infiltration (Muthanna *et al*., 2007; Passeport *et al*., 2009; Hsieh *et al*., 2007a, 2007b), filtration (Hsieh and Davis, 2005; Muthanna *et al*., 2007; Scholz and Yazdi, 2009; Passeport *et al*., 2009), decomposition (Muthanna *et al*., 2007; Scholz and Yazdi, 2009), ion-exchange (Muthanna *et al*., 2007), oxidation-reduction (Hathaway *et al*., 2009) and biological uptake (Hsieh *et al*., 2007a; 2007b; Hathaway *et al*., 2009; Muthanna *et al*., 2007). These processes remove TSS, coliform bacteria, nutrients (e.g., phosphorus and nitrogen), heavy metals, and trace metals with varying degrees of success based on the design of the facility. Proper management of storm water also helps in reducing the quantity of storm water through evapotranspiration. Common strategies under storm water management includes: wet detention basin, storm water wetlands, sand filter, bioretention, grass swales, and extended detention basins/ dry ponds/ dry detention ponds/ detention basin (Hsieh and Davis, 2005; Hathaway *et al*., 2009; Muthanna *et al*., 2007; NCDENP, 1999; Scholz and Yazdi, 2009; Passeport *et al*., 2009). Figure 2.2 schematically compares six strategies that include: extended dry detention pond, wet detention pond, storm water wetland, bioretention area, sand filter, and grass swales.

1. **Extended detention pond/ dry ponds** (Figure 2.2a) are simple facilities and generally less effective. For example, the removal efficiency in case of TSS is as low as ~50% (NCDENP, 1999).
2. **Wet detention ponds** (Figure 2.2b) can hold storm water in a temporary pond first and then it allows it to go into a permanent pond. It may also contain a fore bay to collect the water that can remove suspended sediments. It may have marsh which can increase the biological uptake of the nutrients. Because of this improved design, wet detention ponds are more efficient in removing TSS (~85%).
3. **Storm water wetlands** are arrangements that contain both soil and plants and are effective in removing phosphorous, trace metals, and hydrocarbons through physico-chemical as well as biological pathways (NCDENP, 1999). Figure 2.2c shows the specifications of storm water wetlands (the area generally contains 50% high marsh, 40% low marsh and 10% water).
4. **Bioretention area** (Figure 2.2d) contains a grass buffer strip, a sand bed, plants, ponding area, and planting soil for pollutant removal. Three species of trees and three species of shrubs are essential on the area with certain gradient for the grass buffer strips.

5. **Sand filters** (Figure 2.2e) have sedimentation as well as a sand chamber to remove the particulate matter mainly in addition to moderate bacteria removal. However, sand filters are only suitable for extremely urban and small areas (NCDENP, 1999).
6. **Grass swale** (Figure 2.2f) is the cheapest and the simplest strategy that consists of a trapezoidal or parabolic pond with low depth containing hard grass. It has limited pollutant removal efficiency as compared to other options.

There are basic differences in the structure and design parameters (media depth, retention time, vegetation level and water depth) of these facilities that lead to various degrees of removal efficiencies for different water quality parameters. The percentage removals of TSS for extended dry detention pond, wet detention pond, bioretention area, storm water wetland, grass swales, and sand filter are 50%, 85%, 85%, 35-85%, 85%, 35% and 85%, respectively. Features of storm water treatment strategies are compared in Table 2.3. Weiss *et al*. (2007) provided a detailed discussion on operation and maintenance cost of storm water management strategies. Storm water wetlands, grass swales, and dry detention ponds are generally found to be costly due to high land requisition cost. Therefore they may not be very pragmatic in urban dwellings where land is limited and expensive. Apart from land costs, dry detention ponds and grass swales are comparatively cheaper strategies from an operation view point. Generally, a combination of low cost strategies results in an effective system that ensures higher pollutant removal (Middleton and Barrett, 2008).

Scholz and Yadzi (2009) designed a system involving layer of gravel filter, detention pond and infiltration tank that has a removal efficiency of 77%, 83%, 32% and 47% for BOD_5, TSS, NO_3-N and ortho-phosphate-phosphorus, respectively. However, grass swales are considered aesthetically more pleasing because of their landscaping potential (NCDENP, 1999).

a)

b)

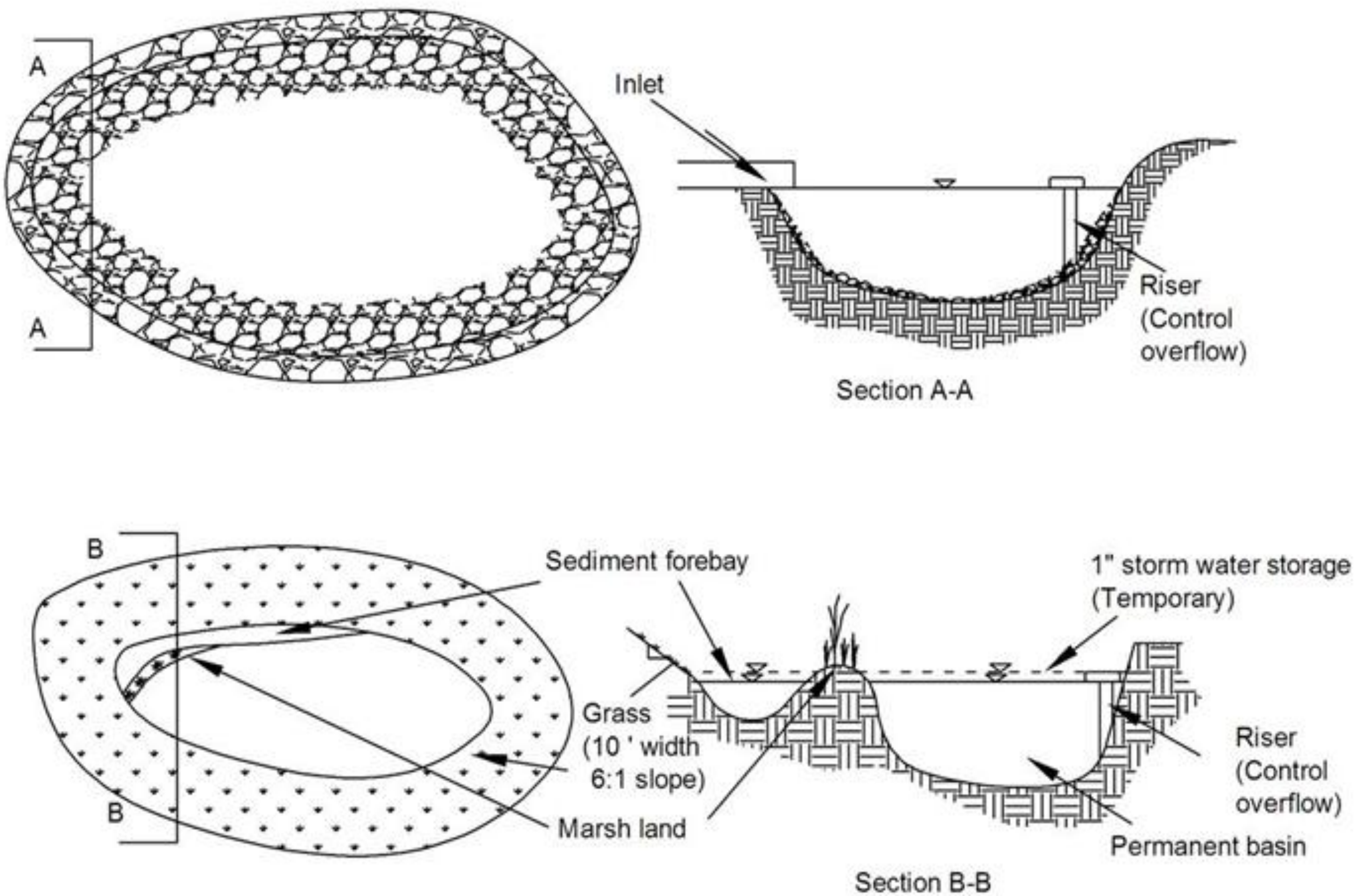
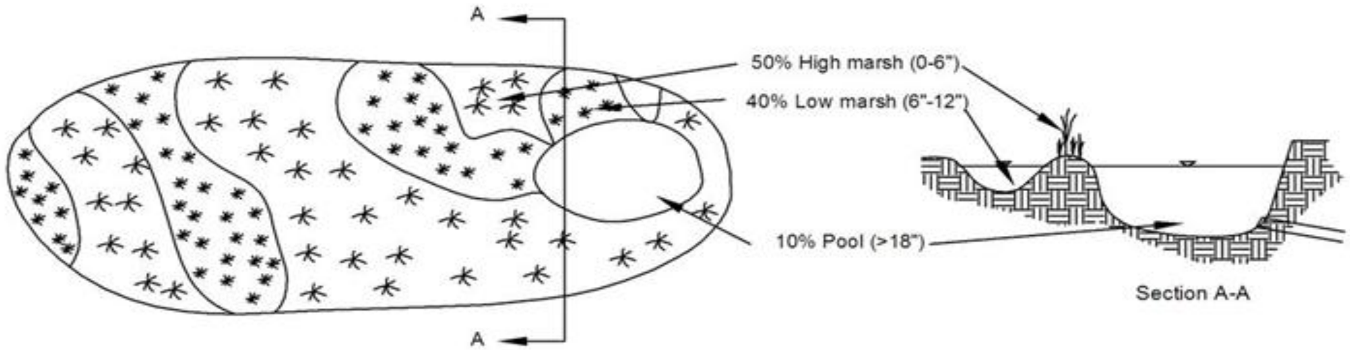


Figure 2.2: Storm water management ponds (NCDENP, 1999) a- Dry extended detention basin b- Wet detention pond

c)



d)

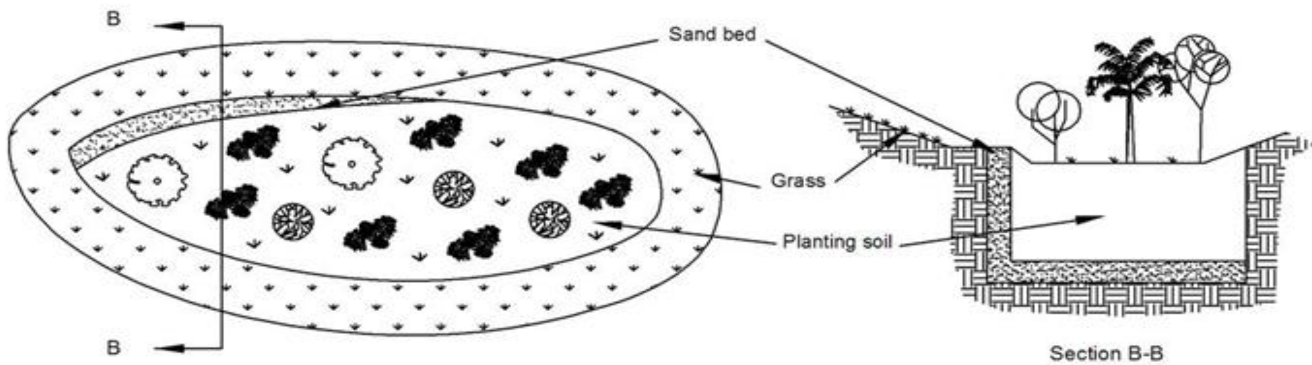
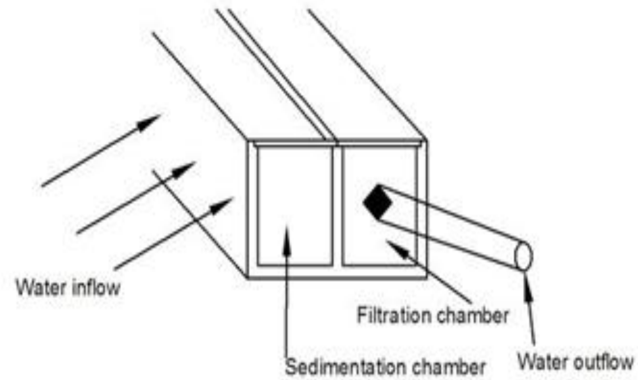


Figure 2.2: Storm water management ponds (NCDENP, 1999) c- Storm water wetland d- Bioretention areas

e)



f)

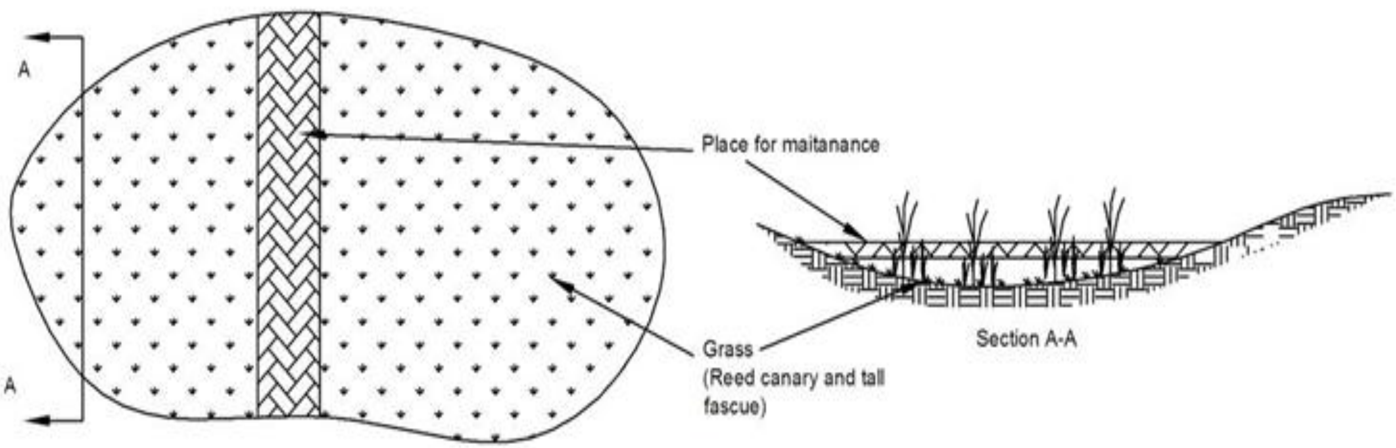


Figure 2.2: Storm water management ponds (NCDENP, 1999) e- Sand filters f- Grass swale

Table 2.3: Basic features of common storm water management strategies (NCDENP, 1999)

Main purpose and mechanism	Advantages	Disadvantages	Special Requisition	O & M cost requirement and amount
Extended detention basins/ dry ponds/ dry detention pond/ detention basins				
Removes less pollutant (50% TSS) which is done with filtration	Removes less pollutant (50% TSS) which is done with filtration	Removes less pollutant (50% TSS) which is done with filtration	Removes less pollutant (50% TSS) which is done with filtration	Removes less pollutant (50% TSS) which is done with filtration
Wet detention basin				
Removes sediments, nutrients and heavy metals with infiltration and sedimentation.	• It can be used in areas with low infiltration rate. • Has an extra temporary pond (above the main pond) to hold 1 inch storm water for 2-5 days.	• Frequent inspection is needed (e.g., 6 month) to run the system properly.	NR	Operation and maintenance cost is 5 % of the total cost.
Storm water wetlands				
Eliminates not only TSS but also phosphorus, trace metals, and hydrocarbons that are adsorbed to the surface of suspended particles with a number of physical, chemical and biological processes.	• The plants increases aesthetic look with proper landscaping. • It has longer detention time which ensures biological nutrient uptake by plants and algae.	• Large area is required. • Proper plant selection is required. • Immediate maintenance after any storm event is necessary.	Special plants are required for pollutant removal[1].	Cost is similar to wet detention basin but large land requirement makes it more expensive.

Bioretention areas				
Removes TSS, nutrients, trace and heavy metals by adsorption, filtration, volatilization, ion-exchange, and decomposition. Grass buffer strip of bioretention captures particles, and limits velocity. Sand bed provides aeration and drainage for microbes. Mulch layer ensures biological growth with organic matter, and petroleum decomposition.	Low cost compared to curbs, gutters for traffic area.	Maintenance of all the materials is necessary.	• Specification for soil and plants are required[2].	Maintenance of all the materials is necessary.
Sand filters				
Removes mainly particulate matter with moderate bacteria by sedimentation and filtration. • Sedimentation chamber of sand filter ensures sheet flow and limits sediments. • Sand chamber traps sediments with pollutants and provides media for microbial removal.	Annual maintenance is required.	Cannot remove TSS and NO_3-N efficiently.	NR	Once in a year is necessary which is moderate.
Grass swales				
• Removes mainly sediments and trace chemicals • Works as bio-filter to filter pollutants. Here, vegetation-lessen the velocity and increase the contact time for filtration	• Low construction and maintenance cost • Ensures replacement of gutter and curb with a better aesthetical view.	• Limited pollutant removal (35% TSS) • Use of fertilizer increases the nutrient amounts • Can generate odor and mosquito problems.	• Permeable and non compacted soil with lower water table (>1ft).	Less costly than gutter and curbs. Extensive sedimentation and erosion repair cost is required.

1- Table 2.2, 4.3, 4.4 (NCDENP, 1999); 2- Table 4.3 and 4.4 based on tolerance and morphology (NCDENP, 1999); 3- NR- Not required; O & M cost- Operation and maintenance cost

Table 2.4: Percent removal of water quality parameters through storm water management

Reference	**Type of SWM**	**TSS**	**TN**	**TP**	**BOD_5**	**Pb**	**FC**	***E. coli***
Middleton and Barrett (2008)	Extended detention basin	91	58	52		69		
Weiss *et al*. (2007)	Extended detention pond	53[a]		25[a]				
Hathaway *et al.* (2009)	Wet detention basin						>50	
Weiss *et al.* (2007)	Wet detention basin	65[a]		52[a]				
Weiss *et al.* (2007)	Storm water wetland	68[a]		42[a]				
Hathaway *et al.* (2009)	Wetlands					>50	>50	
Rusciano and Obropta (2007)	Bioretention	91.5					91.6	
Davis (2007)	Bioretention	41		68		86		
Davis (2007)	Bioretention (anaerobic sump)	22		74		79		
Hsieh and Davis (2005)	Bioretention	>96[a]		74[a]		98[a]		
Lucas and Greenway (2008)	Bioretention-vegetative		81[a]	91[a]				
Lucas and Greenway (2008)	Bioretention		41	73[a]				
Hunt *et al*. (2008)	Bioretention	59.4	32.2	31.4	63	31.4	69	71
Passeport *et al* .(2009)	Bioretention (grass)		56	63			77	
Weiss *et al.* (2007)	Sand filter	82[a]		46[a]				
Scholz and Yazdi (2009)	Combined detention and infiltration system	83		47[b]	77			

a- Change in load (mean) ; b- PO_4-P; TSS- Total suspended sediment; TN- total nitrogen; TP- total phosphorus; BOD_5-Biochemical Oxygen demand for 5 days; FC- Faecal Coliform

Vegetation allows storm water wetlands, bioretention and grass swales to remove nutrients through adsorption on the plants. Nevertheless, the excessive vegetation and its decomposition may also negatively affect the nutrient content in the source water (Li and Davis, 2009). Because of birds and animals' excreta, bacterial growth is possible and that leads to harmful microbial contamination. The information related to their impacts on various water quality parameters is provided in Table 2.4. The percent removals are generally reported by the reduction in event mean concentration (EMC) or by pollutant load reduction. Large variations can be observed for the same strategy due to variability in experimental setups though the basic features were similar. For example, for bioretention, Hunt *et al*. (2008) reported negative results (i.e., concentration increased) in the removal of NO_3-N and NO_2-N, whereas Davis (2007), Hsieh and Davis (2005) and Li and Davis (2009) have reported significant reduction.

Removal efficiency in case of vegetatated systems largely depends on a number of factors such as the soil topography, available nutrients in the soil, pH, vegetation type, and special arrangements such as an internal storage zone. The variability in these factors may cause variability in the removal efficiency. For example, Hunt *et al*. (2006) have suggested a saturation zone or internal storage zone (inside the pond and less permeable soil composition) to create anaerobic conditions for improved nitrate or nitrite removal as compared to normal aerobic conditions. A saturation zone can also increase the retention time and can enhance adsorption of the pollutants (Passeport *et al*., 2009).

Appendix C lists basic considerations for storm water management strategies. A minimum infiltration rate for soil is necessary to ensure a desired contact time between the media and the polluted water. Generally, more than two hours of retention time with < 0.25 m/hr infiltration rate is recommended (Hsieh *et al*., 2007a). Sandy loam or loamy sands have been recommended (NCDENP, 1999) as they provide an infiltration rate of 0.013-0.06 m/hr and ensure a proper retention time. In most cases, the retention time of these soils should be 24-48 hours, which is necessary to achieve effective pollutant removal. For vegetation, local plants that can absorb nutrients from the polluted water should be selected. P-index (phosphorous index) can be helpful to determine available nutrient amounts in soil that can limit excess nutrient release from soil (Hunt *et al*., 2008; Passeport *et al*., 2009). Exposure to sunlight with long retention times promotes coliform removal (Hathaway *et al*., 2009; Passport *et al*., 2009). A medium level of vegetation can ensure nutrient uptake as well as moderate the amount of sunlight exposure.

Generally, the media depth, water depth, vegetation level and retention time are found to be the common design parameters that can effectively improve the pollutant removal if designed properly. Table 2.5 provides the values of these design parameters (i.e., media depth, water depth and vegetation level, and retention time).

An additional strategy permeable pavement can also be effective strategy to limit storm water runoff in urban development. Permeable pavements can be made of a matrix of concrete blocks or a plastic web-type structure with voids filled with sand, gravel, or soil (Fujita, 1994). But, they may suffer some serious limitations due to requirement for frequent maintenance, which is generally provided through vacuum suction (Dietz, 2007). They are suitable in specific situations such as in low traffic areas (e.g., parking area, sidewalks) (USEPA, 2000) or in an area with high clay soil to prevent groundwater contamination and have been found to be unsuitable during winter (Dietz, 2007). In some cases, they were found to be in effective after only six months (Barrett and Shaw, 2007). However, these strategies can be effective if the objective is groundwater recharge (Scholz and Grabowlecki, 2007).

Green roofs can also be used as an SWM strategy, especially for old urban areas due to high imperviousness (USEPA, 2000). Green roofs consist of a vegetative layer, synthetic drain, geotextile and a media. The green roof reduces the flow rate of runoff but in some cases increases the chemical oxygen demand and phosphorus which is not suitable for all places (Bliss *et al*., 2009).

Table 2.5: Basic design parameters for storm water management strategies (NCDENP, 1999)

SWM pond name	Media depth, m	Water depth, m	Vegetation level (type and intensity)	Retention time, hr
Extended dry detention basin	0	0.6	NIL	24-48
Wet detention basin	0	0.9-1.9	NIL or low	48
Storm water wetlands	0	>0.6	Medium: marshes	48
Bioretention areas	1.5-1.8	0.15	High: Grass, shrubs, trees	16-96
Sand filters	>0.46	0.45	NIL	24
Grass swales	0	0.1-1.5	Grass	15

2.3.2 Other SWP strategies

Apart from SWM strategies, numerous best management practices (BMPs) have been adopted to limit pollutants entering into source waters. Natural vegetation such as vegetative cover (e.g. forests), plant cover, mulching, vegetative hedges, grass land management, and vetiver (an special type of plant) fencing have the natural ability to prevent soil erosion or runoff which can contain fertilizers, pesticides, and many other pollutants. Forest management with wetland and riparian areas can maintain surface water quality by protecting against soil erosion (Antoniadis *et al*., 2007; Kennedy and Mayer, 2002). Deforestation can lead to negative impacts such as an increase in sediment of transfer because of accelerated erosion, increase in nutrients after their release from decaying organic matter on the ground or in the water; increase in nutrient organic and inorganic concentrations because of harvesting, fertilization and pesticide application accumulation of slash and other organic debris in water bodies which can lead depletion of dissolved oxygen (DO); and an increase in temperatures because of removal of riparian vegetation; and increase in stream flow due to reduced evapo-transpiration (Ernst *et al*., 2004; Nunez *et al*., 2006).

A vegetated filter strip can perform the same function as forests around source water. Vegetated strips (buffer strips/ filter strips) are found to be very effective in protecting source waters from eroded soil (Grace, 2002), nutrients (Dillaha *et al*., 1989), pesticides (Dosskey, 2001), agricultural pollution (Lee *et al*., 2000; Schoonover *et al.*, 2005; Lowrance *et al*., 2002) and from other nonpoint sources of pollution as well as from runoff from roads or construction sites. Generally, buffer strips/ vegetated filter strips (VFS) consist of stiff and tall grass ranging from 0.75 to 1.2 m width (Kemper *et al.*, 1992; Yuan *et al*., 2009) and surround the source water in order to stabilize the soil using vegetation roots. The Natural Resources Conservation Service (NRCS) has recommended an 8-10 m buffer strip width (Yuan *et al*., 2009). It has been observed that if the width > 5 m, the overall removal efficiency of pollutant loads may approach ~ 80%. Dosskey *et al.* (2005) recommended the use of Global Positioning System (GPS) and Geographical Information System (GIS) for providing variable widths of buffer strips depending on expected pollutant loads around source water. Figure 2.3 provides three constitutive zones of buffer strips (USEPA, 2001e): (a) four/five rows of trees, (b) one/two rows of shrubs and (c) 6.1m to 7.3m feet of grass. The forests and grass area within 6.1 m parallel to the source water can be used as a buffer to ensure good water quality (Herring *et al*., 2006).

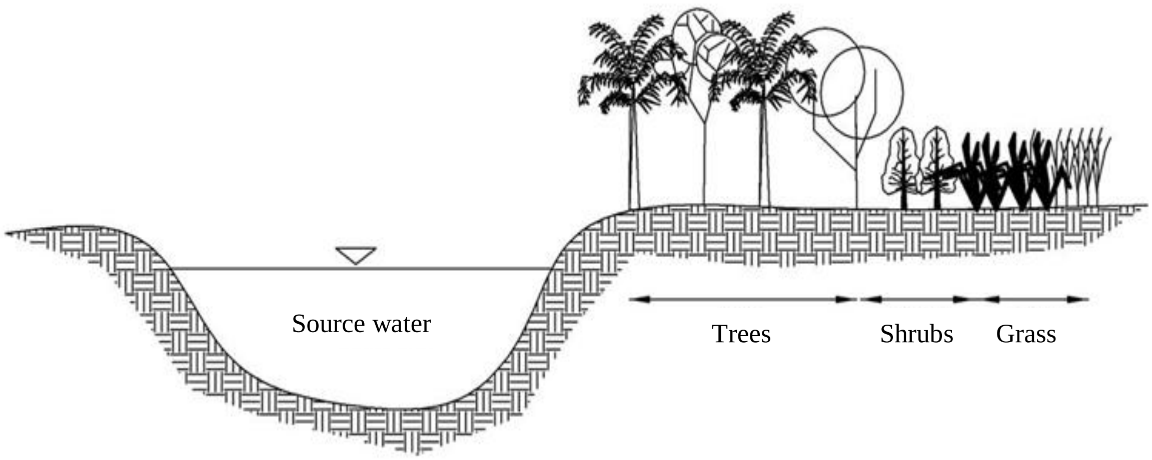


Figure 2.3: Example of a buffer strip (USEPA, 2001e)

Long rooted vegetation is preferable with a gentle slope for better efficiency. The USDA-NRCS recommended combining riparian forest and filtering strip (grassland) for effective water quality management (Herring *et al*., 2006). However, sometimes more than 100 m of buffer strips are recommended around lakes to avoid large pollution loads (Devito *et a*l., 2000). Franti (1997) has discussed the NRCS slope-width relationship which suggests that high sloppy to land area needs larger buffer strips to slow down the velocity of runoff water gradually to slowly infiltrate the water. Table 2.6 highlights the key factors (such as width, slope, length and type of vegetation) of buffer strip and their impacts on removal efficiency of regular water quality parameters as well as pesticides such as atrazine, metolachlor and chlorpyrifor (Arora *et al*., 2003; Borin *et al*., 2010; Patty *et al*., 1997).

Fencing is a simple arrangement to keep livestock away from a source water boundary (physical barrier) to avoid contamination from animal waste and prevent bank erosion caused by trampling of the banks by animals (Bewsell *et al*., 2007; Kolodziej and Sedlak, 2007). It also prevents, depending on the type of fence, the source water from re-suspension of sediments by disturbance in water and also ensures riparian health with undisturbed wetlands (Larsen *et al*., 1994). There have been only few studies (Table 2.6) reported on the impacts of fencing on source water quality. However, a limited reduction in nutrients, TSS and coliform bacteria is expected (McDowell, 2008).

Table 2.6: Effect of other SWP strategies in pollutant removal

Reference	Brief description	Turbidity	TSS	TP	NH_4-N/ NO_3-N	*E Coli*	Pesticides
Fencing							
Miller *et al*. (2010)	Barbed wire fencing (Both sides), length-800 m, distance between fencing and river-40-80m	35.5[1] 34.6[1]	69.3[1] 67.7[2]	0.07[1] 0.07[2]			
McDowell (2008)	Fenced off with riparian vegetation		98	86	91/ 78	92	
Vegetated filter strip (VFS)							
Sullivan *et al.* (2007)	Width-0, 1, 3, 8, 15, 25 m, slope-3.8-7%					99[3]	
Duchemin and Hogue (2009)	Grass: Planted grain corn paired with a 5 m VFS of 45% red fescue (*Festuca rubra L.*), 45% redtop (*Agrostis alba L.)* and 10% perennial ryegrass (*Lolium perenne L.*)		87	86	57/ 33	48	
	Grass/poplar tree: Grain corn with a 5 m VFS with grass and eight hybrid poplar trees arranged in three rows in the grassy area		85	57		57	.
Borin *et al.* (2010)	Length-35m; width-6m, slope- 1.8%, vegetation- two rows of trees			50			75
Watts and Torbert (2009)	VFS with various amount of gypsum ($CaSO_4$), width- 0.3048m			36			
Mankin *et al.* (2007)	Natural succession grasses, width-16m, slope-4.1%,		99.9	98.6			
	A strip of 5 m planted with native grass with three rows of American plum, width-10.6m, slope-3.9%		99.7	93.4			
	A 5-m strip of natural succession grasses followed by three rows of American plum spaced 1 by 2 m, width-8.3m, slope-4.2%		99.5	92.1			
Bhattarai *et al*. (2009)	Filter strip: width-14 m, length-113 m, slope-1.5%, vegetation-grass			70			
Clausen *et al.* (2000)	Width-35m, length-250m		92	73			
Arora *et al*. (2003)	Width- 1.52 m wide, length- 20.12 m, vegetation-grass						*
Patty *et al.* (1997)	Grassed strip, width- 0, 6, 12 or 18 m, slope- 7-15%,						**

1-Upstream concentration (mean), Turbidity in NTU, TSS (Total suspended solids), DO (Dissolved Oxygen), TN (Total Nitrogen), TP (Total Phosphorous) in mg/l, E coli in #/100ml; 2- Downstream concentration (mean), Turbidity in NTU, TSS (Total suspended solids), DO (Dissolved Oxygen), TN (Total Nitrogen), TP (Total Phosphorous) in mg/l, E coli in #/100ml; 3- Faecal coliform; VFS- Vegetated filter strip; *- Atrazine-46.8%, Metolachlor-48.1%, Chlropyrifor-76.9% removal; **-Atrazine- 72% removal

The agricultural practice of mixed cropping instead of monoculture, strip cropping, cover cropping, crop rotations, cultivation of shrubs and herbs, contour cultivation, conservation tillage, land levelling, use of improved variety of seeds, and horticulture increase the productivity of the soil and also its ability to slowly infiltrate water and protect source waters (Kleinman *et al.*, 2005; USEPA, 2001a, 2001b). These strategies can limit fertilizer use and as a result reduce the probability of nutrient contamination in surface water (Kleinman *et al.*, 2005). Therefore, some effective agricultural practices (e.g., cover crop and crop rotation) along with some parameter representing soil properties such as dry bulk density and soil water content can refer to proper agricultural management.

For point sources of pollution, wastewater treatment is required to reduce pollutant loads which in addition to conventional pollution loads may also contain heavy metals and complex organic/ inorganic compounds. Numerous physico-chemical and biological treatment processes have commonly been used for the treatment of industrial, commercial and residential wastewaters before they are discharged into receiving water bodies. Point sources of pollution are not explicitly considered in this research.

2.4 Watershed Models

Watershed models are used to predict a change in water quality based on specific land use, soil properties, precipitation patterns, vegetation type and related environmental factors. Many watershed models are available that use complex mathematical mass balance equations. One example is the universal soil loss equation (USLE) (Bingner *et al.*, 2001; Bjorneberg, 1999; Chen *et al.*, 2003; Irvine *et al.*, 1993; Ovbiebo and She, 1995; Roesner *et al.*, 1988; Williams *et al.*, 1983; Young *et al.*, 1987).

The USLE determines the pollutant load in terms of erosion in ton/ha/year and depends on rainfall patterns, type of soil, crop type and land management practices (Wischmeier and Smith, 1978). Based on these data, the rainfall erosivity index, soil erodibility, topographical factor, plant cover factor and erosion control factor can be determined (Hacisalihoglu *et al.*, 2010). Each of these factors and indices can be derived either from look-up tables or using prescribed mathematical equations that can be based on empirical relationships or simple mass balances. The modified universal soil loss equation (MUSLE) includes additional factors like runoff volume and peak runoff rate that adds complexity (Noor *et al.*, 2010). These models are data demanding which makes their use very limited compared to the export coefficient (EC) approach (discussed earlier in section 2.1).

The USEPA TMDL (Total maximum daily load model)-toolbox provides a platform for a number of models such as Watershed Assessment Model (WAMView), Storm Water Management Model (SWMM), Water Quality Model (QUAL2K) and Watershed Characterization System (WCS). The USEPA TMDL-toolbox is complex and deals with various aspects of hydrologic analysis, water quality and fate & transport modelling (USEPA, 1992). Table 2.7 provides a comparison of commonly used models and tools. The models such as BASINS, P8-UCM, and STORM are based on EC approach and found to be much simpler. Some models such as DRAINMOD, GISPLM, GSSHA, KINEROS2 and WEPP have limited use in dealing with water quality issues. On the other hand BASINS, HSPF, SWMM, TMDL-toolbox, WARMF, and WinHSPF are useful for water quality assessment. Tables 2.7 also compares selected models based on their capability to predict improvement in case of four SWP strategies including SWM-pond (storm water management), VFS (vegetated filter strips), PCAP (e.g., crop rotation, soil properties) and Fen (fencing).

2.5 Water Quality Assessment

Quantitative assessment of water quality can be performed using a unit less measure, called water quality index (WQI) based on selected water quality parameters (WQP). The WQI formulation includes the following three steps:

(1) selecting representative water quality parameters

(2) converting non-commensurable WQP measurements into a monotonic quality scale to obtain sub-indices (unit less measure), and

(3) aggregating sub-indices into a unit less number index (WQI).

2.5.1 Selection of water quality parameters (WQP)

Generally various physico-chemical and microbial parameters have been used for surface water quality monitoring. Water quality can be compromised at the source due to point or non-point pollution sources. To develop a WQI, the selection of water quality parameters depends on the predefined use of water such as bathing, drinking, and agriculture.

Table 2.7: Comparison of various watershed models

Common models	Reference	Complexity level		Water quality issues					SWP strategies			
		Export coefficient	Complex equation	P	N	M	OM	TS	SWM pond	VFS/ Veg.	PCAP	Fen
AGNPS	Young *et al.* (1987)		√	√	√			√	√	√	√	
AnnAGNPS	Bingner *et al.* (2001)		√	√	√			√	√	√	√	
BASINS	Lahlou *et al.* (1998)	√		√	√	√	√	√	√	√	√	
DIAS/IDLMAS	Sydelko *et al.* (2000)		√	√								
DRAINMOD	Skaggs (1980)		√		√					√[a]		
DWSM	Borah *et al.* (2002)		√	√	√			√	√			
EPIC	Williams *et al.* (1983)		√	√	√			√	√	√[a]	√	
GISPLM	Walker (1997)		√		√						√	
GSSHA	Downer and Ogden (2002)		√	√					√	√[a]	√	
HSPF	HSPF (1985)		√	√	√	√	√	√				
KINEROS2	Woolhiser *et al.* (1990)		√	√					√	√	√	
LSPC	USEPA (2002)		√	√	√			√	√	√	√	
MUSIC	Chiew and McMahon (1999)			√					√	√		
P8-UCM	Palmstrom and Walker (1990)	√		√	√			√	√	√	√	
PCSWMM	Irvine *et al*. (1993)		√	√	√	√		√	√	√	√	
SLAMM	Pitt (1993)		√	√	√				√	√	√	
STORM	USACE-HEC (1977)	√		√	√	√						
SWAT	Neitsch *et al.* (2001)		√	√	√			√	√	√	√	
SWMM	Roesner *et al.* (1988)		√	√	√	√	√	√	√		√	
TMDL-Toolbox	USEPA (1992)		√	√	√	√	√	√	√	√	√	
WAMView	Bottcher (1998)		√	√	√	√	√		√	√	√	
WARMF	Chen *et al*. (2003)		√	√	√	√	√			√[a]		
WEPP	Bjorneberg (1999)		√	√							√	

Common models	Reference	Complexity level		Water quality issues					SWP strategies			
		Export coefficient	Complex equation	P	N	M	OM	TS	SWM pond	VFS/ Veg.	PCAP	Fen
WMS	EMRL (1998)		√	√	√	√	√	√	√	√[a]	√	

a- Wetlands; P-Physical/ aesthetic issues; N-nutrients; M- Microbes; OM-organic matter; TS- toxic substances; VFS-vegetated filter strip; Veg-vegetation; PCAP- pollution control by agricultural practice; Fen-fencing;

AGNPS- Agricultural Nonpoint Source Pollution Model; AnnAGNPS- Annualized Agricultural Nonpoint Source Pollution Model; BASINS- Better Assessment Science Integrating Point and Nonpoint Sources; DIAS/IDLAMS- Dynamic Information Architecture System/Integrated Dynamic Landscape Analysis and Modeling System; DRAINMOD- A hydrological model for poorly drained Soils; DWSM- Dynamic Watershed Simulation Model; EPIC- Erosion Productivity Impact Calculator; GISPLM- GIS-Based Phosphorus Loading Model; GSSHA- Gridded Surface Subsurface Hydrologic Analysis; HSPF- Hydrologic Simulation Program FORTRAN; KINEROS2- Kinematic Runoff and Erosion Model v2; LSPC- Loading Simulation Program in C++; MUSIC- Model for Urban Storm water Improvement Conceptualization; P8-UCM- Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds─Urban Catchment Model; PCSWMM- Storm Water Management Model; SLAMM- Source Loading and Management Model ; STORM- Storage, Treatment, Overflow, Runoff Model; SWAT- Soil and Water Assessment Tool; SWMM- Storm Water Management Model; TMDL-toolbox- Total Maximum Daily Load- toolbox; WAMView- Watershed Assessment Model with an Arc View Interface; WARMF- Watershed Analysis Risk Management Framework; WEPP- Water Erosion Prediction Project; Win HSPF- An Interactive Windows Interface to HSPF;

For example for drinking, in addition to microbial indicators (e.g., Faecal coliform, total coliform, *E coli* and *Cryptosporidium*), the aesthetic parameters color and turbidity, as well as the nutrients and toxic substances are important. For recreational activities like swimming, a special emphasis is given to the microbial indicators and less on other factors. In case of agricultural use, generally the microbial indicators are not considered as important as heavy metals and nutrients. A flawed assessment of water quality for a specific usage can lead to adverse consequences in terms of human health.

Table 2.8 presents guidelines and standards for common water quality parameters recommended by various agencies including WHO, USEPA, Heath Canada, European drinking water standard (New Drinking Water Directive, 1998), Australian drinking water standard and BC MOE (British Columbia Ministry of Environment) in terms of health and non-health (Primary and aesthetics) context. The recommended threshold levels vary significantly for the same parameter. It can also be noted that more than one water quality parameter is recommended for a specific water quality characteristic, e.g., conductivity and total dissolved solids (TDS). However, the general rule is that water quality should be assessed using minimum number of parameters by avoiding redundancy where possible without compromising on the assessment accuracy. It is generally recommended to use one or two WQP with respect to microbial, aesthetics, organic substances, heavy metals, nutrients and toxic substances.

Kumar and Alappat (2009) provided a list of nine water quality parameters based on a recommendation by 142 water quality experts. This list includes: dissolved oxygen (DO), Faecal coliform (FC), five day biochemical oxygen demand (BOD_5), nitrate nitrogen (NO_3-N), phosphates (PO_4), temperature (Temp), pH, total solids and turbidity. However, heavy metals and pesticides/ herbicides were not included in this list. In this research, total suspended solids (TSS) have been proposed instead of turbidity (commonly measured for drinking water after treatment) as it has been more frequently used in surface water quality studies (Bordalo *et al*., 2006; Jonnalagadda and Mhere, 2001; Liou *et al*., 2003; Ocampo-Duque *et al*., 2006). Based on detailed literature review, the proposed list may include TSS, Temp, TDS, total organic carbon (TOC), BOD_5, total coliform (TC), Faecal coliform (FC), TN, TP, and lead (Pb). It is important to note that other water quality parameters can be added (or removed) from this proposed list if they are justified based on data availability and water use. For example, if the source water is susceptible to a specific toxic substance, say a pesticide, the list should include that pollutant.

Table 2.8: Water quality standards and guidelines recommended by various agencies

Parameters (units)	WHO		USEPA			Health Canada		Europe[1]	Australia		BC MOE[6]	
	HB	NHB	MCL[2]	MCLG	MCL[3]	MAC	AO		HB	AO	Guideline	Guide-Limit
Microorganism												
Faecal coliform, MPN/100 ml	0*					0*		0*	0*		10**	20**
Total coliform, MPN/100 ml			<1									50**
Primary /physical												
Dissolved Oxygen, %										>85		
pH		6.5-8.5			6.5-8.5		6.5-8.5	6.5-9.5		6.5-8.5	6.5-8.5	6.5-8.5
Turbidity, NTU		<5	0.5-1				<1	<1		5		
Temperature, °C							≤15				15	22
Total dissolved solids, mg/l		1000			500		≤500				500	
Total suspended solids, mg/l												25
Conductivity, μS/cm					4.7 -5.8[4]			2,500		< 400***		
Nutrients												
Total phosphorus, mg/l											0.01	
Nitrate- N, mg/l	10		10	10		10		10			10[5]	
Nitrite-N, mg/l	1		1	1		1		1				
Ammonia, mg/l		1.5										
Nitrate, mg/l									50			
Nitrite, mg/l									3			
Organic matter												
TOC, mg/l			0.05[4]								4	
BOD_5 , mg/l												3
Heavy metals												
Arsenic, mg/l	0.01		0.05			0.01	0		0		0.03	0
Lead, mg/l	0.01		0.015	0		0.01	0		0		0.05	
Mercury, mg/l	0.001		0.002	0		0.001	0		0		0	0

Chromium, mg/l	0.05	0.1	0.1	0.05	0	0.1	
Cadmium, mg/l	0.003	0.005	0.01	0.005	0	0	0
Pesticides							
Atrazine, mg/l	0.002	0.003	0	0.005		0	
Simazine, mg/l	0.002	0.004	0	0.01		0	
TCB, mg/l	0.02	0.07	0.07				
Chlorpyrifos, mg/l	0.03			0.09			
Each pesticides, mg/l					0		

HB- Health based guideline
NHB- Non- health based guideline
MCL- Health-related standards called the Maximum Contaminant Levels (MCLs) which are the maximum permissible level of a contaminant in water delivered to users of a public water system under the Safe Drinking Water Act
MCLG- Maximum Contaminant Level Goals (MCLGs) at levels where no known or anticipated adverse effects on health occur.
MAC- The maximum acceptable concentration
AO- Aesthetic objectives
TCB- Trichlorobenzene (1, 2, 4)
MPN/ 100ml- Most probable number per 100 ml

*-Drinking water related
**-CFU/100ml- Colony forming unit per 100 ml
***- Electric conductivity unit

1- European drinking water standard (98/83/EC)
2- Primary MCL
3- Secondary MCL
4- USP 23-Standad for purified water imposed by USEPA regulations for drinking water
5- Instead of nitrate-nitrogen the amount is for total nitrogen
6- Environmental standards

2.5.2 Transformation into sub-indices

The units of water quality parameters are non-commensurate. In addition, some parameters positively impact ‘water quality’ whereas others are negatively correlated with water quality. For example, a higher value of DO is desirable and represents a good quality, whereas, a lower value of TSS is desirable and represents a good quality. Therefore, before aggregation is performed, a transformation (using appropriate functions) is required to convert the real values of each WQP into a monotonic quality scale $\in [0, 1]$, where 1 represents the *best* quality and 0 represents the *worst* quality. The transformed values of a water quality parameter are referred to as sub-index, where each sub-index $\in [0, 1]$ regardless of the original units. Two types of functions are required to convert the real WQP value into sub-index, e.g., quality (parameter representing good water quality, e.g., DO) and pollutant (parameter representing bad water quality e.g., TSS) parameters. Figure 2.4 shows WQP transformations based on these functions denoted as sub-index $_{\text{increasing}}$, and sub-index $_{\text{decreasing},}$ respectively.

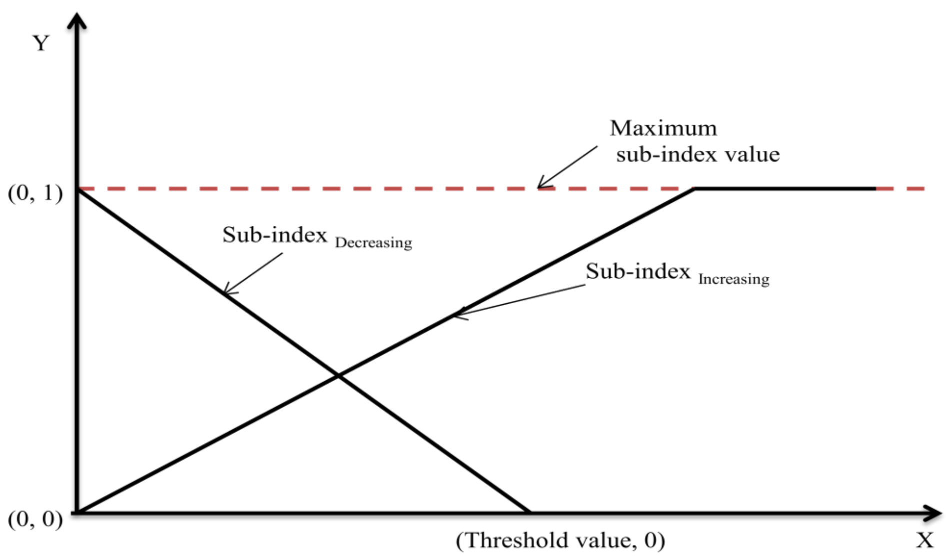


Figure 2.4: Typical sub-index transformations for water quality parameters

Numerous functions have been proposed for transformation of real values into sub-indices (Banerjee and Srivastava, 2009; Cude, 2001; Swamee and Tyagi, 2000). Figure 2.5 represents the sub-index functions for ten selected water quality parameters. Normalization functions are adapted from different studies (Banarjee and Srivastava, 2009; Brown *et al.,* 1970; Cude, 2001; Liou *et al.*, 2004; Ocampo-Duque *et al.*, 2006) with little modification. However, a simple linear sub-index$_{\text{decreasing}}$ function can be used for any additional WQP representing pollutants in source water which is stated below:

$$\text{Sub-index}_{\text{Decreasing}} = 1 - \frac{X}{TV} \tag{2.1}$$

where

$\text{Sub} - \text{index}_{\text{Decreasing}}$ = Sub-index value of WQP $\in$ [0-1]

X = WQP concentration, mg/l

TV = Threshold value, mg/l

It should be noted that the sub-index value can be different depending on the intended use of water. For example, the sub-index value of FC should be different for drinking water quality from source water quality if the issue is other than drinking (Figure 2.5).

2.5.3 Aggregation formulations

After transformation, the final step is an aggregation of sub-indices. There are four common types of aggregation formulations that include additive, multiplicative, logical or based on water quality guidelines. A few common formulations used for developing water quality indices are provided in Appendix D. These include: National Sanitation Foundation (NSF-WQI), Oregon (O-WQI), P-W WQI (Pesce and Wunderlin, 2000), Central Pollution Control Board (CPCB-WQI) (Sarkar and Abbasi, 2006), River Pollution Index (RPI) (Liou *et al.,* 2004), Universal water quality index (U-WQI) (Boyacioglu, 2007), S- WQI (Said *et al.*, 2004), Simplified Water Quality Index (ISQA), CCME- WQI (Canadian Council of Ministers of the Environment Water Quality Index) and S-T WQI (Swamee and Tyagi, 2000).

Aggregation formulations commonly encounter problems as a result of the abstraction of data. This includes ambiguity, eclipsing, compensation and rigidity. For example, weighted arithmetic mean has an eclipsing problem (i.e., one or more sub-indices show poor quality but the overall index does not reflect it), whereas *root sum power addition* suffers from an ambiguity problem (i.e., all sub-indices show acceptable quality but the overall index shows unacceptable quality). Minimum and maximum operators are free from ambiguity and eclipsing, but they fail to reflect the change in any sub-index other than the lowest (or highest) sub-index value in the group.

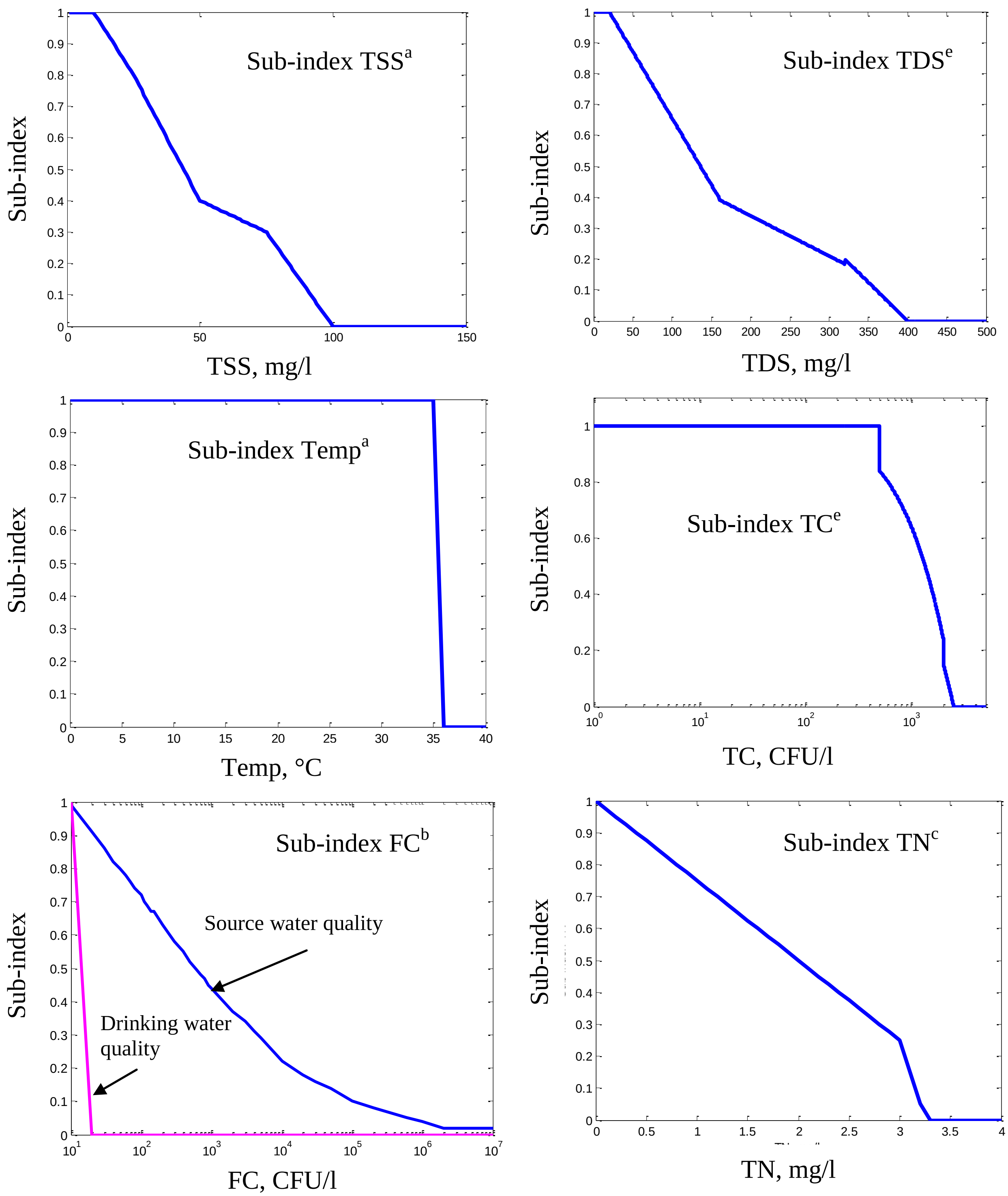


Figure 2.5: Sub-index functions for selected water quality parameters (continued next page)

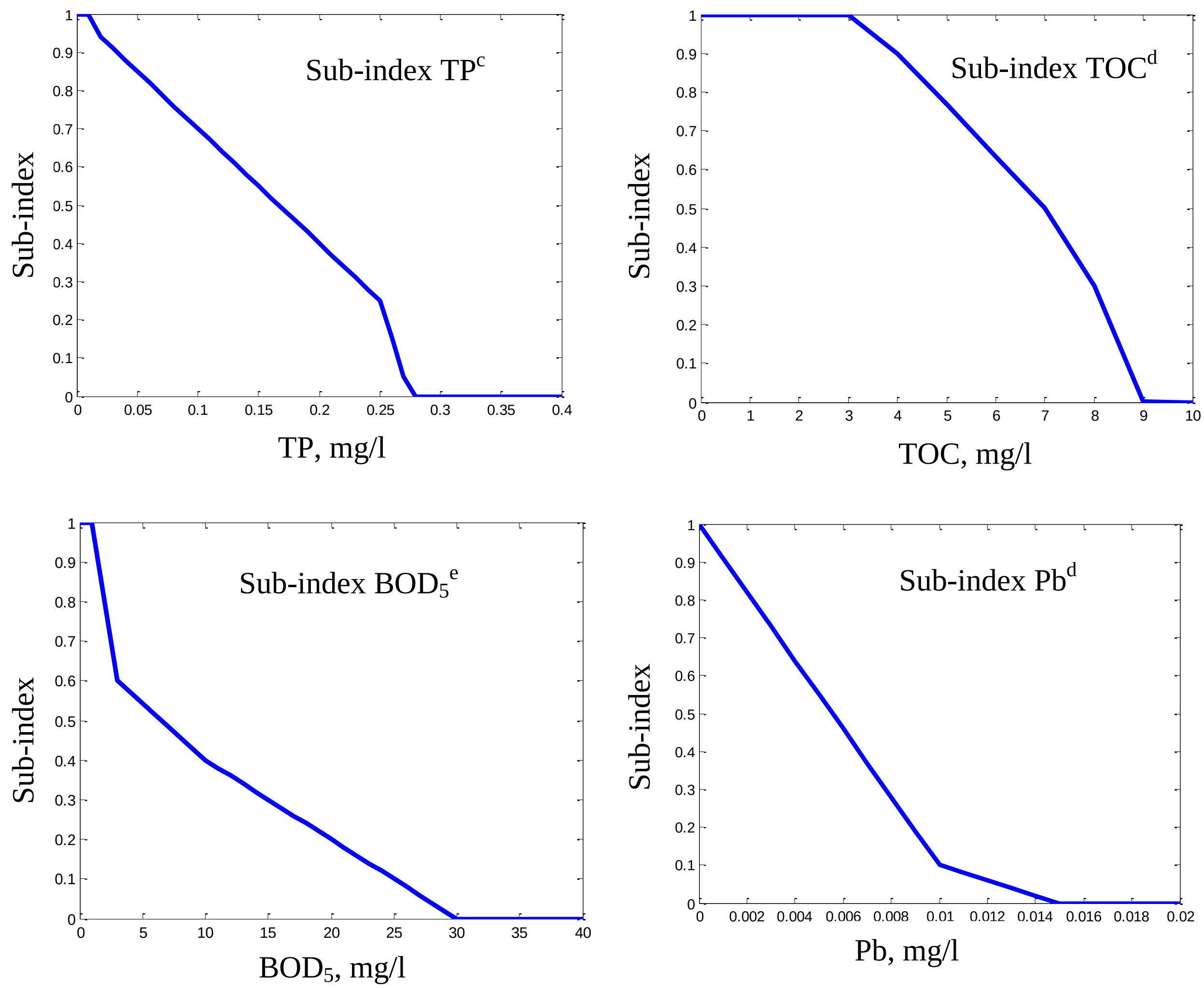


Figure 2. 5: Sub-index functions for selected water quality parameters

a- Liou *et al.*, 2004; b- Brown *et al.*, 1970; c- Cude, 2001; d- Ocampo-Duque *et al.*, 2006; e- Banarjee and Srivastava, 2009.

The minimum and maximum operators do not recognize the importance of contributing sub-indices (i.e., lack of compensation) and suffer from insensitivity.

Commonly WQI formulations are based on the ‘value’ of water quality parameters. However, sometimes it also includes other factors, e.g., CCME-WQI, which is a well accepted index uses three factors[2]: F_1 (scope), F_2 (frequency) and F_3 (amplitude) for the development of WQI. The CCME-WQI can be based on any number of water quality parameters (Lumb *et al*., 2006;

[2] F1 (*scope*): percentage of variables that do not meet their objectives at least once,
F_2 (*frequency*): % of individual tests that do not meet their objectives
F_3 (*amplitude*): amount by which failed tests do not meet their objectives.

Rickwood and Carr, 2009). The values of index that may range from 0 to 100 are sub-divided into five water quality categories (excellent, good, fair, marginal, and poor). Recently, Khan *et al.* (2004) suggested including a 'very good' category to match with experts' judgments. A compensation property helps to account for the contribution of all sub-indices, i.e., WQI should not be biased toward extremes (i.e., highest or lowest sub-index value).This property contradicts the situation where ambiguity-free and eclipsing-free models are desired. For example, maximum (or minimum) operators are skewed to the extremes and show poor properties with respect to compensation. As a result, there is a trade-off between ambiguity (and eclipsing) and compensation. Swamee and Tyagi (2000) proposed a model which minimizes ambiguity and eclipsing but suffers rigidity. Recently, Swamee and Tyagi (2007) have improved their formulation which minimizes ambiguity, eclipsing as well as rigidity. Sadiq *et al.* (2010) have developed penalty functions to deal with these issues in aggregation formulations. Table 2.9 provides a qualitative comparison of various WQI formulations based on their capacity to deal with various aggregation issues.

Common watershed and water quality assessment models do not explicitly consider interconnection or interdependencies among the parameters. In addition, 'acceptance' is a qualitative concept, which cannot be effectively handled through the mathematical formulations provided in Appendix D. Various advanced statistical/ mathematical methods, soft computing and artificial intelligence techniques (e.g., fuzzy rule-based, neural-network) have been effectively used for developing indices (Chang *et al*., 2001; Juahir *et al*., 2010; Icaga, 2007; Ocampo-Duque *et al*., 2006). In this study, we focus on soft-computing methods which are briefly discussed in the following section.

2.6 Soft Computing Methods

Source water protection is a complex problem that requires an integration of watershed modelling with water quality assessment. Figure 2.6 was developed on the basis of the conceptual framework highlighting the impacts on water quality in the surface source and relating it to the selected SWP strategies. Numerous interconnections among water quality parameters and SWP strategies can be described through quantitative or qualitative relationships. Soft-computing methods are a good candidate to describe these interconnections and dependencies.

Table 2.9: Common issues in formulations for water quality indices (Sadiq *et al*., 2010)

Water Quality Index (WQI)*	Eclipsing[a]	Ambiguity[a]	Rigidity[a]	Unsuitable for different water use	Unable to handle missing data	Complexity[3]	Lack of handling Interconnection	Lack of handling Redundancy
NSF-WQI	H	Nil	H	M	H	Nil	H	H
O-WQI	Nil	H	M	M	H	H	H	H
P-W WQI	L	Nil	H	H	H	M	H	H
CPCB-WQI	H	Nil	H	H	H	M	H	H
RPI	M	Nil	M	M	H	M	H	H
U-WQI	H	Nil	M	L	H	M	H	H
S-WQI	Nil	Nil	H	M	H	Nil	H	H
ISQA	M	Nil	H	H	H	L	H	H
CCME-WQI	M	Nil	Nil	Nil	Nil	M	H	H
S-T WQI	Nil	Nil	Nil	L	H	H	H	H

*definitions are described in the text

a- Discussed in section 2.5.3

L-Low; M- Medium; H- High level presence of that particular problem

[3] Complexity in terms of using complex equations

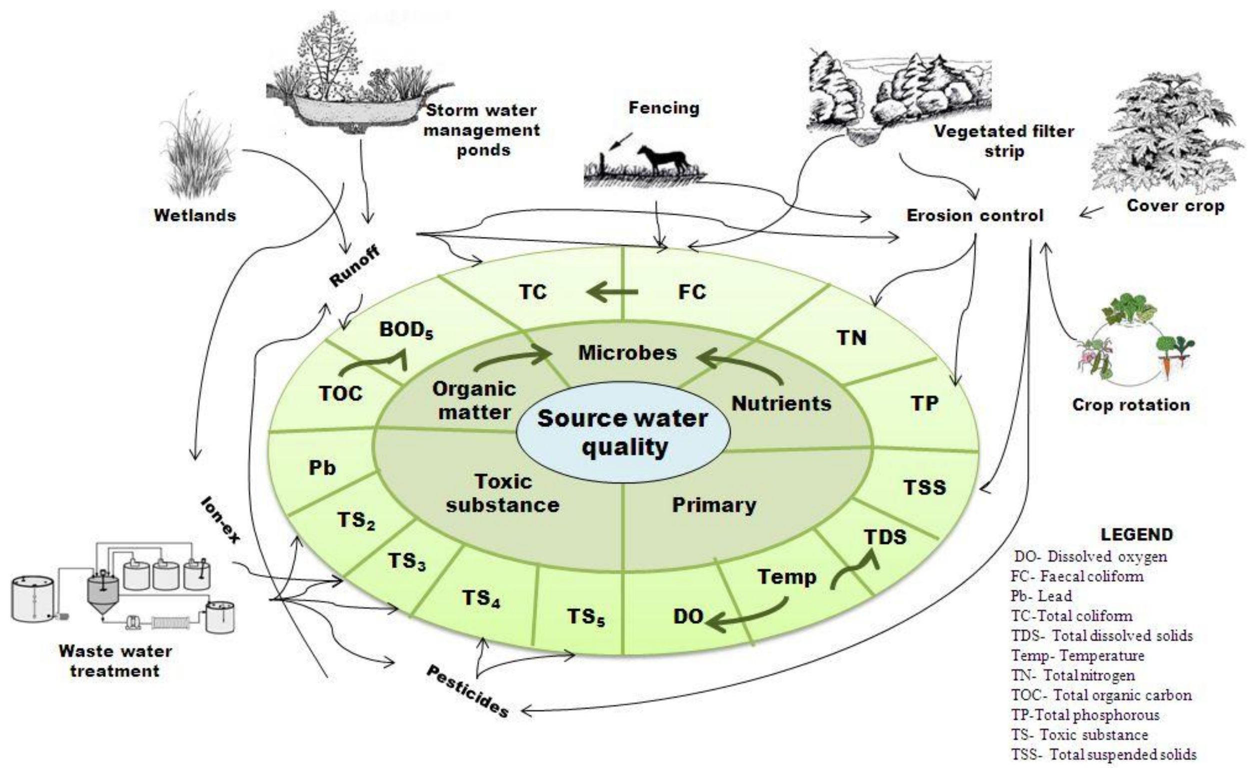


Figure 2.6: Source water protection strategies and water quality assessment

Soft computing techniques consist of an array of heuristic approaches, such as fuzzy logic, evidential reasoning, and artificial neural networks (ANN). These techniques offer innovative solution for complex and uncertain problems.

The ANN is a mathematical technique mainly used in data intensive conditions and has been used in many applications related to water quality management (e.g., Juahir *et al*., 2010; Kuoa *et al*., 2007; Rankovic *et al*., 2010; Singh *et al*., 2009). The main concept behind ANN is to use a number of input variables and determine their weights through hidden layers to predict the response of the system. For example, Chen *et al.* (2010) used back propagation ANN to predict downstream total phosphorous, total nitrogen and dissolved oxygen based on monthly river flow, temperature, flow travel time, rainfall, upstream total nitrogen and total phosphorous. Generally, the ANN performs better than multiple regression analysis in handling non-linear responses (Juahir *et al.,* 2010).

Other soft-computing methods such as evidential reasoning (ER), rough set theory, ordered weighted averaging (OWA) have also been used for water quality management. Evidential reasoning can handle both aleatory (natural stochasticity) and epistemic (ignorance) uncertainty.

Commonly, aleatory uncertainty is dealt with using traditional probability theory, whereas the epistemic uncertainties using Bayesian approach. There is no reported study related to water quality assessment using evidential reasoning approach. However, the evidential reasoning approach was used for predicting water quality failure in distribution networks (Sadiq *et al*., 2006).

Fuzzy-based methods are found to be very effective in handling complex environmental problems (Subbarao *et al.*, 2004; Jaramillo *et al*., 2009). These methods help to transform the natural language into quantitative values and have been used in developing water quality indices (Chang *et al*., 2001; Icaga, 2007; Ocampo-Duque *et al*., 2006) and water management (Liou *et al.*, 2003; Spinella *et al*., 2008; Hajkowicz and Collins, 2007; Li *et al*., 2009). Fuzzy synthetic evaluation (FSE) (Francisque *et al*., 2009; Chang *et al*., 2001; Dahiya *et al*., 2007) and fuzzy clustering analysis (FCA) (Kung *et al*., 1992) have been used extensively in water quality management. In addition, the fuzzy inference system (FIS), e.g., Mamdani, and Takagi, Sugeno and Kang (TSK) algorithms, is also becoming popular in describing water quality status (Icaga, 2007; Lermontov *et al*., 2009; Ocampo-Duque *et al*., 2006) because of its capabilities such as easy interpretability and improved capability to represent cause-effect relationships and dependencies.

Table 2.10 was developed to compare common soft computing methods such as ANN, evidential reasoning, bayesian network, rough set, and fuzzy-based approach in the context of water quality assessment. This comparison is based on the following criteria: simplicity, interpretability, vagueness, randomness, causality and redundancy. Simplicity refers to less use of complex equations or less number of data set requirements for water quality assessment. Interpretability means expert can interpret certain output (e.g., WQI) based on different parameter values. Redundancy means the ability to address certain parameter redundancy inside the assessment formulations (for example Faecal coliform is a subset of total coliforms). Among the soft computing experts, there is a general consensus that fuzzy-based techniques are the most versatile and flexible. Table 2.11 summarizes advantages and disadvantages of fuzzy-based models considering different studies (Chang *et al*., 2001; Hajkowicz and Collins, 2007; Icaga, 2007; Jaramillo *et al*., 2009; Li *et al*., 2009; Liou *et al.*, 2003; Ocampo-Duque *et al*., 2006; Spinella *et al*., 2008; Subbarao *et al.*, 2004).

Table 2.10: A comparison of soft computing methods for water quality assessment

Assessment criteria	ANN	Fuzzy sets	Evidential reasoning	Bayesian network	Rough sets
Simplicity	L	H	M	M	M
Interpretability	Nil	H	M	H	H
Vagueness	Nil	H	M	M	H
Randomness	Nil	L	H	H	M
Cause & effect	H	H	H	H	M
Redundancy	Nil	H	Nil	Nil	Nil

ANN- artificial neural network; L- Low; M- medium; H- High

The relative scale represents efficiency and effectiveness of soft computing methods to deal with different water quality assessment issues.

Table 2.11: Advantages and disadvantages of fuzzy-based methods

Advantages	Disadvantages
• Easy interpretable by natural language	• Not free of eclipsing but can be handled with trial and error process
• Can handle complex and vague situation	• Cannot incorporate guideline values for water quality parameters
• Can incorporate experts opinion with hard data	• Suffer rigidity to some extent (careful selection of parameter can reduce it)
• Can describe a large number of nonlinear relationships through simple rules	• Easy to manipulate or can be biased due to human subjectivity
• Provides a transparent mathematical model	
• Able to account interconnection (inter-dependencies) among parameters	
• Capable to handle missing data without influencing the final WQI value	
• Free of ambiguity and can represent different water quality usage if parameters are selected carefully	

This research, focussed on two fuzzy-based methods; fuzzy-rule-based model (FRBM) and fuzzy measures theorem (FMT). FRBM is an inferencing method, whereas fuzzy measures theorem (FMT) is a multi-criteria decision-making technique that considers redundancy and interconnections among aggregating factors (Sugeno, 1974). The details of these methods are given below.

2.6.1 Fuzzy rule-based model (FRBM)

Zadeh (1965) first introduced fuzzy sets in his pioneering paper, where he argued that probability is an insufficient form to represent uncertainty because it lacked the ability to model human conceptualizations of the real world. Fuzzy-based techniques introduce robustness into systems by allowing a certain amount of imprecision to exist that paved a way to represent human linguistic terms as fuzzy sets, hedges, predicates and quantifiers. Fuzzy logic has played an important role in the management of uncertainties, especially in the areas of expert systems and rule-based models (Ross, 2004). During the last four decades the practical results of fuzzy systems have led to their general acceptance in various engineering disciplines.

Fuzzy Logic is applicable to a problem if an approximate solution is acceptable. Although the input may be crisp, the approximation of the outcome is dependent upon the accuracy of the rule set, the inference technique and the selection of membership functions. Contrary to classical set theory where elements of a set may have ‘0’ or ‘1’ membership, fuzzy sets allow to define membership in an interval of [0, 1]. Fuzzy-based techniques are applicable where input based on human expertise, judgment, and intuitions are required. Fuzzy-based techniques have been successfully applied to a large number of real world problems, and have gained acceptance in the design and control of a variety of systems (Kosko, 1994; Yager and Filev, 1994).

A typical fuzzy rule-based system has four components: fuzzifier, rule-base, inference engine, and defuzzifier. The fuzzifier determines the degree of membership of a crisp input in a fuzzy set through functions known as membership functions. The rule-base represents the fuzzy relationships between input and output fuzzy variables. The output of the rule-base is determined based on the degree of membership specified by the fuzzifier. The inference engine uses membership functions to determine conclusions of rules. Optionally, if needed, a defuzzifier converts fuzzy outputs into crisp values. In the case of multiple inputs, fuzzy rule-based models face ‘dimensionality’ issues, which can be overcome by the use of hierarchical structures to reduce the number of rules. The most popular fuzzy rule-based systems include Mamdani (1977) and Takagi-Sugeno-Kang (TSK) (Takagi and Sugeno, 1985). The main difference between these two models is the consequent part of fuzzy rules. The Mamdani model describes the consequent part using linguistic variables, while the TSK model uses the linear combination of the input variables. Both models use linguistic variables to describe the antecedent part of fuzzy rules.

In FRBM, relationships between variables are represented by means of fuzzy *if-then* rules of the form *If* antecedent proposition *then* consequent proposition. The antecedent proposition is always a fuzzy proposition of the type '*X* is *A'* where *X* is a linguistic variable and *A* is a linguistic constant term. The proposition's truth-value (or membership value), which is a real number between zero and 1, depends on the degree of similarity between *X* and *A*. This linguistic model (Mamdani, 1977) has the capacity to capture qualitative and imprecise/uncertain knowledge in the form of *if-then* rules such as

$$\boldsymbol{R_i}\text{: } \textit{If } X \text{ is } A_i \textit{ then } Y \text{ is } \boldsymbol{B_j} \qquad i = 1, 2, \ldots, L; \qquad j = 1, 2, \ldots, N \tag{2.2}$$

where, R_i is the rule number i, X is the input (antecedent) linguistic (fuzzy) variable and A_i is a fuzzy subset, which corresponds to an antecedent linguistic constant (one of L in set A). Similarly, Y is the output (consequent) linguistic (fuzzy) variable and B_j is a fuzzy subset, which corresponds to a consequent linguistic constant (one of N in set B). A fuzzy rule can be regarded as a fuzzy relation, i.e., simultaneous occurrence of values X and Y.

For example, Equation 2.2 can be applied as follows,

R: **If** slope level is *medium* **then** VFS efficiency is *low*

where X denotes levels of slope, A denotes a fuzzy linguistic constant (a fuzzy subset) *medium* over the universe of discourse of slope levels (e.g., *low*, *medium, high*), Y denotes VFS efficiency, B denotes a fuzzy linguistic constant (or a fuzzy subset) *low* in the universe of discourse of VFS efficiency, and rules R defines their fuzzy relationship:

Things become a little more involved when X is not exactly equal to *medium* but rather has a membership of, say, $\mu_{A_2}(x) = 0.5$ to *low* and $\mu_{A_3}(x) = 0.5$ to *medium*. It is clear that since the slope is less than *medium* VFS efficiency will likely be less than *low*. The full relationship between X and Y according to rule i can be computed in two basic ways, either by using fuzzy implications or fuzzy conjunctions (Mamdani, 1977). In the proposed approach, the Mamdani method is used, in which conjunction $A \wedge B$ is computed by a *minimum* (and type *t*-norm or conjunctive) operator. The interpretation of conjunction $A \wedge B$ is 'it is true that A and B

simultaneously hold'. The relationship is symmetric and can be inverted: Each rule is regarded as a fuzzy relation denoted by $R_i\ (X \times Y) \rightarrow [0, 1]$.

$$R_i = A_i \times B_j,\ i.e.,\ \mu_{R_i}(x, y) = \mu_{A_i}(x) \wedge \mu_{B_j}(y) \tag{2.3}$$

The *minimum* operator of Equation (2. 3) is applied to the Cartesian product space of X and Y, i.e., for all possible pairs of X and Y. The union of all fuzzy relations R_i comprises the entire model and is given by the disjunction $A \vee B$ (*union*, *maximum*, or type, s-norm) operator of the L individual relations (rules) R_i (i = 1, …, L):

$$R = \bigcup_{i=1}^{L} R_i, \quad i.e.,\ \mu_R(x, y) = \max_{i=1,2,\ldots,L}\left[\mu_{A_i}(x) \wedge \mu_{B_j}(y)\right] \tag{2.4}$$

Remembering that each relationship R_i is symmetric and can be inverted, the entire rule-set is now encoded in the fuzzy relation (rule) set $\boldsymbol{R}$. Equation (2. 4) can be restated as

$$y = x \circ R \tag{2.5}$$

where the output of the linguistic model is computed by applying the *max-min* composition (denoted by the operator 'o') to the input or antecedent proposition. Suppose that A' is an input fuzzy number (or a singleton), which is mapped on set A, and B' is an output fuzzy number which is mapped on a set B, such that:

$$\mu_B(y) = \max_X \left[\mu_{A'}(x) \wedge \mu_R(x, y)\right] \tag{2.6}$$

Substituting $\mu_R\ (x, y)$ from Equation (2. 6), the above expression can be rearranged as

$$\mu_B(y) = \max_{i=1,2,\ldots,L}\left(\max_X \left[\mu_{A'}(x) \wedge \mu_{A_i}(x)\right] \wedge \mu_{B_j}(y)\right) \tag{2.7}$$

Defining $\beta_i = \max_X\left[\mu_{A'}(x) \wedge \mu_{A_i}(x)\right]$ as the degree of fulfillment of the antecedent of the ***i***-th rule, the output fuzzy set of the linguistic model becomes

$$\mu_B(y) = \max_{i=1,2,\ldots,L}\left[\beta_i \wedge \mu_{B_j}(y)\right] \tag{2 8}$$

The above algorithm is called the Mamdani inference. It is developed in Equations 2. 3 through 2. 8 for a SISO (Single-input-single-output) model. It can be extended to MISO (Multiple-inputs-single-output) model. For example, a two-input model will be:

$$R_{i,j}\text{: If } X_1 \text{ is } A_i \text{ and } X_2 \text{ is } C_j \text{ then } y \text{ is } B_k; \qquad \begin{array}{l} i = 1, 2, \ldots, L \\ j = 1, 2, \ldots, M \\ k = 1, 2, \ldots, N \end{array} \tag{2.9}$$

This model is a special case of SISO, where the antecedent proposition is obtained as the Cartesian product of fuzzy sets *A* and *C*, hence the degree of fulfillment is given by:

$$\beta_{i,j} = \left\{ \max_{X_1} \left[\mu_{A_i}(x_1) \wedge \mu_{A'}(x_1) \right] \wedge \max_{X_2} \left[\mu_{C_j}(x_2) \wedge \mu_{C'}(x_2) \right] \right\} \tag{2.10}$$

The extension of MISO to *Q* antecedents is straightforward. The algorithm can also be extended to multiple outputs (MIMO) model, which is a set of MISO models. Other conjunctive operators such as *product* can also be used (Yager and Filev, 1994) to make inferences.

Consider an effect node B, which is connected by two causal concepts A and C. A graphical representation of the causal relationships is shown in Figure 2.7.

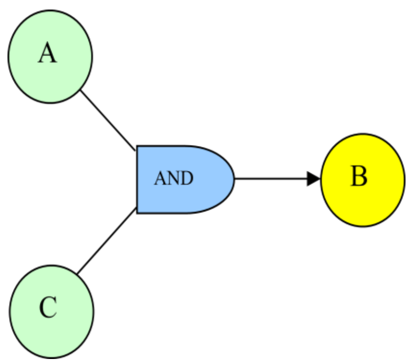
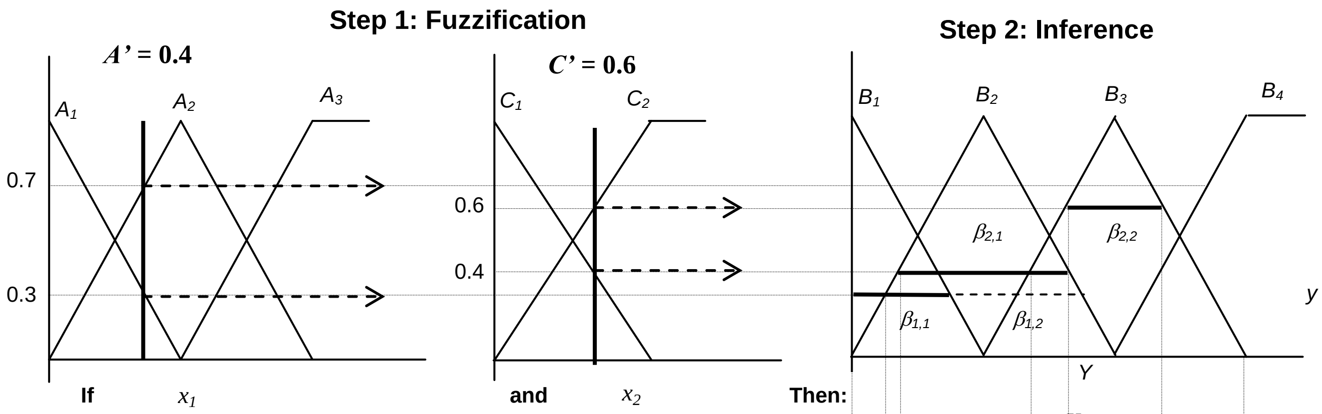


Figure 2.7: Two causal concepts connecting to an effect concept

The AND action represents that both A and C are simultaneously required for B to occur. The details of this two-input MISO model are graphically shown in Figure 2.8. The process is shown in three distinct steps, namely, fuzzification, inference (a rule base and an inference engine) and defuzzification. Assume that causal concepts A and C are activated at levels of *A'* = 0.4 and *C'* = 0.6, respectively. The rule set consists of 6 rules (3 × 2) and input activation signals (*A'*) and (*C'*) fire the first 4 rules to determine output *B'* which is defined over the universe of discourse *Y*. The defuzzification step provides a discrete (crisp) value of an output of B, i.e., *B'*.



Rule-base ($R_{i,j}$):

Antecedent 1 = A_i; $i = 1,\ldots, L$; $L = 3$

Antecedent 2 = C_j; $j = 1,\ldots, M$; $M = 2$

Consequent = B_k; $k = 1,\ldots, N$; $N = 4$

Total number of rules = $3 \times 2 = 6$

Rule 1 $R_{1,1}$: *If* A_1 *and* C_1 *then* B_1

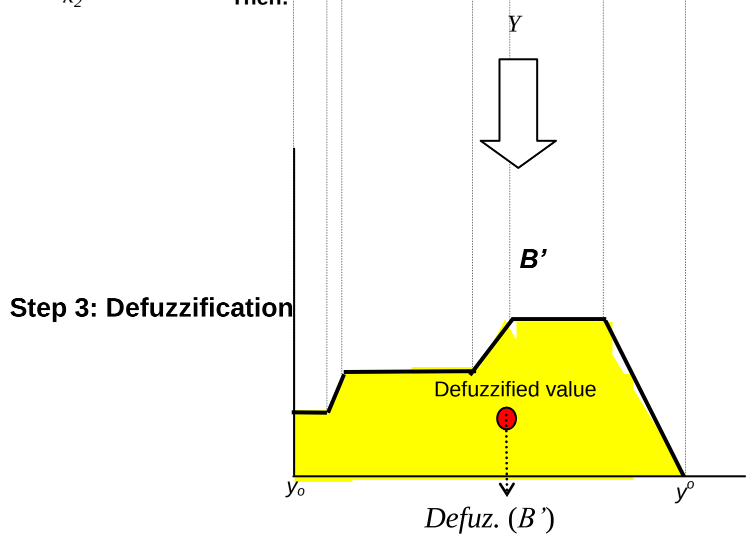
Rule 2 $R_{1,2}$: *If* A_1 *and* C_2 *then* B_2

Rule 3 $R_{2,1}$: *If* A_2 *and* C_1 *then* B_2

Rule 4 $R_{2,2}$: *If* A_2 *and* C_2 *then* B_3

Rule 5 $R_{3,1}$: *If* A_3 *and* C_1 *then* B_3

Rule 6 $R_{3,2}$: *If* A_3 *and* C_2 *then* B_4



- x_1 has support (membership >0) in A_1 and A_2, and x_2 has support in C_1 and C_2, consequently only the first 4 rules are 'fired' (or activated).
- Rule 1: $\mu_{A_1}(x_1) = 0.3$, : $\mu_{C_1}(x_1) = 0.4$ $\Rightarrow$ $\beta_{1,1} = 0.3 \wedge 0.4 = 0.3$ $\Rightarrow$ $\mu_{B_1}(y) = 0.3$
- Rule 2: $\mu_{A_1}(x_1) = 0.3$, : $\mu_{C_2}(x_1) = 0.6$ $\Rightarrow$ $\beta_{1,2} = 0.3 \wedge 0.6 = 0.3$ $\Rightarrow$ $\mu_{B_2}(y) = 0.3$
- Rule 3: $\mu_{A_2}(x_1) = 0.7$, : $\mu_{C_1}(x_1) = 0.4$ $\Rightarrow$ $\beta_{2,1} = 0.7 \wedge 0.4 = 0.4$ $\Rightarrow$ $\mu_{B_2}(y) = 0.4$
- Rule 4: $\mu_{A_2}(x_1) = 0.7$, : $\mu_{C_2}(x_1) = 0.6$ $\Rightarrow$ $\beta_{2,2} = 0.7 \wedge 0.6 = 0.6$ $\Rightarrow$ $\mu_{B_3}(y) = 0.6$

Use center or area method to calculate the defuzzified value,

$$Defuz.(B') = \left(\int \frac{\mu(y).ydy}{\mu(y)dy} \right)$$

Defuz. (B') = **0.54**

Figure 2.8: Fuzzy rule-based model-making inference using two 'causal factors'

The crisp value approximates the deterministic characteristics of the fuzzy reasoning process based on the output fuzzy set $\mu_{B_k}(y)$, which helps convert the uncertainty into an applicable action when solving real-world problems. The defuzzification method described in Figure 2.8, uses center of area method (Ocampo-Duque *et al*., 2006).

2.6.2 Fuzzy measures theorem (FMT)

A significant aspect of aggregation in multi-criteria decision analysis is the assignment of weights to the different criteria. Until recently, the most often used weighted aggregation operators were averaging operators, such as the quasi-linear means. However, the weighted arithmetic means and, more generally, the quasi-linear means have limitations. None of these operators are able to model interaction between factors (concepts) in some comprehensible manner, which makes them unsuitable when it is important to consider interaction between concepts.

Sugeno (1974) first introduced the term *fuzzy measure*. However, this term referred to a notion that was first introduced by Choquet (1953) and named *capacity*. Over the years the same notion has been used by many different names, such as confidence measure (Dubois and Prade, 1980), non-additive probability (Schmeidler, 1986, 1989), and weighting function (Tversky and Kahneman, 1992). Complex interactions between factors (i.e., sub- and super-additive) are best introduced by assigning a non-additive set function that permits the definition of weights to a subset of criteria rather than to an individual criterion. It is now widely accepted that additivity is not suitable as a required property of set functions in many real situations, due to lack of additivity in many facets of human reasoning (Ross, 2004).

Sugeno (1974) proposed to replace the *additivity* property by a weaker one – *monotonicity* – and called these non-additive monotonic measures as *fuzzy measures*. It is important to note however, that fuzzy measures are not related to fuzzy sets (Sugeno, 1974). For a discrete universal set $X = \{x_1, x_2, \dots, x_n\}$, a fuzzy measure is a set function, such that $\mu: (2^n - 2) \rightarrow [0, 1]$ satisfying the following conditions (where n is the cardinality of a set)

- $\mu(\phi) = 0$, $\mu(X) = 1$, (where ϕ is a null subset)
- $S \subseteq T \Rightarrow \mu(S) \leq \mu(T)$. (monotonicity)

For any $S \subseteq X$, $\mu(S)$ can be viewed as the weight or strength of the combination S for the particular decision problem under consideration. Thus, in addition to the usual weights on criteria taken separately, weights on any combination of criteria can also be defined. Monotonicity means that adding a new element to a combination cannot decrease its importance (Marichal, 1999). For example, $S = \{x_1\}$ and $T = \{x_1, x_2\}$ are the (sub) sets of $X = \{x_1, x_2, x_3\}$. The corresponding fuzzy measures, e.g., $\mu(\{x_1\}) = 0.5$ and $\mu(\{x_1, x_2\}) = 0.7$ fulfill the monotonicity condition. The fuzzy measure $\mu(\{x_1, x_2, x_3\})$ of a universal discrete set X (or sample space) will always be 1.

The assessment of fuzzy measures by human experts is a daunting task, since the non-additivity property of a fuzzy measure requires $(2^n - 2)$ subsets. Sugeno (1974) proposed a so-called λ-fuzzy measure, which identifies the fuzzy measure of combined attributes from single attributes, expressed as

$$\mu(A \cup B) = \mu(A) + \mu(B) + \lambda\,\mu(A)\,\mu(B);\ (\lambda > -1) \tag{2.11}$$

The parameter λ is used to describe an interaction between factors that are combined. According to the value of λ, the above equation can be interpreted as

If $\lambda > 0$, then $\mu(A \cup B) > \mu(A) + \mu(B)$ (super-additive),

if $\lambda = 0$, then $\mu(A \cup B) = \mu(A) + \mu(B)$ (additive), and

if $\lambda < 0$, then $\mu(A \cup B) < \mu(A) + \mu(B)$ (sub- additive).

For $\lambda > 0$, the super-additive relationship arises, which implies a synergy effect or strengthening dependency between factors, meaning that the combined contribution of factors A and B is greater than the sum of their contributions. For $\lambda < 0$, the sub-additive relationship arises, which implies a redundancy condition or dependency between factors, meaning that the combined contribution of factors A and B is lower than the sum of their contributions. If $\lambda = 0$, Equation (2.11) reduces to an additive measure, meaning that each factor acts independently. Sugeno's λ-fuzzy measure can be generalized for $X = \{x_1, x_2, \ldots, x_n\}$ as follows:

$$\mu(\{x_1, x_2, \cdots x_n\}) = \frac{1}{\lambda}\left[\prod_{i=1}^{n}\left(1 + \lambda\,\mu(\{x_i\})\right) - 1\right]; \quad \lambda \neq 0 \tag{2.12}$$

The value of λ is obtained through the boundary condition, $\mu(X) = 1$, which yields a polynomial equation with respect to λ, given by

$$1+\lambda=\prod_{i=1}^{n}\left(1+\lambda\,\mu\left(\{x_i\}\right)\right) \tag{2.13}$$

As Sugeno (1974) has shown, there exists a unique λ, which is greater than '-1' and not equal to zero, satisfying Equation (2. 13). The fuzzy measure over the given set $S \subset X$ is computed as

$$\mu(S)=\frac{1}{\lambda}\left[\prod_{\forall x_i \in S}\left(1+\lambda\,\mu\left(\{x_i\}\right)\right)-1\right] \tag{2.14}$$

One possible meaning of a fuzzy measure can be defined as the *level of importance* or the *degree of belief* of a single factor towards the overall evaluation of the system..

Sugeno (1974) also introduced the idea of *fuzzy integrals* to develop tools capable of integrating all values of a function in terms of the underlying fuzzy measure (μ). An integral for fuzzy measures in a sense represents an aggregation operator, which contrary to the weighted arithmetic means, describes interactions between factors ranging from redundancy (negative interaction, i.e., sub-additive) to synergy (positive interaction, i.e., super-additive). Several classes of fuzzy integrals exist, among which the most representatives are those suggested by Choquet and Sugeno (Marichal, 1999).

The Choquet integral $C_\mu(X)$, first proposed by Schmeidler (1986) and later by Murofushi and Sugeno (1989, 1991), is based on an idea introduced in capacity theory by Choquet (1953). $C_\mu(X)$ is an aggregation operator, where the integrand is a set of n values $X = \{x_1, x_2, \ldots, x_n\}$. The Choquet integral of a function x with respect to μ is defined by

$$C_{\mu}(X)=\sum_{i=1}^{n}\left[x_{(i)}-x_{(i+1)}\right]\bullet\,\mu\left(\{x_{(1)},x_{(2)}\cdots x_{(i)}\right) \tag{2.15}$$

where $x_{(1)} \geq x_{(2)} \geq \cdots \geq x_{(n)}$ represent the order of x_i (also called utility values in utility theory) in set X in descending order. The values $x_1,\ldots, x_n$ in our case can be replaced by activation values of causal nodes. Therefore, the Choquet integral can be re-written to make inference as

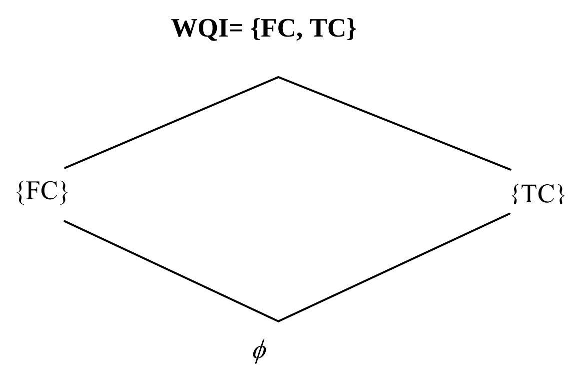
$$A_j=\sum_{i=1}^{n}\left[A_{(i)}-A_{(i+1)}\right]\bullet\,\mu\left(\{A_{(1)},A_{(2)}\cdots A_{(i)}\right) \tag{2.16}$$

where $\mu\left(\{A_{(1)},A_{(2)}\cdots A_{(i)}\right)$ are fuzzy measures similar to causal weights (w_{ij}). Interested readers should refer to Grabisch (1996) for details.

In the Equation (2. 16), A is the activation level in case of WQP sub-index to determine water quality groups and water quality parameter group WQI to determine overall WQI.

We use an example for describing the inference procedure in FMT for WQI considering only FC, and TC sub-index. Figure 2.9 shows how the activation values (sub-index) from FC and TC feed into an effect node for WQI. Therefore, the sample space for WQI = {FC, TC}. The power set $2^{|B|}$ requires defining 4 fuzzy measures as given in Figure 2.9, where $|B|$ is the cardinality of sample space, which is 2. The fuzzy measures here are derived arbitrarily based on semantics (expert judgment). However, alternative objective methods based on data, λ-fuzzy measure and heuristics can be used to derive these measures (Grabisch, 1996).

Lattice representation of the power set of B is also shown in Figure 2.9. It can be noticed in our example that the fuzzy measures are sub-additive, because μ ({FC}) + μ ({TC}) ≥ μ ({FC, TC}). It shows that redundancy exist in the causal nodes. But, μ ({FC}) and μ ({TC}) ≤ μ ({FC, TC}), which represents the monotonicity of the fuzzy measures. Therefore, under these conditions WQI is activated at a level of 0.46.

Fuzzy measures	μ_i	Lattice representation for the power set B
$\mu(\phi)$	0.0	
μ ({FC})	0.5	
μ ({TC})	0.3	
μ (Microbial WQI)= μ ({FC, TC})	1.0	

The activation values for FC and TC are 0.4 and 0.6, respectively, i.e.,

$A_{(\{A\})} = FC' = FC_1 = 0.4$ $A_{(\{C\})} = TC' = TC_2 = 0.6$

Re-ordering is required to use Choquet integral. The activation values in descending orders are

$A_{(1)} = 0.6$ $A_{(2)} = 0.4$ (where parenthesis shows the ordinal position)

Using Equation (2. 16), the activation value for WQI can be determined as follows

$A_{\{\mathrm{WQI}\}} = WQI' = [A_{(\{\mathrm{TC}\})} - A_{(\{\mathrm{FC}\})}] \times \mu(\{\mathrm{TC}\}) + [A_{(\{\mathrm{FC}\})}] \times \mu(\{\mathrm{FC, TC}\})$

$B' = [0.6 - 0.4] \times 0.3 + [0.4] \times 1 = 0.06 + 0.4 = \mathbf{0.46}$

Figure 2.9: Fuzzy measures theorem-making inference using two ‘causal factors’

3. MODEL DEVELOPMENT

3.1 Conceptual Framework

A conceptual framework is proposed in Figure 3.1 that can link selected SWP strategies to the improvement in drinking water quality described by WQI. The conceptual framework has three components:

1) Reduced pollutant load calculations based on selected SWP strategies
2) Estimation of pollutant concentration in the source
3) Estimation of water quality index

The first two components of the model are related to pollutant load assessment in a given watershed. Third component of the conceptual model is related to water quality assessment in the source water. The proposed framework involves six steps as shown in Figure 3.1.

3.1.1 Reduced pollutant load calculations

To determine the reduction in pollutant load the following two steps are performed:

- The first step involves estimation of potential land use and pollutants produced using the export coefficient approach for a predefined land use. In the case of pasture and livestock land use, the numbers of animals are used to estimate the pollutant load for each water quality parameter.
- The second step involves estimating the percentage of pollutant reduction based on the efficiency of selected SWP strategies. Storm water management (SWM), vegetated filter strip (VFS), fencing, pollution control by agricultural practice (PCAP), and wastewater treatment (WWT) options are used in the proposed model. For each selected SWP strategy, the parameters described in Chapter 2 are used to estimate the removal efficiency of a specific pollutant.

3.1.2 Estimation of pollutant concentration in the source

This component of the proposed model is described in step 3 which estimates the pollutant (water quality parameter) concentration using a mass balance over a pre-defined time period.

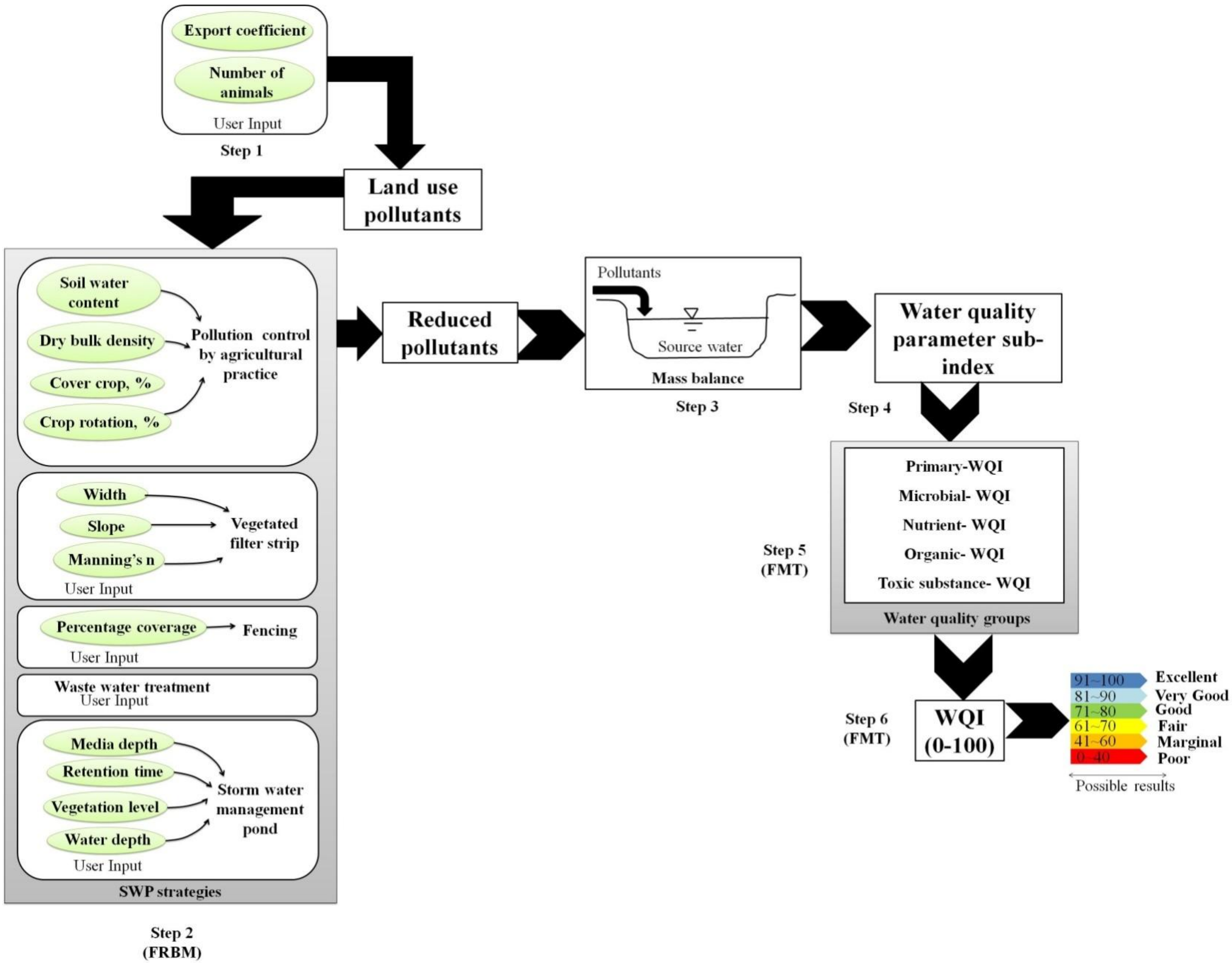


Figure 3.1: Proposed model based on conceptual framework

To avoid complexity related to mixing, time period, reactions and other physico-chemical processes occurring in the source water, a simple steady-stead mass balance approach is recommended in this study.

3.1.3 Estimation of water quality index (WQI)

Component 3 of the proposed model is related to water quality assessment that involves three steps (Figure 3.1). Step 4 transforms previously calculated concentrations of WQP (step 3) into unitless sub-indices. In step 5, the water quality parameters are classified into five water quality groups:

(1) Primary or aesthetic –WQI
(2) Nutrient-WQI
(3) Microbial –WQI
(4) Organic-WQI and
(5) Toxic substances-WQI.

Each water quality group may include one or more water quality parameters. For example, the Primary-WQI includes total suspended solids, TDS, and temperature; Nutrient-WQI includes total phosphorous, total nitrogen; Microbial-WQI includes faecal coliform and total coliform; Organic-WQI includes BOD_5 and total organic carbon; and finally Toxic substance-WQI may include substances such as heavy metals (e.g., lead) and other user defined substances. Finally, the overall WQI can be derived using these five water quality groups in step 6. The value of WQI is in the range $\in$ [0 to 100], where 0 refers to the *worst* and 100 refers to the *best* quality water. Based on these values, we define six qualitative levels of water quality: poor (0-40), marginal (41-60), fair (61-70), good (71-80), very good (81-90) and excellent (91-100) water quality. Moreover, the WQI for five water quality groups can also be classified using these levels.

3.1 Pollutant Loads based on Land Use

Proposed model can account for a maximum of 14 water quality parameters (10 fixed and four user-defined toxic substances). The model recommends using at least one water quality parameter in each water quality group that includes TSS (Aesthetic), TN and TP (nutrient), FC and TC (microbial), BOD_5 (organic) and Pb (toxic substances). The export coefficient (EC) concept is used to estimate the concentration of selected water quality parameters for different land use (except livestock and pasture) to represent the pollutants. If the information for EC of a specific water quality parameter is not available, the average seasonal concentrations are recommended. The following phases describe the detailed procedure to estimate the concentration of a selected water quality parameter using the EC concept:

Phase 1: Define the area boundary (watershed or sub-watershed) that contributes to source water.

Phase 2: Divide the total land area into a number of segments based on land use.

Phase 3: Calculate the area for different land uses such as agriculture, farming (livestock), pasture/forage, urban, and forests. In case of urban (developed) land, define the non-point (e.g., highway/ roads) and point pollution sources (e.g., commercial, residential).

Phase 4: Collect information for monthly and/ or yearly precipitation for the selected region to estimate the flow rates.

Phase 5: Collect a soil variability map for the watershed that help determining the percentage of the precipitation that becomes the direct runoff (a portion of the rain will be infiltrated and will not become the part of runoff). The portion of precipitation that becomes direct runoff can be calculated using a runoff coefficient (k) $\in$ [0-1], a concept similar to the 'Rational method', where higher value means more impervious area and vice versa. For example, k = 80% for concrete and k= 30% for forests (Martinez-Martinez and Campos-Aranda, 2010).

Phase 6: Use the USEPA (2001i) formulation for EC approach to obtain EMC for a particular pollutant. Here, the formulation to estimate water quality parameter concentration (mg/l) was developed with the EC formula (USEPA 2001i) combined with runoff formulation as follows:

$$C = R\,\frac{\sum_{i=1}^{n} EC_i \times A_i}{\sum_{i=1}^{n} k \times P \times A_i} \tag{3.1}$$

where

C = Pollutant concentration [mg/l] (for coliform CFU/ l)

i = Order of land use type

EC_i= Export coefficient for i^{th} number land use [Kg/ha/yr] or [Kg/ha/month]

A_i= Area of the i^{th} land use [ha]

k = Runoff coefficient representing amount of precipitation after infiltration (unit less) depending on the land use and land cover [%]

P = yearly/ monthly total precipitation [mm]

R= conversion factor (100)

Equation (3.1) can be used for both monthly/ yearly data depending on the precipitation and export coefficient. Table 2.1 shows a high variability in the EC values for same land use. Therefore, a careful expert judgement is required to select an appropriate value of EC for a specific land use. The USEPA (2001i) proposed typical EC values for different land uses (Table 2.2) and also corresponding pollutant concentrations. In case of missing information, other studies have been considered to assume respected EC values (Table 3.1). It should be noted that the land use EC values can be user defined and can be replaced if the site-specific values become available.

For microbial indicators (FC and TC), the average concentration for different land use has been used, e.g., for FC, the event mean concentration (EMC) can be used (USEPA, 2001i; Mishra *et al*., 2008). To calculate the numbers of total coliforms from sources like agriculture, urban type 1 and forest land use, a multiplier of 2-4 times of Faecal coliform concentration are recommended. As the precipitation patterns can vary significantly in the reported studies, the monthly precipitation ratio can be used to convert monthly concentration from the reported data to the monthly concentration of a particular area.

In case of manure load, the ASAE (2003) approach can be used to calculate monthly or yearly load in terms of kg/month or kg/year. Appendix E provides general statistics for total generated manure in terms of different parameters, e.g., total solids, TN, TP, BOD_5, FC, TC and Pb. In addition, the average weights of different livestock have also been reported. The pollutant loads generated from manure are described in kg/(1000 kg body weight-day). Appendix E presents the amount of pollutants in fresh manure which usually contains 88-92% water for non-poultry based livestock and 73-75% for poultry based livestock (Ohio Livestock Manure Management Guide, 2006).

Table 3.1: Typical EC (kg/ha/yr) from USEPA (2001i)

Land use type	TSS	TN	TP	BOD_5	Pb
Agriculture (crop land)	2242	17.6	1.1	18	0.0014^{a}
Forests	250^{b}	2.5^{b}	0.2^{b}	37^{c}	0^{d}
Urban type 1 (Highway/ roads)	1100	7	2.8	98	e
Urban type 2: Commercial	660	11	2.3	60.50	*
Urban type 2: Residential	390	8	2.2	47	*
Urban type 2: Industrial	780	11	5.4	52.5	*

a- Elrashidi, 2007
b- USEPA, 1976
c- Badar and Romshoo, 2008
d- USEPA (2001i) assumed no Pb for forests
e- Monthly concentration used from Boller *et al.* (2007); for yearly analysis average 0.03 mg/l has been assumed
* Unavailable and can be replaced by expert judgment

Therefore, the equation for estimating concentration for pasture or forage land use generation was developed with ASAE (2003) formulation combined with runoff equation as follows:

$$C_{WQP} = S * \frac{\sum_{m=1}^{n} G-WQP_m \times BW_m \times MMF_m \times ND}{k \times P \times A_P \text{ (or } A_L)} \tag{3.2}$$

where

C_{WQP}= Concentration of WQP [mg/l]

m= Order of livestock type from 1- n

BW_m= Average body weight of particular livestock [kg] (Appendix E)

$G-WQP_m$= Generated WQP in terms of mass for specific livestock type [kg/(1000 kg BW.day)]

MMF_m= Moisture multiplying factor (12%~8% for non-poultry based and 27%~25% for poultry based livestock)

$A_{P/L}$= pasture/ livestock land area [ha]

ND = number of days (for monthly or yearly variation)

S = multiplication factor (100)

3.2 Reduced Pollutant Loads

The SWP strategies shown in step 2 (Figure 3.1) depends on area distribution of land use. A watershed or part of watershed can be divided into three zones (Figure 3.2): zone 1 is generally a source that generates point or non-point pollution; zone 2 is the area where a SWP strategy like storm water management will receive pollutant loads; and zone 3 is the designated place for vegetated filter strip (VFS). Figure 3.3 describes component 1 of the proposed framework that highlights these three zones. In zone 1, the pollutant loads are generated from non-point pollution sources like agricultural ($Load_{ANPS}$) (crop land), urban (e.g., uncontrolled runoffs from roads) ($Load_{UNPS}$), forests ($Load_{FNPS}$), pasture/forage ($Load_{PNPS}$), livestock farms ($Load_{LNPS}$), and point pollution sources like urban (e.g., controlled commercial, industrial and residential discharges) ($Load_{UPPS}$). Pollution control by agricultural practice (PCAP) and fencing (Fen) can be used to control non-point pollution from agricultural and pasture land use ($Load_{ANPS}$ and $Load_{PNPS}$) (Figure 3.3).

Equation (3.1) is used to calculate pollutants from forests, agriculture, urban type 1 and urban type 2 land uses. Moreover, Equation (3.2) is used to calculate the pasture and livestock pollutants (total manure pollutants). Beaulac and Reckhow (1982) have suggested that approximately 2-10% of the total load can potentially enter into the source water. As livestock don't graze for the whole day, approximately 1-5 % of the total manure pollutants can be considered as pasture/forage pollutants. These pollutants can be reduced by providing physical barriers like fencing (Fen) (Figure 3.3).

In case of fencing, three types of land boundaries around a pasture area are possible, e.g., barbed fencing (B. Fen.), vegetated fencing (V. Fen.) and bare land (BL). The developed fencing efficiency equation using those three conditions are stated as follows:

$$\text{Fen}=\frac{P_{BF}\times Fen_{BF}+P_{VF}\times Fen_{VF}}{P_{BF}+P_{VF}+P_{BL}} \qquad (3.3)$$

where

Fen= Total effective fencing efficiency [%]

P_{BF}= Percentage perimeter of land area covered by B. Fen.

P_{VF}= Percentage perimeter of land area covered by V. Fen.

P_{BL}= Percentage perimeter of land area covered by BL

Fen_{BF}= B. Fen pollutant removal percentage, [2% assumed]

Fen_{VF}= V. Fen pollutant removal percentage, [4% assumed]

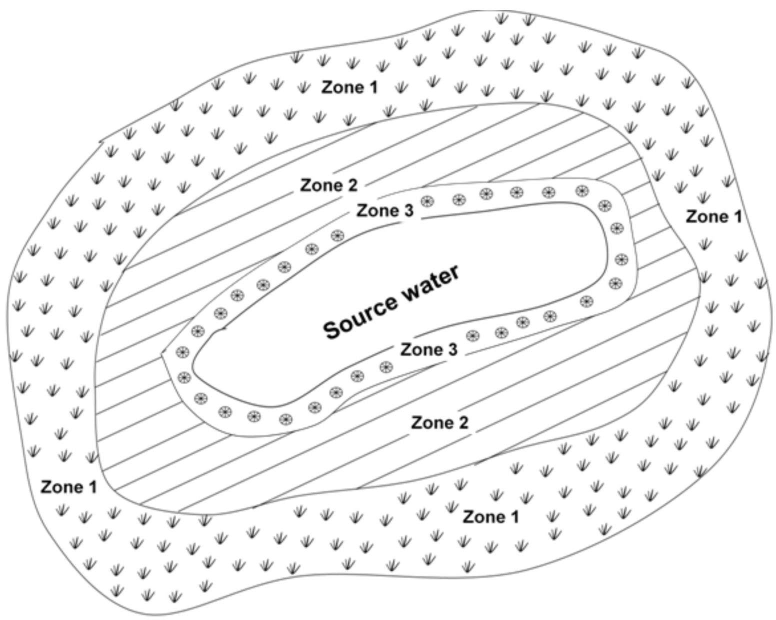


Figure 3.2: Typical three zones in a watershed or a sub-watershed

The main focus in this research is on NPS, however for type-2 urban land (Figure 3.3) where wastewater is usually treated before discharge, a *user-defined* input for treated wastewater load is allowed in the model. The total nonpoint and point pollutant loads are called $Load_{NPS1}$ and $Load_{UPPS}$, respectively. The $Load_{NPS1}$ can go into the source water with or without going through the storm water management ponds. The value X represents the percent pollutants ($Load_{NPS1}$) discharged without SWM ($Load_{NO\_SWM}$) and Y represents the percent load discharged after passing through SWM ($Load_{SWM}$). Figure 3.4 highlights the second scenario.

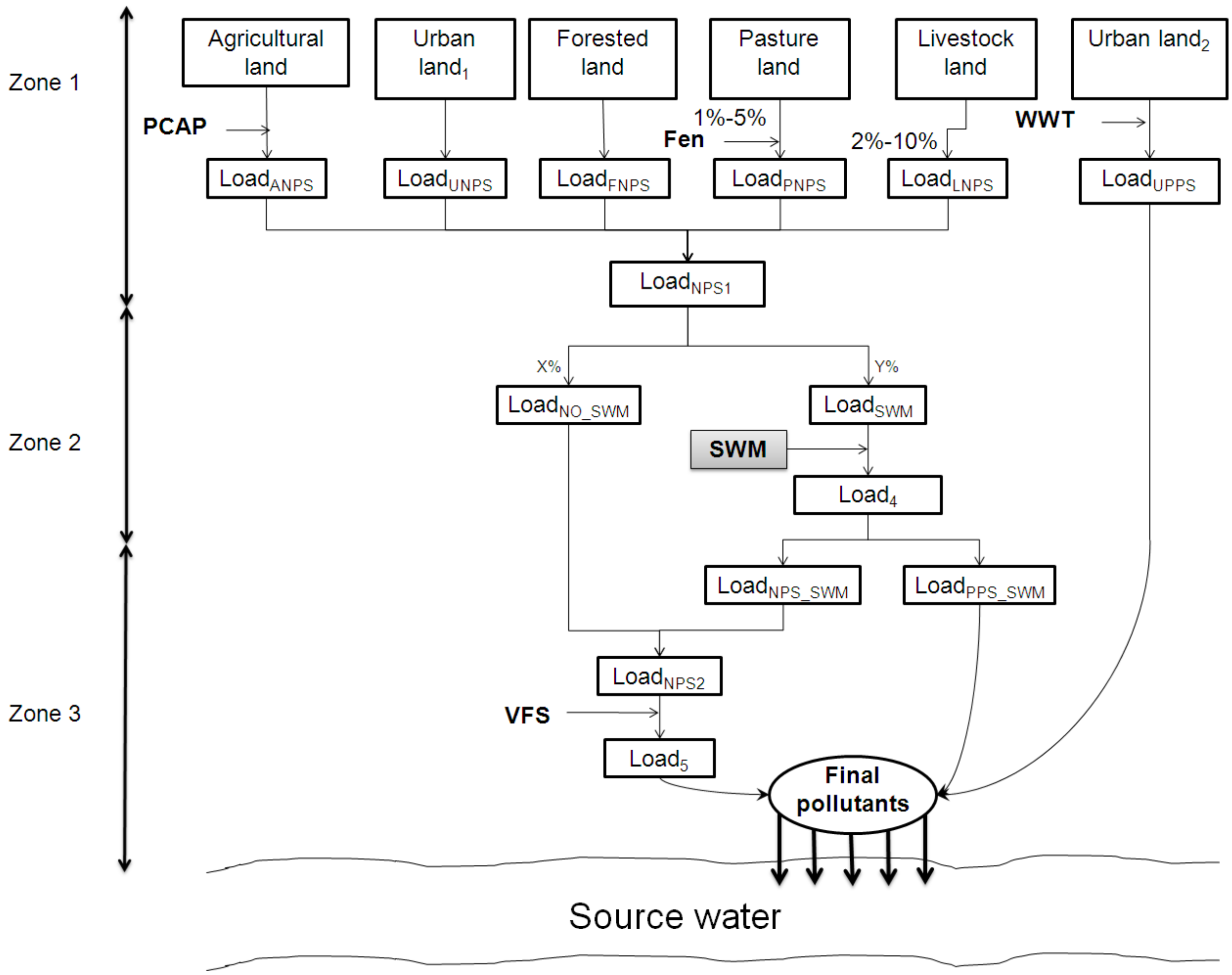


Figure 3.3: Predicting pollutant reduction using different land uses (step 1-2 in Figure 3.1)

The strategies of storm water management can be based on a series of ponds. In case of interconnected ponds, the pollution loads will be reduced further because SWM ponds will perform like a plug flow reactor. After passing through SWM ponds, the reduced load ($Load_4$) will be either directly discharged into the source water as PPS ($Load_{PPS\_SWM}$) or as NPS ($Load_{NPS\_SWM}$) in case of overland flow during heavy rainfall. The $Load_{NPS\_SWM}$ and $Load_{NO\_SWM}$ will define the total NPS load ($Load_{NPS2}$) going into the source water.

Further reduction is possible through VFS, where the pollutant removal efficiency is defined as the following developed equation:

$$Ef_{VFS} = \frac{P_{VFS} \times EVFS_{VFS}}{P_{VFS} + P_{BL}} \qquad (3.4)$$

where

Ef_{VFS} = Total effective vegetative filter strip (VFS) efficiency [%]

P_{VFS}= Percentage of source water boundary covered by VFS

P_{BL}= Percentage source water boundary covered by BL

$EVFS_{VFS}$= VFS pollutant removal percentage based on VFS width, manning's *n* and VFS slope

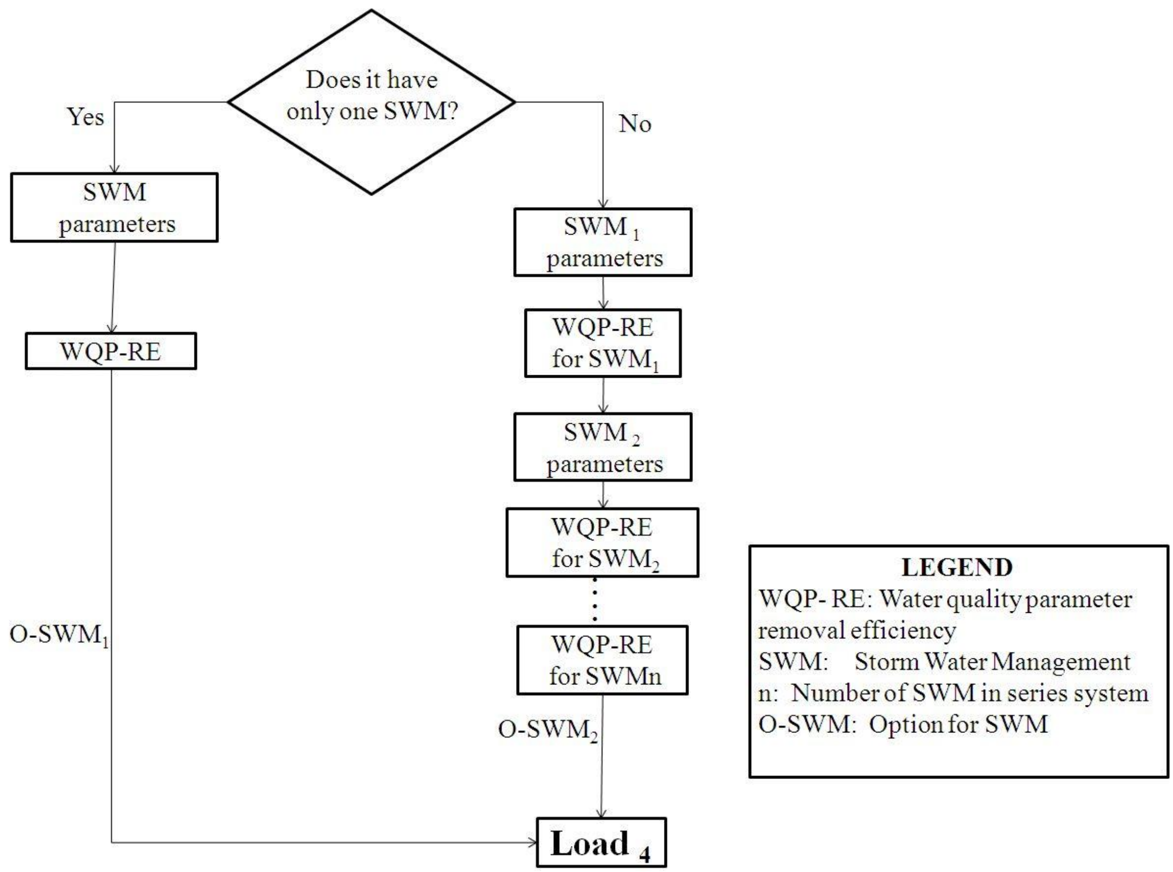


Figure 3.4: Decision diagram for storm water management model

The $Load_5$ can be estimated from $Load_{NPS2}$ after reduction through VFS (Figure 3.3). Finally, $Load_5$, $Load_{PPS\_SWM}$, and $Load_{UPPS}$ are combined to get the final pollutants to the source water (Figure 3.3). It can be noted that, all the pollutant concentrations are derived using mass balance related to flow rates. For example, $Load_{NPS2}$ is estimated from mass balance of $Load_{NPS\_SWM}$ and $Load_{NO\_SWM}$ (Figure 3.3):

$$C_{NPS2_p} = \frac{Q_{NPS\_SWM} \times C_{NPS\_SWM_P} + Q_{NO\_SWM} \times C_{NO\_SWM_P}}{Q_{NPS\_SWM} + Q_{NO\_SWM}} \quad (3.5)$$

Similarly, for Load_{NPS1} and final pollutant concentrations (C_{NPS1_p} and C_{Final_p}) are estimated as:

$$C_{NPS1_p} = \sum_{i=1}^{5} \frac{Q_{LAND\ USE_i} \times C_{LAND\ USE_{P_i}}}{Q_{LAND\ USE_i}} \quad (3.6)$$

$$C_{Final_p} = \frac{Q_{load_5} \times C_{load_{5_p}} + Q_{PPS_{SWM_5}} \times C_{PPS_{SWM_p}} + Q_{UPPS} \times C_{UPPS_p}}{Q_{load_5} + Q_{PPS_{SWM_5}} + Q_{UPPS}} \quad (3.7)$$

where

Q = Pollutant flow rate

C = Pollutant concentration

p = Order of water quality parameter

i = Order of land use for forests, agricultural, pasture, livestock and urban type 1 [1-5]

In case of pollution control by agricultural practice (PCAP), the removal efficiency of TSS depends on dry bulk density (DBD), soil water content (SWC), cover crop (CC) and crop rotation (CR). A simple FRBM is proposed to estimate the removal efficiency of TSS (Step 2 in Figure 3.1). The membership functions and inference rules are presented in Figure 3.5 and Table 3.2, respectively. The membership functions and inference rule for SWM and VFS efficiency are provided in Appendix F and G respectively.

3.3 Pollutant Mass Balance

The SWP strategies aim at controlling pollutant loads entering into the source water. Pollutant loads discharged into surface water over a certain time period are not only diluted (advected) but also go through chemical reactions, diffusion, dispersion and other attenuation processes. Therefore, the magnitude of the surface water quality parameter varies with time. To account for the effect of SWP strategies on surface water, the fate of selected water quality parameters in source water needs to be determined through mass balance equations. Based on advection-diffusion equations and chemical reactions many studies have identified mass balance formulations for selected water quality parameters (Wang *et al*., 2008; Covelli *et al*., 2002; Jha *et al*., 2007; Kasih and Kitada, 2004).

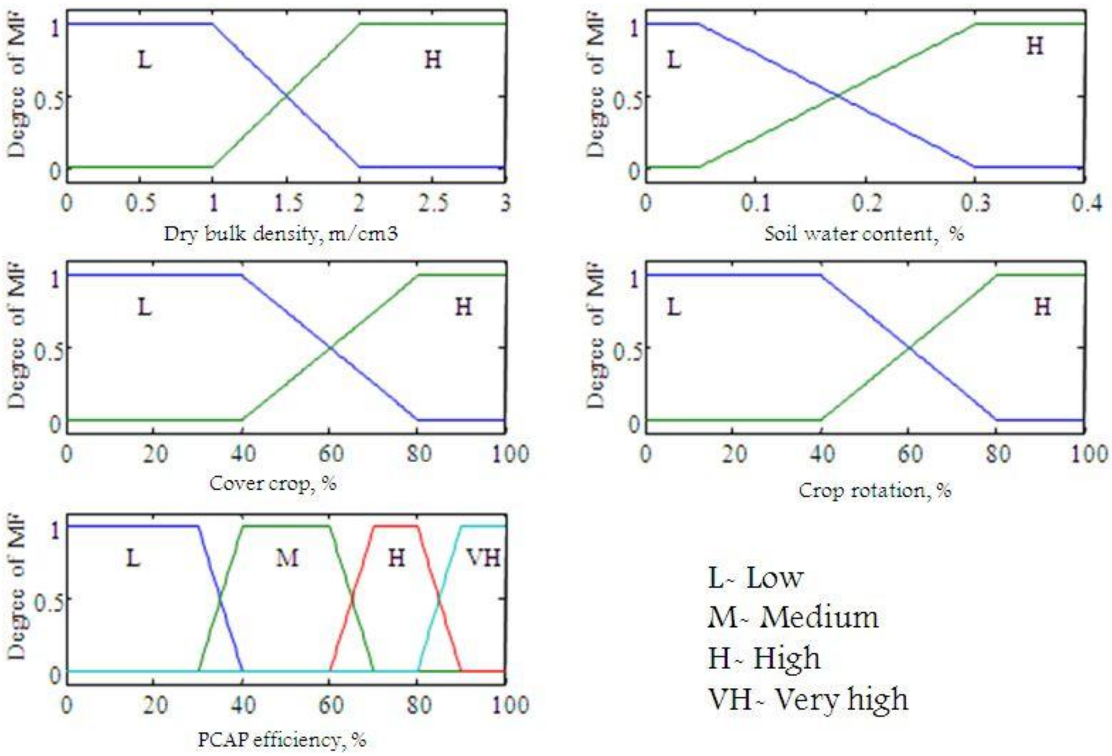


Figure 3.5: Membership functions for input parameters and removal efficiency of TSS in PCAP

Table 3.2: PCAP rule-set for TSS removal

Rule no		DBD		SWC		CC		CR		PCAP
1	if	L	and	L	and	L	and	L	then	L
2	if	L	and	L	and	L	and	H	then	M
3	if	L	and	L	and	H	and	L	then	M
4	if	L	and	L	and	H	and	H	then	H
5	if	L	and	H	and	L	and	L	then	M
6	if	L	and	H	and	L	and	H	then	H
7	if	L	and	H	and	H	and	L	then	H
8	if	L	and	H	and	H	and	H	then	VH
9	if	H	and	L	and	L	and	L	then	L
10	if	H	and	L	and	L	and	H	then	L
11	if	H	and	L	and	H	and	L	then	M
12	if	H	and	L	and	H	and	H	then	M
13	if	H	and	H	and	L	and	L	then	L
14	if	H	and	H	and	L	and	H	then	M
15	if	H	and	H	and	H	and	L	then	M
16	if	H	and	H	and	H	and	H	then	H

DBD- Dry bulk density; SWC- Soil water content (field capacity); CC- Cover crop; CR- Crop rotation; PCAP- pollution control by agricultural practice; L- low; M- medium; H- high; VH- very high

Park and Lee (1996) proposed the segment travel river ecosystem autograph model (STREAM). This model used the assumption of cells in series for representing the whole stream. Each cell was assumed to be a complete mixed flow reactor and used for BOD_5, TSS, TDS, TC, TC, TOC, Pb and nitrogen and phosphorous species mass-balance determination. Appendix H lists common surface water quality models based on mass-balance equations. These models include Enhanced Stream Water Quality Model (QUAL2E) (Cox, 2003; Lin *et al*., 2010; USEPA, 1985), SIMulation of CATchments (SIMCAT, 2004), Temporally Overall Model for CATchments (TOMCAT) (Bowden and Brown, 1984), QUAlity Simulation Along River systems (QUASAR) (Whitehead *et al*., 1997) and MIKE 11 (DHI Water & Environment MIKE 11, 2005). Appendix H highlights the level of complexity due to the interactions among water quality parameters, e.g., the case of DO which depends on BOD, NH_3-N, and NO_3-N (USEPA, 1985). Various constants and coefficients used in these formulations and their descriptions are presented in tabular form in Appendix I. However, the dissolved oxygen (DO) usually depends on the unsteady state mass balance equation involving other parameters such as BOD_5 and NH_3-N. As the focus of this research is on pollutants loads, we did not consider DO in water quality assessment.

To estimate the overall impact of selected SWP strategies, we proposed a simple mass balance (only advection process) and assumed water quality parameters are conservative over the time of analysis. For example, we define a time period, say one year, and calculate the concentration of pollutants using selected WQP mass balance. For a large flowing system such as a river, the source water can be divided into a number of segments. Each segment will have an initial (Q_o C_o), and incoming (Q_{in} C_{in}) mass flow rates and pollutant concentrations based on selected WQP (Figure 3.6). Under steady state conditions the basic equation for flowing system (e.g., creek or a river) will be (Figure 3.6):

$$C_{in(i)} \times Q_{in(i)} + C_{o(i)} \times Q_{o(i)} = C \times (Q_{in(i)} + Q_{o(i)}) \qquad (3.8)$$

where

C_{in}= Incoming pollutant concentration [mg/l] after implementing a SWP strategy (also C_{Final_p} in Equation 3.7)

Q_{in}= Incoming flow [liter/month] or [liter/year]

C_o= Initial concentration of the water quality parameter [mg/l] inside the system

Q_o= Flow of the surface water [liter/month] or [liter/year]

C = Concentration [mg/l] of the pollutant or water quality parameter in the surface water,

i = Order of source water segment= 1, 2, 3,…, (n-1), n

Equation (3.8) can be re-arranged as

$$C = \frac{C_{in(i)} \times Q_{in(i)} + C_{o(i)} \times Q_{o(i)}}{Q_{o(i)} + Q_{in(i)}} \quad (3.9)$$

The Equation (3.9) can be modified for small flowing system, e.g., creek by assuming one section only. Then, the equation reduces to:

$$C = \frac{C_{in} \times Q_{in} + C_o \times Q_o}{Q_o + Q_{in}} \quad (3.10)$$

The equation for pond or lake system should consider volume (Volume = flow rate × time) rather than flow rate. Therefore, the modified Equation (3.9) for lake system will be:

$$C = \frac{C_{in} \times V_{in} + C_o \times V_o}{V_o + V_{in}} \text{ (for small lake system, Figure 3.7)} \quad (3.11)$$

For large lake system, similar type of equation (Equation 3.9) can be determined assuming the system a continuous stirred-tank reactor (CSTR).

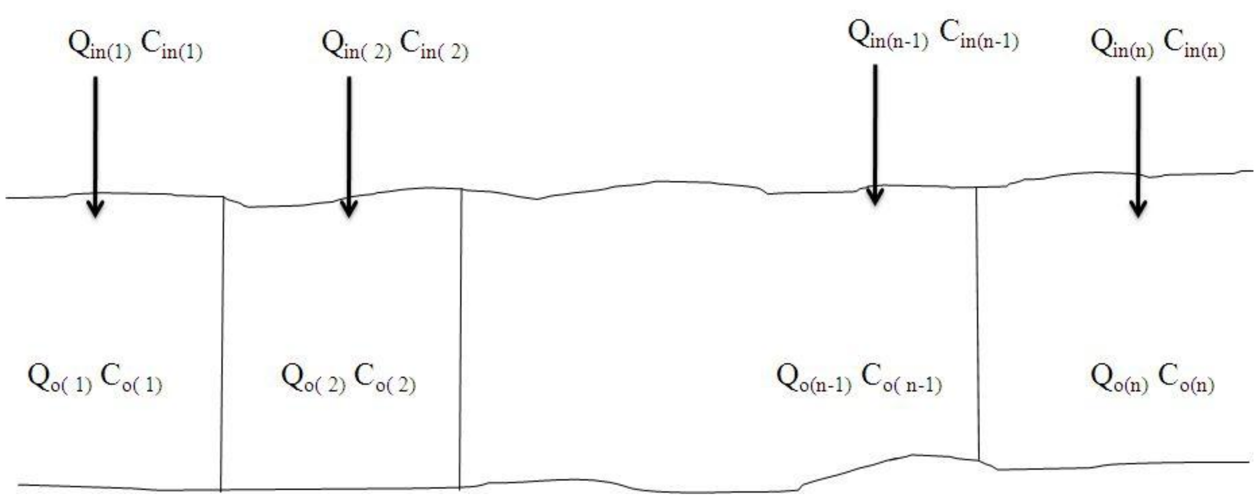


Figure 3.6: Typical mass balance for a flowing system

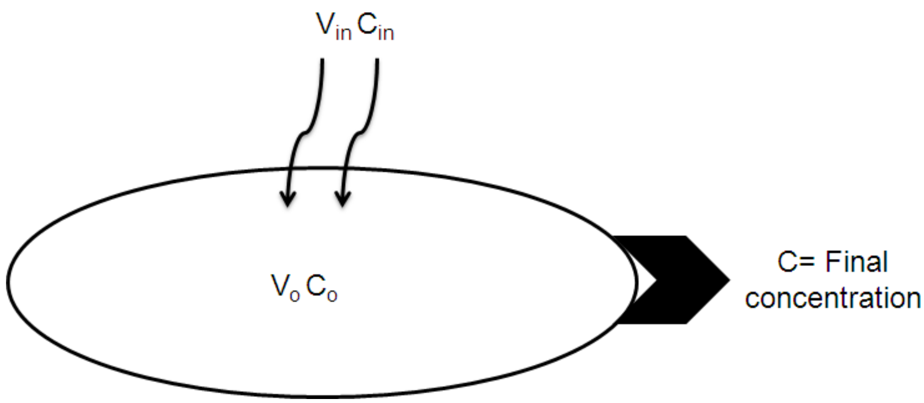


Figure 3.7: Typical mass balance for a lake system

Finally, Steps 3-5 of the proposed framework requires transformation of pollutant concentrations into sub-index values followed by a two-step aggregations using FMT (Section 2.6.1). An illustrative example is provided below to describe the steps involved in the proposed conceptual framework.

3.4 Illustrative Example

The example provides step-by-step calculations using the developed model based. We assume a watershed of 100 ha area which is divided into two segments: segment 1 (S_1) – agricultural (crop land) and segment 2 (S_2): urban type 1 land use (Figure 3.8a). The source water in this watershed is a small flowing system. Figure 3.8 provides two possible scenarios: baseline (current condition) and proposed (with new SWP strategies). Figure 3.8b shows two newly proposed SWM ponds that collect runoff from the watershed and then allows discharging treated water into the receiving water body. In addition, there is still some possibility that some untreated runoff can enter into the source water as non point pollution source. A vegetated filter strip is proposed to reduce some of these pollutant loads (Figure 3.8b). Additional strategies included cover crop (CC) and crop rotation (CR) to as a part of pollution control by agricultural practice (PCAP) to reduce pollutant loads from agricultural land use.

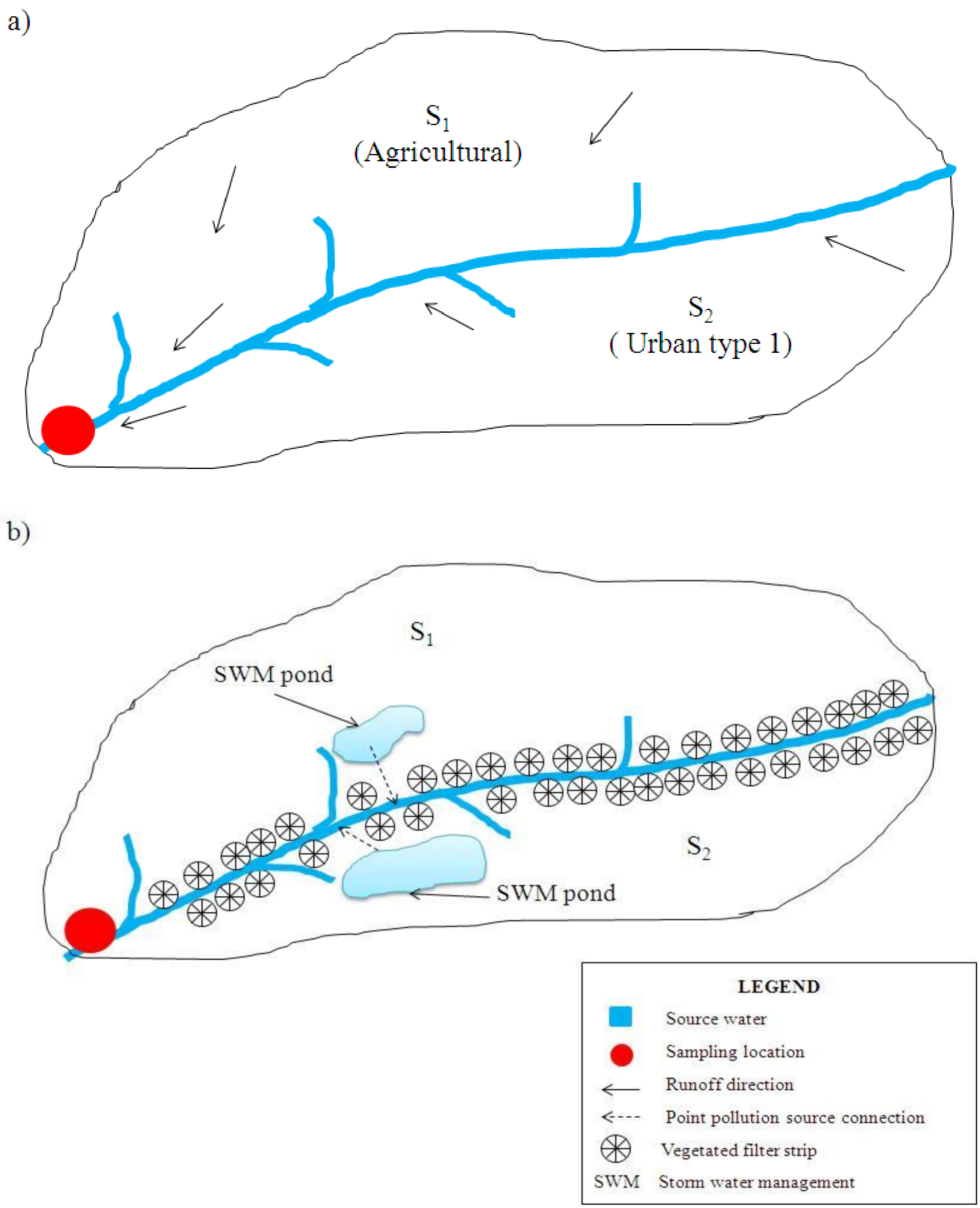


Figure 3.8: Scenarios for illustrative example a) baseline b) proposed

To estimate the water quality improvement in the receiving water body, the six steps procedure described earlier are followed for both scenarios using a monthly analysis. Table 3.3 provides the required input to perform these two scenarios. Table 3.4 provides step-by-step results of the component 1 of the conceptual framework.

For both scenarios, the reduced pollutant loads are estimated using the efficiency of selected SWP with respect to TSS. Figure 3.3 is followed to estimate the pollutant concentrations and loads. The fuzzy rule-based model is used to estimate the efficiencies of selected SWP strategies where applicable. Matlab *Fuzzy toolbox* is used to perform the analysis. An example of pollution control by agricultural practice (PCAP) efficiency based on DBD, SWC, CC and CR is provided in Figure 3.9. The value for the DBD and SWC depends on the type of soil. For example, the dry bulk density for sand, silt loam and clay 1.52 g/cm^3, 1.28 g/cm^3 , and 1.2 g/cm^3 (Linsley *et al.*, 1982). Water holding capacity (field capacity) also depends on the soil type. The Field Estimation of Soil Water Content report (2008) provides a range of the soil water content (SWC) for different soil types. The average DBD, SWC (weighted average based on area proportion) for segment 1 (S_1) is calculated (Table 3.3). Finally, DBD, SWC, CC, CR determine the PCAP efficiency using FRBM. In our case the PCAP efficiency for TSS is estimated as 73.3 % (Figure 3.9).

Chapter 2 (Tables 2.4 and 2.6) provided the percent removals of different water quality parameters in terms of event mean concentration (EMC) for different SWP strategies. The inferences in terms of the removal efficiency of TSS using fuzzy-rule-based models for different SWP strategies are used to project the removal efficiency of other water quality parameters as TSS is one of the commonly used parameter to perform case studies related to SWP strategies. Therefore, following formulation is used to estimate other pollutant removal efficiency using TSS efficiency:

$$\text{Percent removal of a WQP (for given SWP)} = \frac{\text{Percent removal of EMC for a given WQP} \times \text{Percent removal of TSS using FRBM}}{\text{Percent removal of EMC for TSS}} \tag{3.13}$$

$$\text{Percent removal of a WQP (for given SWP)} = \text{Factor} \times \text{ Percent removal of TSS using FRBM} \tag{3.14}$$

The above factor is estimated (ratio of percent removal of EMC for given WQP divided by percent removal of EMC for TSS) for each water quality parameter and each SWP strategy using Table 2.4 and 2.6.

Table 3.3: Required inputs to perform analysis using developed model

Source water info		Land use info		
depth (m)	3	Segment no	1	2
Width (b) (m)	3.5	Type of land use	Agricultural (crop land)	Urban type 1
n	0.03	Area (ha)	70	30
s	0.50%	Type of soil	50% sand and 50% clay	30% silt and 70% clay
Initial water quality parameter (Co^{a})		Runoff coefficient	0.4	0.8
TSS, mg/l	100	Land area slope (%)	3	4
TN, mg/l	3	**Temporal info**		
TP, mg/l	0.5	Month	April	
FC, mg/l	200			
TC, mg/l	2000	No of days	30	
BOD5, mg/l	10	Precipitation (mm)^{b}	200	
Pb, mg/l	0.00004	Flow depth (d) (m)	2	
Temp, ◦C	20			

SWP strategy info

Pollution control by agricultural practice (PCAP)

Segment no	DBD (g/cm^3)	SWC (%)	Cover crop (%)		Crop rotation (%)	
			Base line	Proposed	Base line	Proposed
1	1.36	0.27	20	100	30	100

Storm water management (SWM) ponds (proposed)

Segment no	Type of SWM pond	Number of ponds	Dispose as (Figure 3.3)	Water depth (m)	Vegetation level (1-5)	Retention time (hr)	Media depth (m)
1	Wet detention	1	50% NPS_SWM and 50% PPS_SWM	1.9	1	48	0
2	Wet detention	1	50% NPS_SWM and 50% PPS_SWM	1.9	1	48	0

Vegetated filter strips (VFS)

Segment no	ECL (m)	VFS length (m)	P_{VFS} (%)	P_{BL} (%)	VFS slope (%)	VFS width (m)	n*
Base line							
1	1000	30	3	97	2	5	0.4
2	990	10	1.01	98.99	2.5	3	0.3
Proposed							
1	1000	900	90	10	2	5	0.4
2	990	990	100	0	2.5	3	0.4

ECL- existing creek length; BL- bare land; DBD- dry bulk density; SWC- soil water content; *- manning's n ; a- All the parameter except Temp: b- Precipitation represents both snowfall, and rainfall; P- percentage of source water boundary covered by certain facility (e.g., BL or VFS)

Table 3.4: Step-by-step results of component 1 of the conceptual framework

Step 1: Estimate land use pollutants								
Segment no	Pollutant flow rate (liter/month)= kPA	Pollutant concentration (using Equation 3.1)						
		TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)[a]	TC (CFU/l)[a]	BOD_5 (mg/l)	Pb (mg/l)
1	5.60E+07	233.54	1.83	0.11	50000	100000	1.88	0.000146
2	4.80E+07	57.34	0.36	0.15	14000	42000	5.11	0.03[a]
Step 2: Estimation of reduced pollutants								
Pollution control by agricultural practice (PCAP) (valid for Segment 1)								
Segment no	Scenario	Removal efficiency (using FRBM)						
		TSS (%)	TN (%)	TP (%)	FC (%)	TC (%)	BOD_5 (%)	Pb (%)
1	Base line	37.9	30.3	30.3	18.9	18.9	34	7.6
	Proposed	73.3	58.6	58.6	36.7	36.6	65.9	14.7
$Load_{ANPS}$ or $Load_{NPS2}$								
Segment no	Scenario	TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)	TC (CFU/l)	BOD_5 (mg/l)	Pb (mg/l)
1	Base line	145	1.3	0.08	40525	81050	1.24	0.000135
	Proposed	62.4	0.8	0.05	31675	63350	0.6	0.000124
		Storm water management (SWM) ponds						
Segment no	Scenario	Removal efficiency (using FRBM)						
		TSS (%)	TN (%)	TP (%)	FC (%)	TC (%)	BOD_5 (%)	Pb (%)
1 and 2	Proposed	92.5	49.9	49	92.5	92.5	83.3	46.3
$Load_4$								
Segment no	Scenario	TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)	TC (CFU/l)	BOD_5 (mg/l)	Pb (mg/l)
1	Base line	145	1.3	0.08	40525	81050	1.24	0.000135
	Proposed	10.9	0.6	0.04	3039	6079	0.21	0.000072
2	Base line	57.3	0.4	0.15	14000	42000	5	0.03
	Proposed	4.3	0.18	0.07	1050	3150	0.9	0.016
Segment no	Type of load (Figure 3.3)	Flow rate (liter/month)	Segment no	Type of load (Figure 3.3)	Flow rate (liter/month)			
1	NPS_SWM	2.8E+07	1	PPS_SWM	2.8E+07			
2	NPS_SWM	2.4E+09	2	PPS_SWM	2.4E+09			
Vegetated filter strip (VFS)								
Segment no	Scenario	Removal efficiency (using FRBM and Equation 3.4)						
		TSS (%)	TN (%)	TP (%)	FC (%)	TC (%)	BOD_5 (%)	Pb (%)
1	Base line	2.6	2	2	1.3	1.3	2.3	0.5
	Proposed	0.9	0.7	0.7	0.4	0.4	0.8	0.17
2	Base line	77.5	62	62	38.8	38.8	69.7	15.5
	Proposed	86	69	69	43	43	77.5	17

Load$_5$								
Segment no	Scenario	TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)	TC (CFU/l)	BOD$_5$ (mg/l)	Pb (mg/l)
1	Base line	141.28	1.25	0.08	40002	80003	1.2	0.000134
	Proposed	10.78	0.63	0.04	3026	6053	0.2	0.000072
2	Base line	12.91	0.14	0.06	8576	25727	1.55	0.025351
	Proposed	0.6	0.06	0.02	598	1794	0.19	0.013348

Final pollutant concentrations ($C_{in/}$ C_{Final_p}) (using Equation 3.7)								
Condition	Flow rate (Q_{in}) (liter/month)	TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)	TC (CFU/l)	BOD$_5$ (mg/l)	Pb (mg/l)
Base line	4.86E+09	36.4	0.3	0.1	11622	34402	3.3	0.03
Proposed	4.86E+09	2.6	0.13	0.05	850	2513	0.5	0.01

a- Assumed concentration (discussed in Section 3.2)

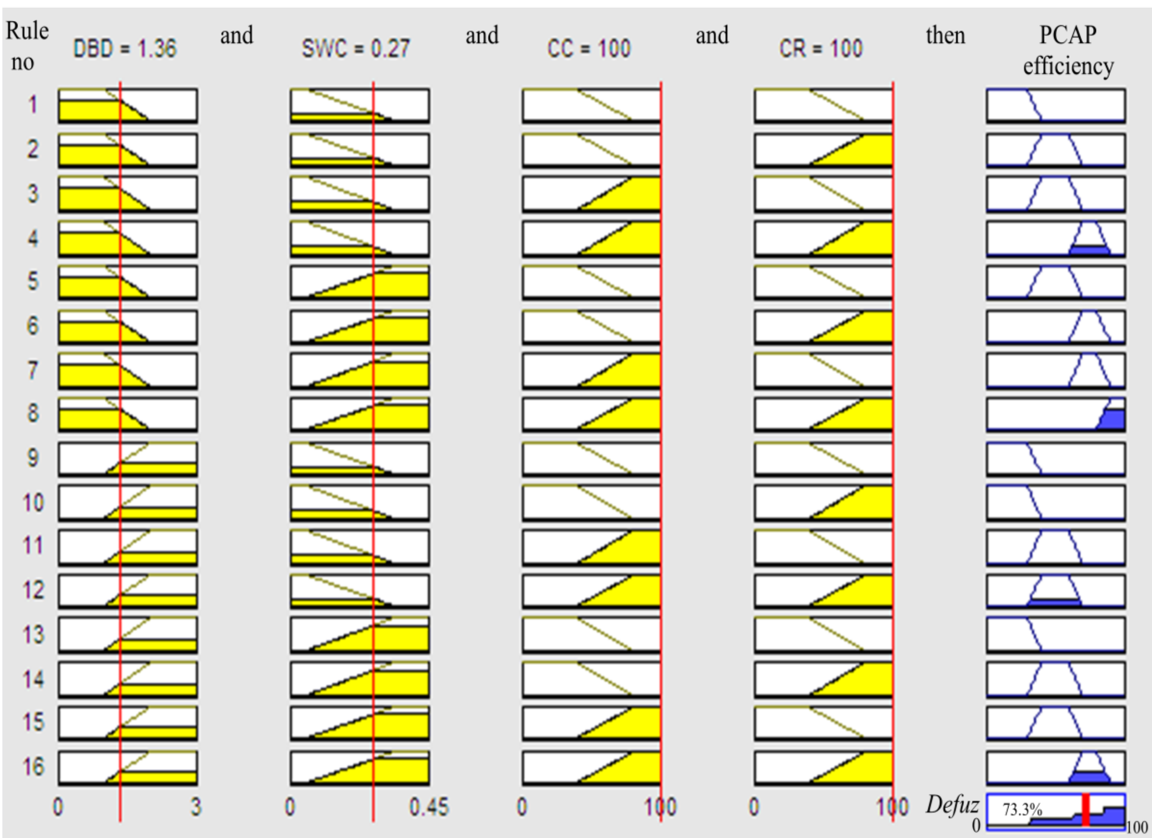


Figure 3.9: Results of a PCAP fuzzy rule-based model for the removal of TSS

For example for storm water management ponds, the removal percentage of TSS is multiplied by 0.54 for TN, 0.53 for TP, 0.90 for BOD_5, 1.0 for FC, 1.0 for TC, and 0.5 for Pb. For the vegetated filter strip efficiency, the multiplication factors are 0.80, 0.80, 0.90, 0.50, 0.50, and 0.20, respectively. Same factors have been assumed for PCAP. Finally, for Fencing, the multiplication factors of 0.9, 0.8, 0.9, 0.9, 0.9 and 0.5 are estimated. The estimated removal efficiency for TN, TP, FC, TC, BOD_5 and Pb are 58.64, 58.64, 36.65, 36.65, 65.97 and 14.66%, respectively (Table 3.4). Similarly, the removal efficiency of other SWP strategies are estimated and pollutant concentrations are derived in component 1 (Table 3.4).

Table 3.5 summarizes results of steps 3-6. A simple mass balance is applied in step 3 using Equation 3.10. The values assumed for initial concentration of water quality parameters inside the source water are provided in Table 3.3. Manning's equation is used to calculate the monthly flow rate. Assuming that the source water has a rectangular cross section (b = 3.5 m, d = 2m and s = 0.5%), the flow rate is calculated (Table 3.5). Water quality parameter sub-indices are estimated (Table 3.5) in step 4 using functions described in Figure 2.5. Finally, fuzzy measures theorem (FMT) is used to estimate WQIs (steps 5 and 6).

Figure 3.10 provides a vignette of results for all the steps involved in the proposed conceptual framework. Using enhanced SWP strategies, the WQI was improved to 46.52 (proposed scenario) from 42.47 (baseline scenario). The higher flow rates of the source water were the main cause of this small improvement in WQI. The SWP ponds with higher volumes can improve the results further however such decisions should be based on a detailed economic analysis. To further demonstrate the developed model, the next chapter provides a real life case study of Page Creek in Clayburn watershed, Abbotsford, BC, Canada.

Table 3.5: Results for component 2 and 3 (an illustrative example)

Step 3: [a]Mass balance (using Equation 3.10)

Scenario	TSS (mg/l)	TN (mg/l)	TP (mg/l)	FC (CFU/l)	TC (CFU/l)	BOD_5 (mg/l)	Pb (mg/l)
Base line	93	2.7	0.46	1415	5446	9.3	3.2E-03
Proposed	89.6	2.7	0.45	269	2055	9	1.1E-03

Step 4: Water quality parameter sub index (A) using functions in Figure 2.5

Scenario	Sub index TSS	Sun index Temp	Sub index TN	Sub index TP	Sun index FC	Sun index TC	Sun index BOD_5	Sub index Pb
Base line	0.08	1	0.3	0	0.40	0	0.42	0.7
Proposed	0.12	1	0.3	0	0.60	0.13	0.43	0.9

Step 5: Water quality groups (using FMT Equation 2. 16)

	TSS	Temp	TN	TP	FC	TC	BOD_5	Pb
Assigned weights (μ)	0.4	0.2	0.4	0.4	0.5	0.3	1	1

Water quality (issue) WQI

Scenario	Primary- WQI	Nutrient - WQI	Microbial-WQI	Organic -WQI	Toxic Substance-WQI
Base line	26.5	12.9	20.3	42	71
Proposed	30	13	36.3	43	90

Step 6: Overall WQI (using FMT Equation 2. 16)

	Primary- WQI	Nutrient - WQI	Microbial-WQI	Organic -WQI	Toxic Substance-WQI
Assigned weights (μ)	0.3	0.5	0.5	0.3	0.5

Condition	**WQI**
Base line	**42.47**
Proposed	**46.52**

a- Equation 26 needs Q_o in source water. Manning's equations is used to calculate the flow rate, $Q_o = \frac{1}{n} A R^{2/3} s^{1/2}$; n = 0.03 (for clean and straight natural channel); s = slope = 0.5%, b = average width = 3.5m; d = 2m (stated in Table 3.3); A= b*d; P = b+2*d; and R=A/P

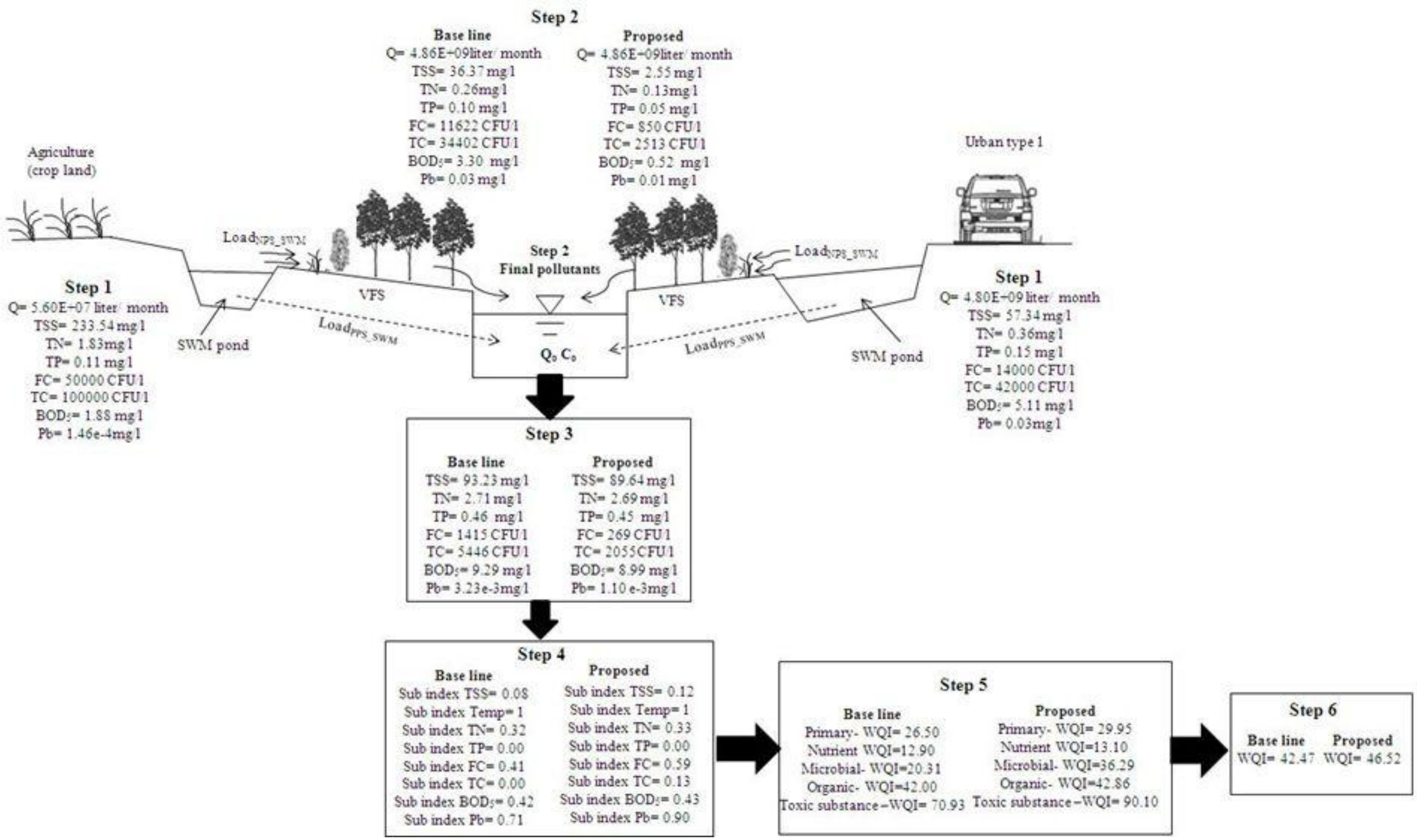


Figure 3.10: Illustrative example results-a snapshot

4. PAGE CREEK CASE STUDY

4.1 Study Area

Page Creek is a sub-watershed of the Clayburn watershed (city of Abbotsford) in the Fraser valley (British Columbia, Canada). Abbotsford is located in the Coastal Western Hemlock Biogeoclimatic zone which is known for a cool mesothermal climate with relatively cool summers. The area is in class C of the Köppen climate classification and maritime temperate with most of the area is a coastal rainforest. The average annual precipitation is around 1,573.2 mm/yr (Environment Canada, 2004). The variation of the monthly total precipitation shows that the area remains comparatively dry during summer from June to September (Figure 4.1) (Statistics, 2010). The location for monitoring Page Creek water quality has been identified in Figure 4.2.

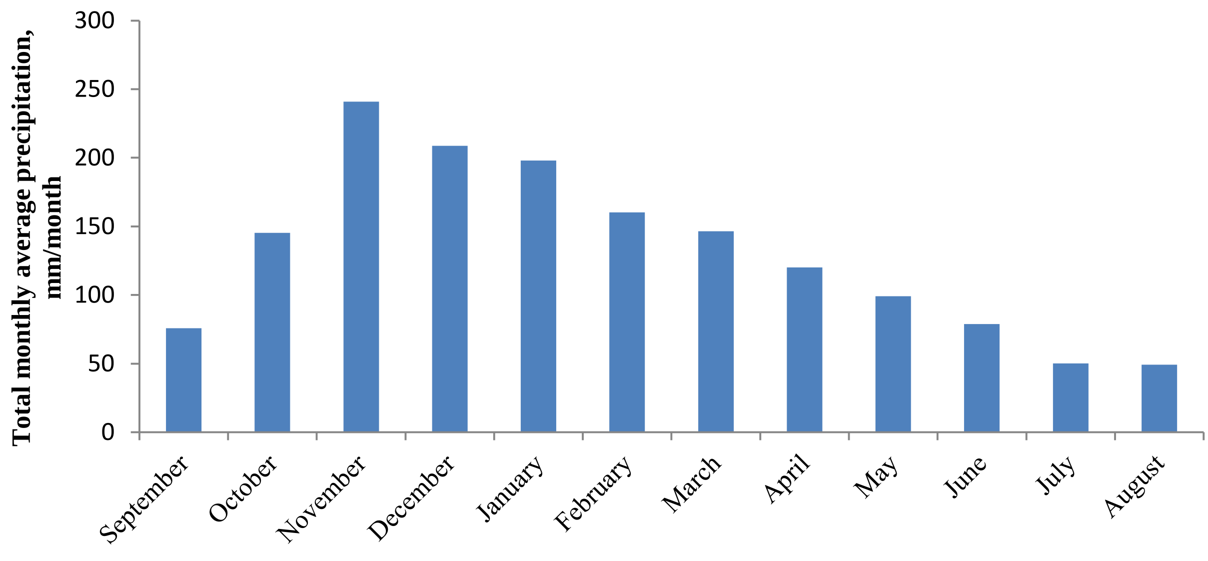
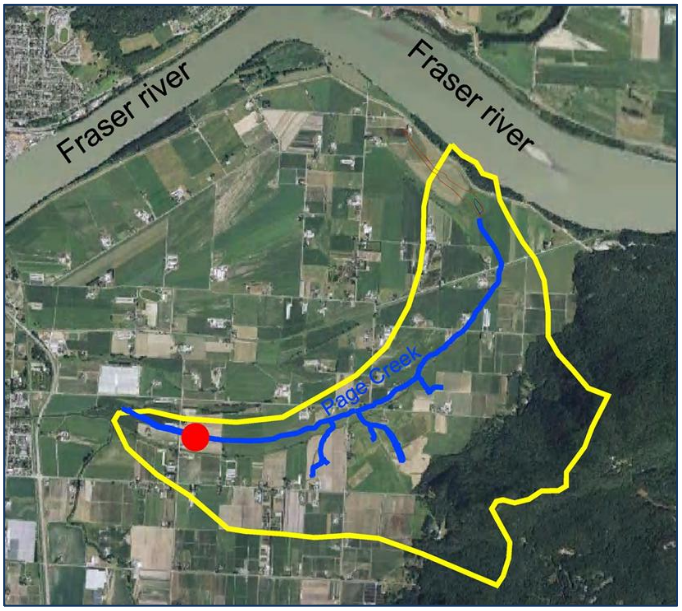


Figure 4.1: Average monthly total precipitation (mm) in Abbotsford



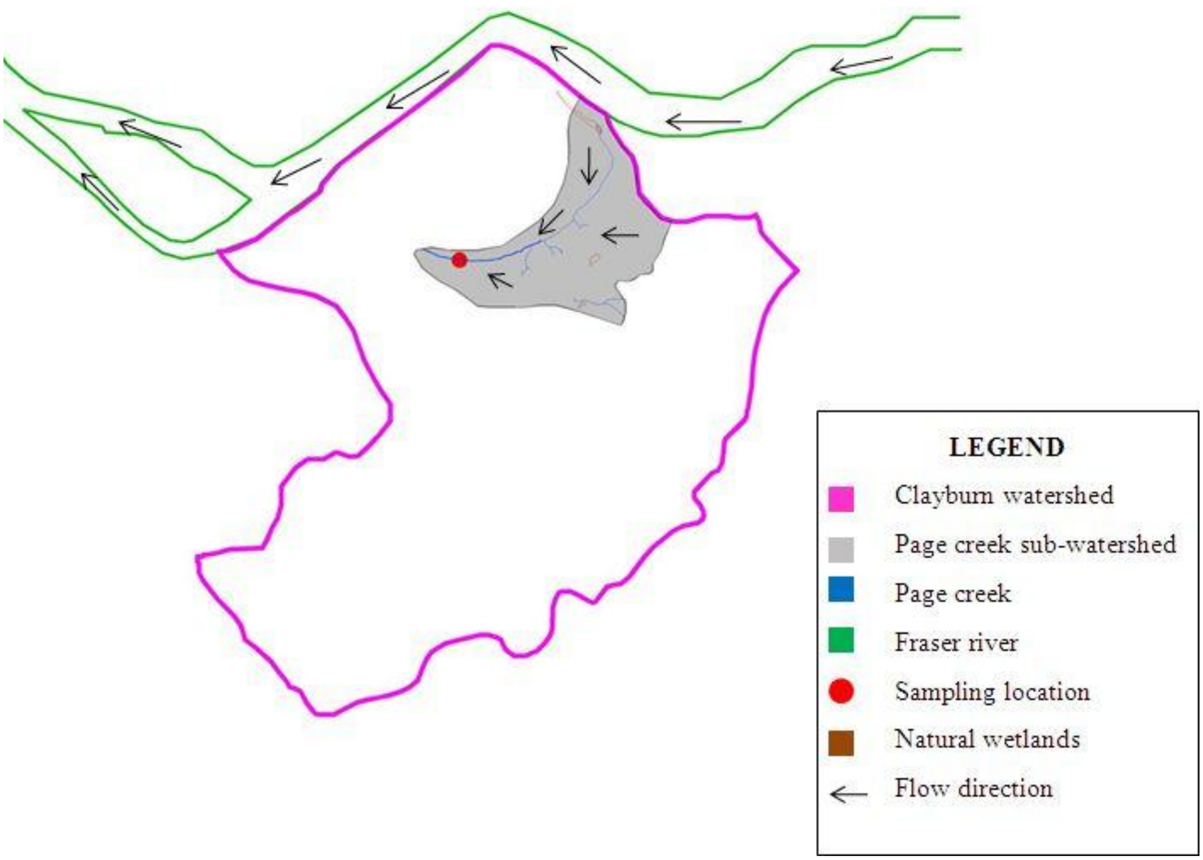


Figure 4.2: Page Creek sub-watershed area in Clayburn watershed

The total area of Clayburn watershed is 7,451 ha (City of Abbotsford, 2009) where the Page Creek sub-watershed has area around 798 ha (calculated from a contour map). The sub-watershed has been slightly modified to get the effective drainage area for the Page Creek sampling station.

The total land area of the effective Page Creek sampling station is approximately 761 ha. The water quality monitoring data has been identified based on a study by Brown (2009). Page Creek is small in width ranging from ~2.5-5m (with an average of 3.75 m) and depth ranging from ~0.30-1.5 m (with an average of 0.9 m) unlike other creeks in this area (Fraser Salmon and Watersheds Program, 2009). In certain periods of the year it may remain dry or have a very low flow. The slopes of the creeks in this area vary between 0-3 percent (Barstead, 2004). The average slope is approximately 0.5% as the Page Creek is located in one of the flatter parts of the Clayburn watershed[4].

Based on the average monthly precipitation, the creek water flow depth has been assumed. Water depth in November is assumed to be the highest (0.70 m) as the precipitation is the highest during this month. It should be noted that precipitation represents both snowfall and rainfall. Assumed water depths from September to December are 0.221m, 0.422 m, 0.700 m, 0.606 m, 0.576 m, 0.466 m, 0.425 m, 0.349 m, 0.288 m, 0.229 m, 0.146 m and 0.143 m which is determined with precipitation proportion multiplied by the highest depth in November. Manning's equation was used to estimate the flow rate of Page Creek from September to December (Appendix J). Figure 4.3 plots flow rates in the creek around the year that are based on precipitation intensity.

Page Creek sub-watershed is an agricultural and farming area. The land use map (Figure 4.4) shows the diversity of the land use type, e.g., berry (43ha), swine (7.5 ha), poultry (11 ha), dairy (104 ha), hobby (1 ha) farms, beef livestock (26 ha), forage/pasture (125 ha), forests (97 ha), nursery (14.5 ha) areas, impervious roads (7 ha) and some un-identified area (192 ha which is assumed as pasture for simplicity).

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[4] Observed from the contour map downloaded from http://webmap.abbotsford.ca/WebMap/main.asp

4.2 Data Preparation

The main objective of the developed model is to estimate an improvement in the source water quality after implementation of selected SWP strategies. The input data requirements of the developed model are: land use distribution, selected water quality parameters, soil properties, types of SWP strategies, and creek water quality monitoring data. The model can predict the improvement in water quality after the implementation of SWP strategies. The following sections describe the data preparation for analysis.

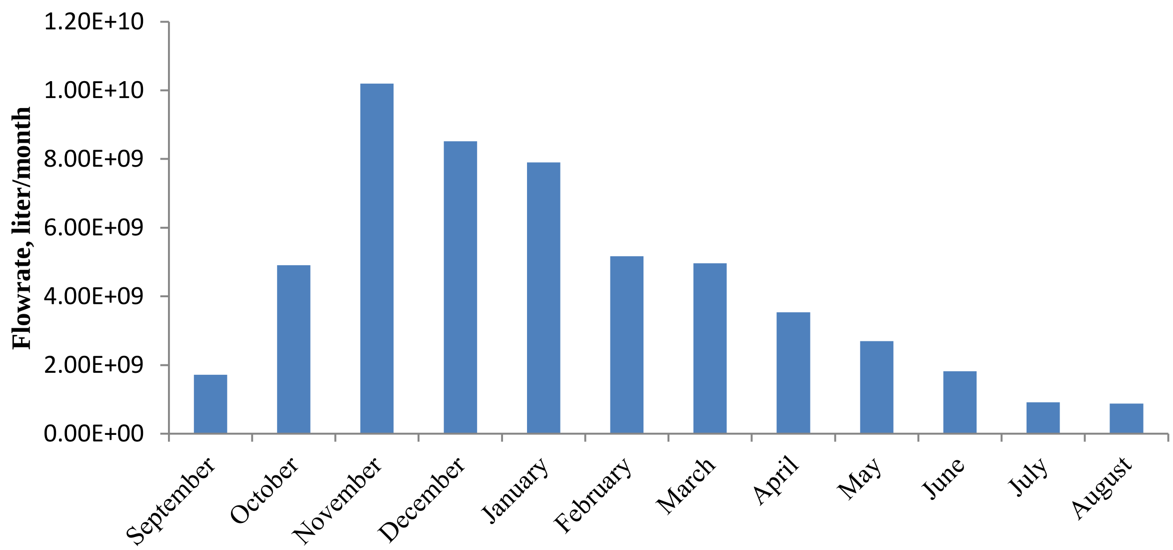

Figure 4.3: Monthly flow rate prediction in Page Creek

4.2.1 Pollutant load calculations

To calculate pollutant loads, the effective area of the creek is divided into six segments (Figure 4.4). These segments have been defined to estimate various factors that may impact the creek water quality. Table 4.1 provides the distributions of different land use within each segment (S_1 to S_6). Six basic land use categories including agriculture, pasture/forage, livestock farms, forests, urban type 1 (NPS from roads-U_1) and urban type 2 (Commercial PPS-U_2) are considered in this study (Table 4.1 and 4.2). These land use areas have been estimated using maps collected from the City of Abbotsford (2004). Monthly water quality data were collected from September 2007 to August 2008, therefore the channel flow rate and export coefficient (EC) values are also used in monthly units (Brown, 2009).

Table 4.1: Land use area distribution for six segments (m^2)

Land use	Category	S_1	S_2	S_3	S_4	S_5	S_6
Berry farm	Agricultural	496506	0	374285	0	53414	0
Forage/ pasture	Pasture	174961	336313	384532	288890	155398	84036
Dairy farm	Livestock	432491	171317	320735	296289	151465	102303
Forest	Forests	0	610072	361936	0	0	0
Beef cattle	Livestock	0	28665	8056	220727	6117	0
Poultry farm	Livestock	109759	0	48645	14093	0	46352
Swine farm	Livestock	0	0	0	74822	0	0
Hobby farm	Agricultural	0	0	0	0	9881	0
Nursing	Agricultural	145379	0	0	0	0	0
Roads	Urban type 1	0	0	15304	55975	0	0
Unknown area	NA	0	1566480	355155	0	0	0
Total area (m^2)		**1377466**	**2712847**	**1868648**	**963627**	**371612**	**233652**
Total area (ha)		**137.75**	**271.28**	**186.86**	**96.36**	**37.16**	**23.37**

Table 4.2: The distribution for six land use types (ha)

Segment	Agricultural area	Pasture area	Livestock area	Urban type 1 area	Forest area	Urban type 2 area
S_1	64.19	17.50	54.23	0.00	0.00	0.00
S_2	0.00	190.28	20.00	0.00	61.01	0.00
S_3	37.43	73.97	37.74	1.53	36.19	0.00
S_4	0.00	28.89	60.59	5.60	0.00	0.00
S_5	6.33	15.54	15.76	0.00	0.00	0.00
S_6	0.00	8.40	14.87	0.00	0.00	0.00
Total area (ha)	**107.95**	**334.58**	**203.18**	**7.13**	**97.20**	**0.00**

The EC approach was used to calculate pollutant concentrations. The EC values for selected water quality parameters were used in this case study. In case of missing values, the land use concentrations have been employed. As the precipitation patterns vary significantly in the reported studies from the Clayburn, the monthly precipitation ratio has been used to convert the monthly concentration from the reported data into the monthly concentration of Calyburn watershed. Equation (3.1) has been developed to determine the concentrations of selected water quality parameters (pollutants). Equation (3.2) is used to calculate the concentration of pollutants for livestock and pasture land use from total manure mass production calculations (ASAE, 2003).

City of Abbotsford (2004) has provided the information to estimate the numbers of dairy and beef. However, in case of poultry and swine, the area ratio has been used to estimate the poultry and swine livestock numbers. Based on information available for years 1995, 2000 and 2005 (Abbotsford Agricultural Strategy, 2009), the average livestock number in 2007 was estimated. Table 4.3 provides an estimation of different livestock numbers in six segmental areas in year 2007. In this analysis we assume that there is no pasture livestock from December-February. To perform the yearly analysis, livestock numbers are also estimated for years 2008-18 in the same way.

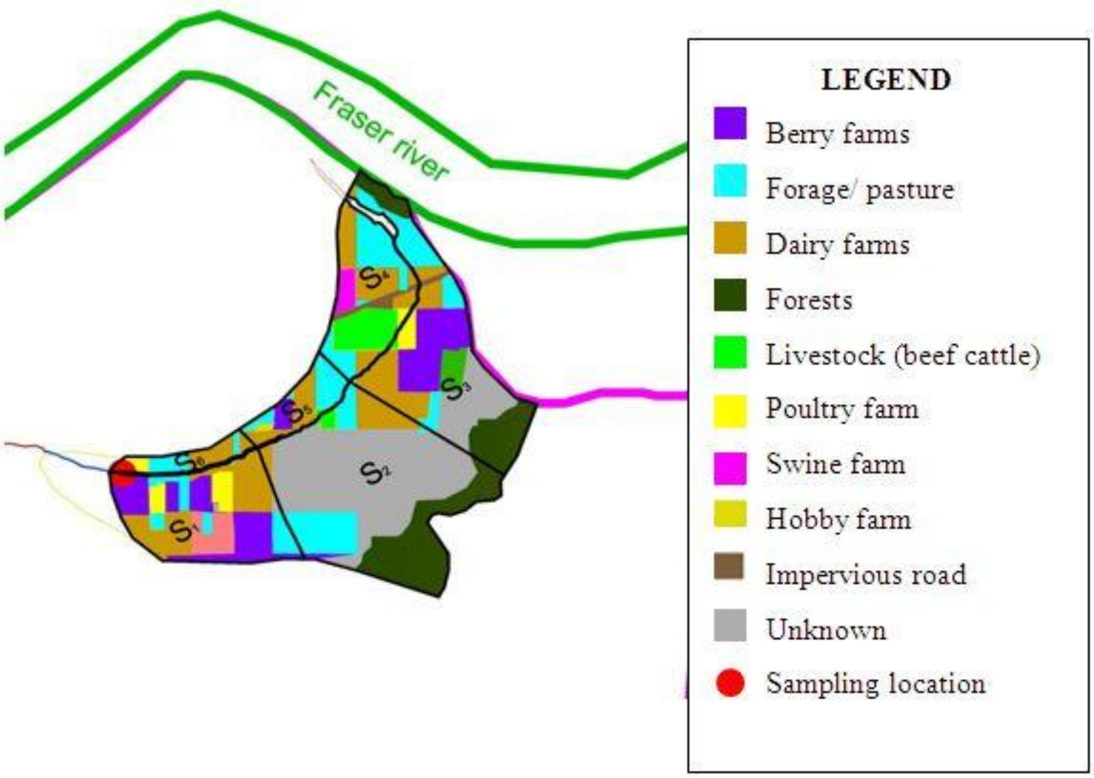

Figure 4.4: Six segments in the Page Creek effective area

Table 4.3: Pasture/forage livestock numbers in the study area for year 2007

Segment	Total livestock area (ha)	Dairy cattle (Number)	Beef cattle (Number)	Swine (Number)	Layer (Poultry) (Number)
S_1	54.2	242	0	0	48,864
S_2	20	115	6	0	0
S_3	37.7	181	2	0	21,767
S_4	60.6	167	107	1,377	6,219
S_5	15.76	101	1	0	0
S_6	14.87	52	0	0	20,434

4.2.2 SWP strategies

The model considers four types of SWP strategies including PCAP, fencing (Fen), storm water management (SWM) ponds (six types of ponds) and VFS. The data requirements for each SWP strategy are discussed below:

Figure 4.5 provides information related to the type of soil of the study area which consists of sandy silt, peat, granite, volcanic rock and silty clay. The dry bulk densities (DBD) of the basic soils are discussed earlier in Section 3.5. For granite soil and volcanic rock, 2.4 g/cm^3 DBD has been assumed. Schwarzel *et al.* (2002) provided a DBD range of 0.14- 0.36 g/cm^3 for the peat soils. In this research, we have assumed a value of 0.30 g/cm^3 for peat. The average DBD is calculated based on the weighted average of land area proportion. Soil water content (SWC) is also estimated using average area proportion. The SWC for peat soil is assumed as 0.45 as it can hold the highest amount of water due its structure rich in organic matter (grain of mulches). For silt and granite soil (also for volcanic rock), the SWC are assumed as 0.20 and 0.02, respectively. Due to lack of reliable information, it was also assumed that there are no cover crops (CC) or crop rotation (CR) practices prevalent in the study area. Therefore, 100% CC and 100% CR have been proposed for the agricultural areas (except segments 4 and 6 because there was no crop production area). Table 4.4 provides a summary of the PCAP data derived for the six segments.

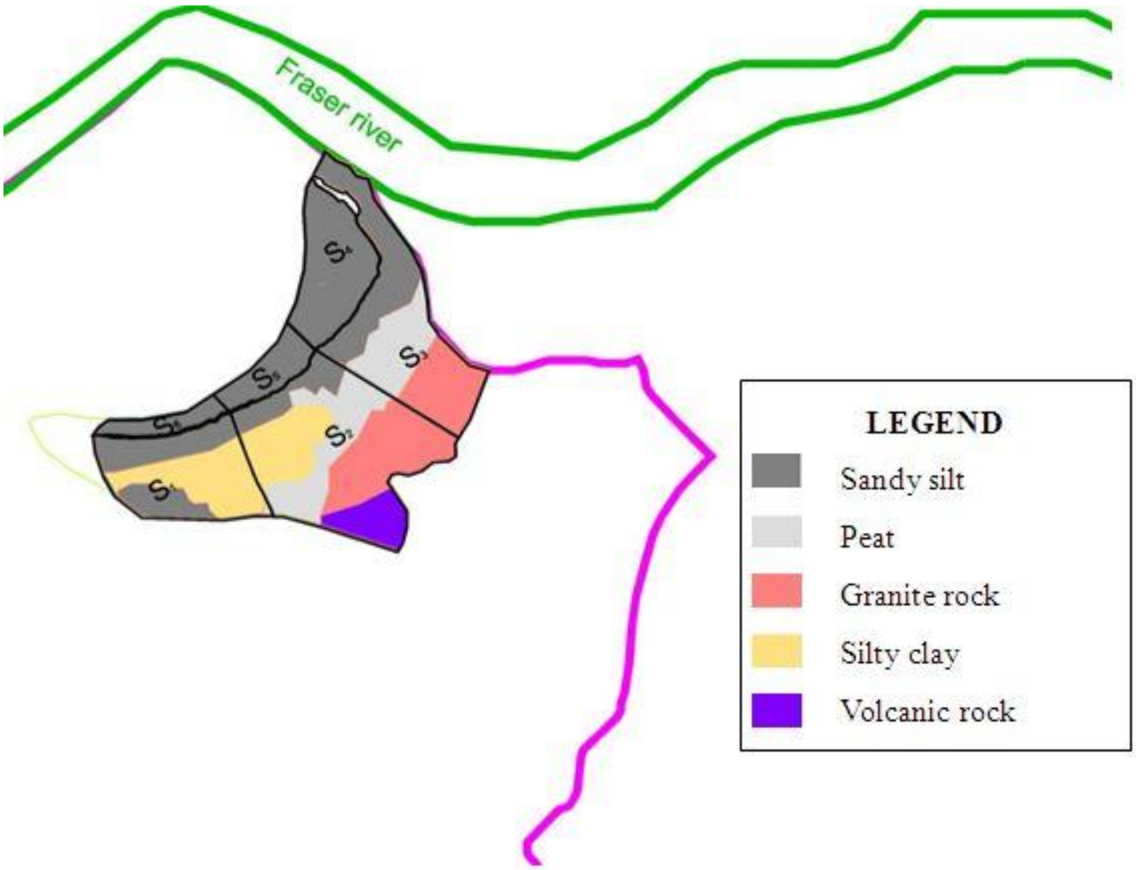

Figure 4.5: Soil type distribution in the study area

Table 4.4: Summary data for pollution control by agricultural practice (PCAP)

Segments	Area proportions (m^2)				DBD (g/cm^3)	SWC	Future PCAP recommendations	
	Sandy silt	Peat	Granite rock	Silty clay			CC (%)	CR (%)
S_1	700, 770	14, 051	0	669, 206	1.31	0.24	100	100
S_2	325, 328	684, 931	1,176, 210	523, 485	1.53	0.20	100	100
S_3	798, 625	524, 698	537, 610	0	1.38	0.21	100	100
S_4	963, 627	0	0	0	1.40	0.17	0	0
S_5	371, 612	0	0	0	1.40	0.17	100	100
S_6	233, 652	0	0	0	1.40	0.17	0	0

DBD- Dry bulk density; SWC- soil water content (field capacity); PCAP- pollution control by agricultural practice

Generally fencing is provided for pasture/ forage area to keep animals away from the water source. Because of lack a data, conservative estimates of 2% and 4% load reduction has been assumed for the barbed ($\mathrm{Fen_{BF}}$) and vegetated ($\mathrm{Fen_{VF}}$) fencing. It is very common to have partial fencing therefore we used Equation (3.3) to estimate the efficiency in case of partial fencing.

Figure 4.6 shows the storm water collection in Abbotsford. There is no SWM pond identified in the study area, however, there are a few natural wetlands. Therefore, a SWM system can be proposed to control the storm water entering into the creek at higher flow rates. One SWM pond for each segment is proposed. Wet detention ponds, storm water wetlands, and dry detention ponds are recommended. However, for a smaller area, dry detention pond has been proposed. Table 4.5 provides the design parameters for recommended SWM ponds. It can be assumed that 50% (by volume) SWM treated water will be directly disposed to the creek water through pipeline. The remaining 50% will be discharged in to the creek as NPS.

Table 4.5: Future storm water management pond options for six segments

Segments	**Land area (ha)**	**Type of SWM pond**	**SWM parameters recommendations**			
			Water depth (m)	Vegetation level (1-5)	Retention time (hr)	Media depth (m)
S_1	137.75	Storm water wetlands	0.7	3	48	0
S_2	271.28	Wet detention pond	1.9	1	48	0
S_3	186.86	Wet detention pond	1.9	1	48	0
S_4	93.36	Storm water wetlands	0.7	3	48	0
S_5	37.16	Dry detention pond	0.6	0	24	0
S_6	23.36	Dry detention pond	0.6	0	24	0

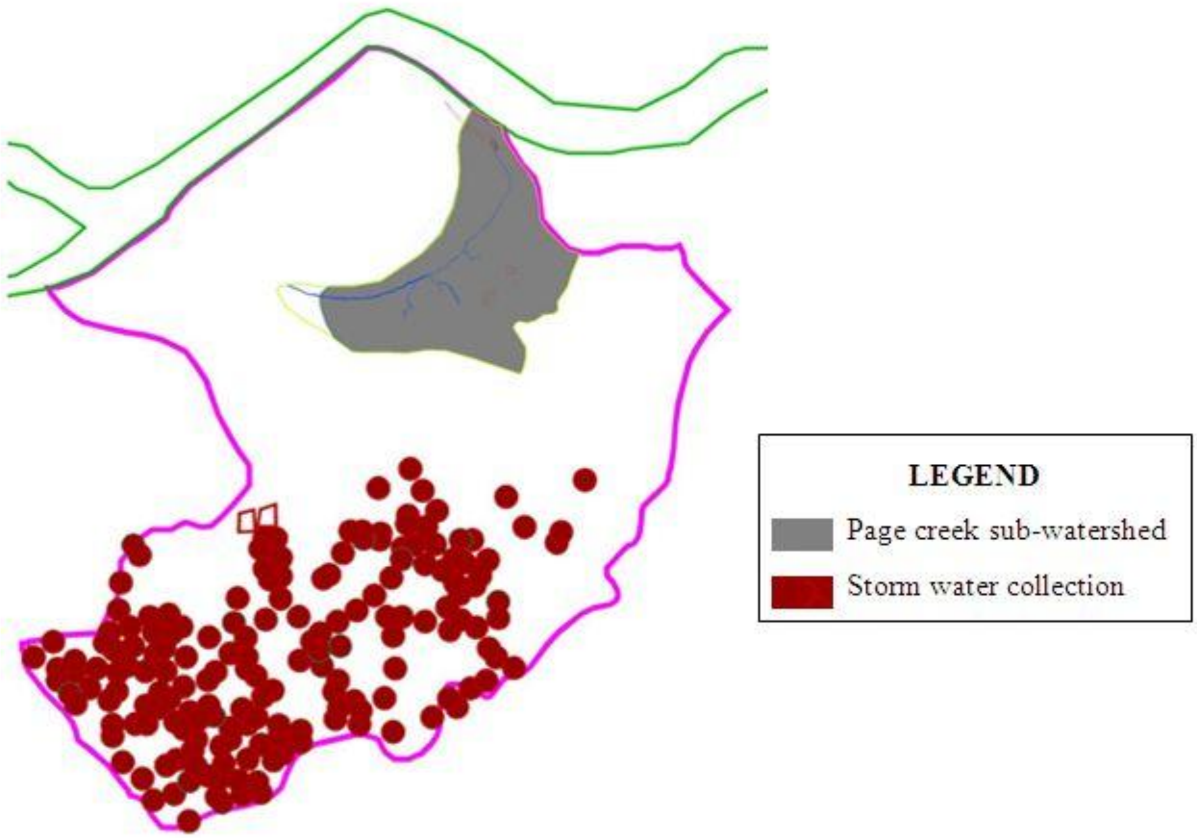

Figure 4.6: Storm water collection in Clayburn watershed

In case of VFS, the parameters required for estimating the efficiency of VFS ($EVFS_{VFS}$) are provided in Table 4.6, which shows both current VFS condition and suggests some improvements in the future. The monitoring data for Page Creek are available only for TSS, temperature, PO_4, TN, FC, and Pb. As the minimum requirement of the model is to have monitoring data for TSS, TN, TP, FC, TC, BOD_5, and Pb, some assumptions have been made for the missing data. It should be noted that PO_4/ TP ratio of 0.45[5] has been used to derive TP from PO_4 data

[5] Correlations between trophic indicators (OECD) available at http://www.chebucto.ns.ca/ccn/info/Science/SWCS/TPMODELS/OECD/correlations.html#opo4

Table 4.6: Inputs for VFS around the Page Creek-current and future recommendation

Segment	ECL (m)	Avg. Channel width (m)	VFS length (m)	P_{VFS} (%)	P_{BL} (%)	VFS area slope[1] (%)	Avg. VFS width (m)	n*
Current								
S_1	1, 458	5.0	448	30.73	69.27	0.5	15	0.2
S_2	1, 161	4.5	120	10.34	89.66	0.5	30	0.3
S_3	2, 460	2.5	178	7.24	92.76	0.5	19	0.3
S_4	2, 376	2.5	32	1.35	98.65	0.5	30	0.4
S_5	1, 159	4.5	0	0.00	100.00	0	0	0
S_6	1, 455	5.3	0	0.00	100.00	0	0	0
Future recommendations								
S_1	1, 458	5.0	1, 458	100	0	0.5	15	0.4
S_2	1, 161	4.5	1, 161	100	0	0.5	15	0.4
S_3	2, 460	2.5	2, 460	100	0	0.5	15	0.4
S_4	2, 376	2.5	2, 376	100	0	0.5	15	0.4
S_5	1, 159	4.5	1, 159	100	0	0.5	15	0.4
S_6	1, 455	5.3	1, 455	100	0	0.5	15	0.4

1. Slope was assumed
ECL- Effective creek length for each segment; VFS- Vegetated filter strip; BL- Bare land; P_{VFS} and P_{BL} discussed in Equation 3.4.
* Manning's constant

4.3 Results and Discussions

A detailed analysis has been performed using the model for both monthly and yearly time steps. The WQI has been predicted monthly from September 2007 to August 2008 and yearly for years 2007 to 2018. A sensitivity analysis based on land use variations has been performed to observe the effects of different land use on the creek water quality in comparison with base line condition (present land use and SWP strategy conditions). The sensitivity analysis also allows the prediction of the final conditions from 2008 to 2018 using proposed SWP strategies compared to the base line conditions. Finally, water quality assessment based on monitored creek has been compared with NFS-WQI.

4.3.1 Predicted WQI–monthly variation

Monthly analysis has been performed from September 2007 to August 2008. September 2007 water quality monitored data have been considered as the initial creek water quality parameter value (C_o) to carry out the analysis. The yearly cycle is divided into summer season (S) from April to September and winter season (W) from October to March. Results are presented for these two seasons using box-and-whisker diagrams for $Load_{NPS1}$, $Load_{NPS2}$ and the final pollutant loads entering into the creek based on zones 1, 2 and 3 (Figure 3.2 and 3.3). Box-and–whisker is a diagram to represent a set of data using, median, lower quartile (25th percentile), upper quartile (75th quartile), maximum and minimum value (explained in Appendix K). Pollutant load calculations and estimation of SWP (PCAP and Fen) efficiencies are used to predict $Load_{NPS1}$ in zone 1. Equations 3.1 and 3.2 are used to calculate the possible pollutant concentration for the land uses (e.g., agricultural, pasture, livestock, forest, and urban type 1). Finally, PCAP and Fen were implemented to reduce pollutants for agricultural and pasture land use in zone 1. Previously identified PCAP parameters were utilized to obtain the PCAP efficiency using FRBM. Finally, Equation (3.3) has been used to calculate the efficiency for Fencing (Fen).

Figure 4.7 shows the changes in water quality parameters for $Load_{NPS1}$ with and without implementation of PCAP and Fencing in Zone 1. Significant reductions in the concentrations of TSS, moderate in case of TN, FC, and TC and minimal in case of TP, BOD_5 and Pb are estimated. The results suggest that PCAP and Fencing are more effective to remove (or to protect the source water from) TSS as compared to other pollutants (water quality parameters). However, more strategies are required as the concentrations of most of the pollutants were above the guidelines. Comparison between summer (S) and winter (W) analyse predict that water quality is generally worse during summer months.

Zone 2 receives polluants from zone 1 ($Load_{NPS1}$). In this zone, storm water management is used to reduce the pollutant concentrations. Six storm water management ponds have been proposed to reduce $Load_{NPS1}$. Finally, $Load_{NPS2}$ is calculated based on $Load_{NPS1}$ and storm water management pond efficiency. Figure 4.8 shows the $Load_{NPS2}$ for zone 2.

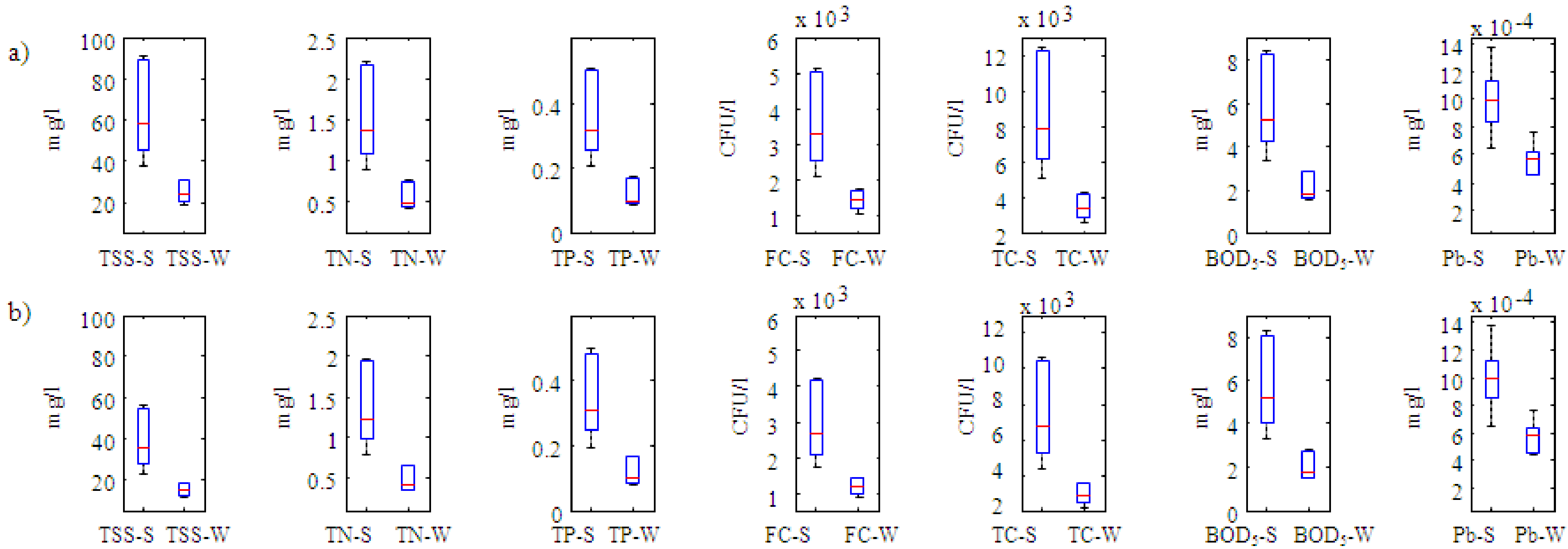

Figure 4.7: NPS1 loading change for the seven pollutants a) without PCAP & fencing and b) with PCAP and fencing

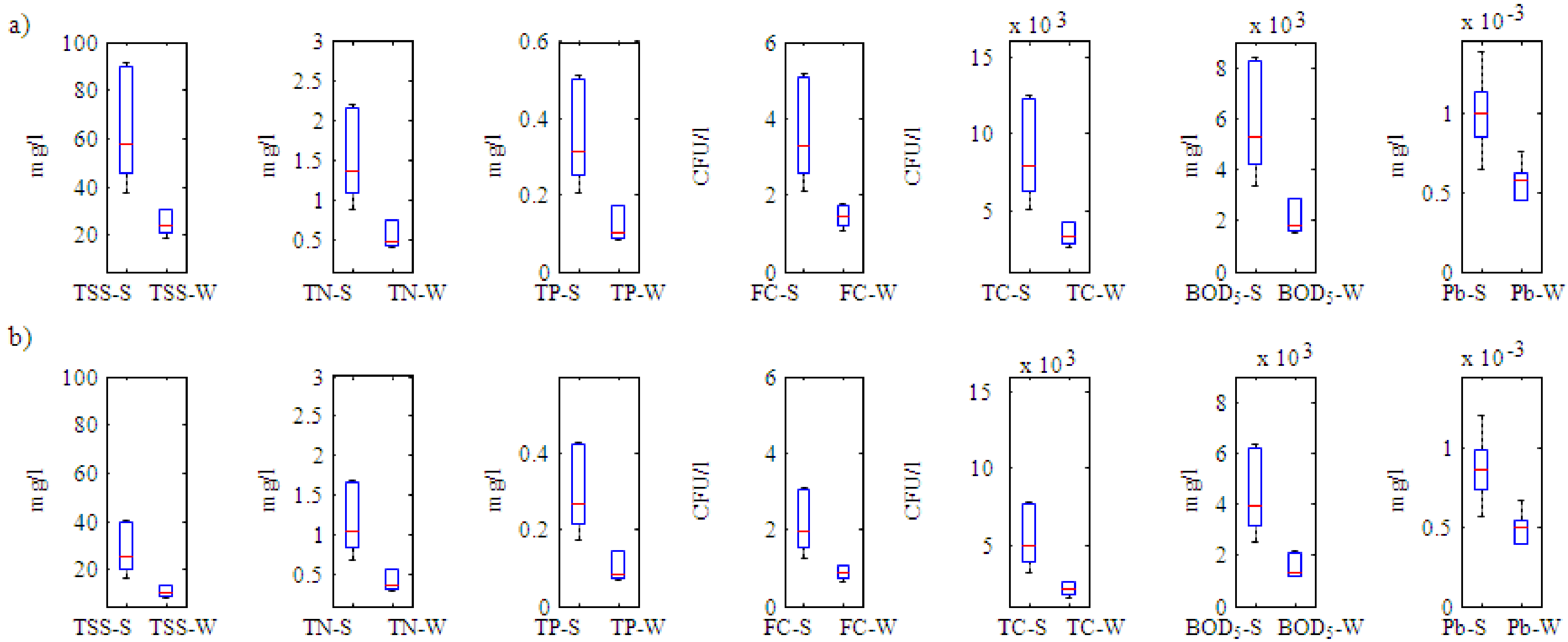

Figure 4.8: NPS2 loading change a) without storm water management pond and b) with storm water management pond

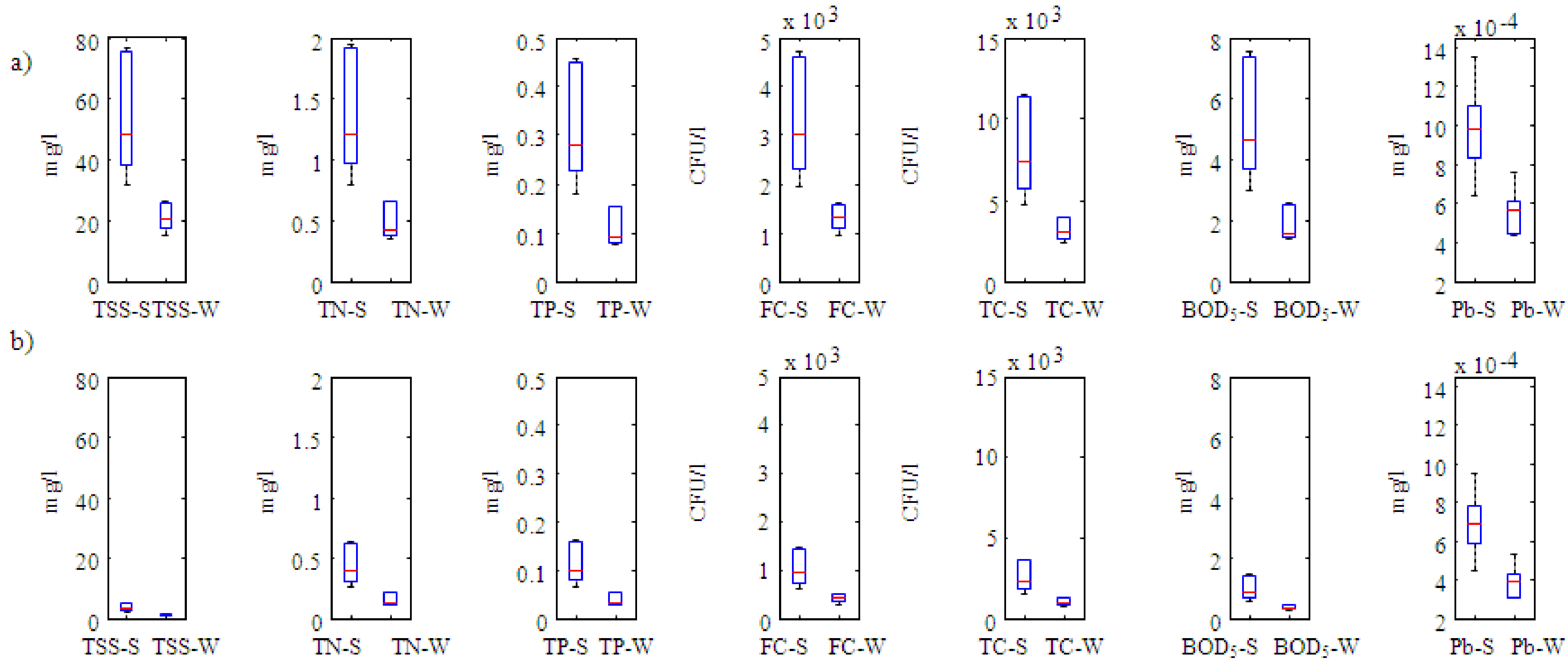

Figure 4.9: Final pollutant loading change for the seven parameters a) without vegetated filter strip and b) with vegetated filter strip

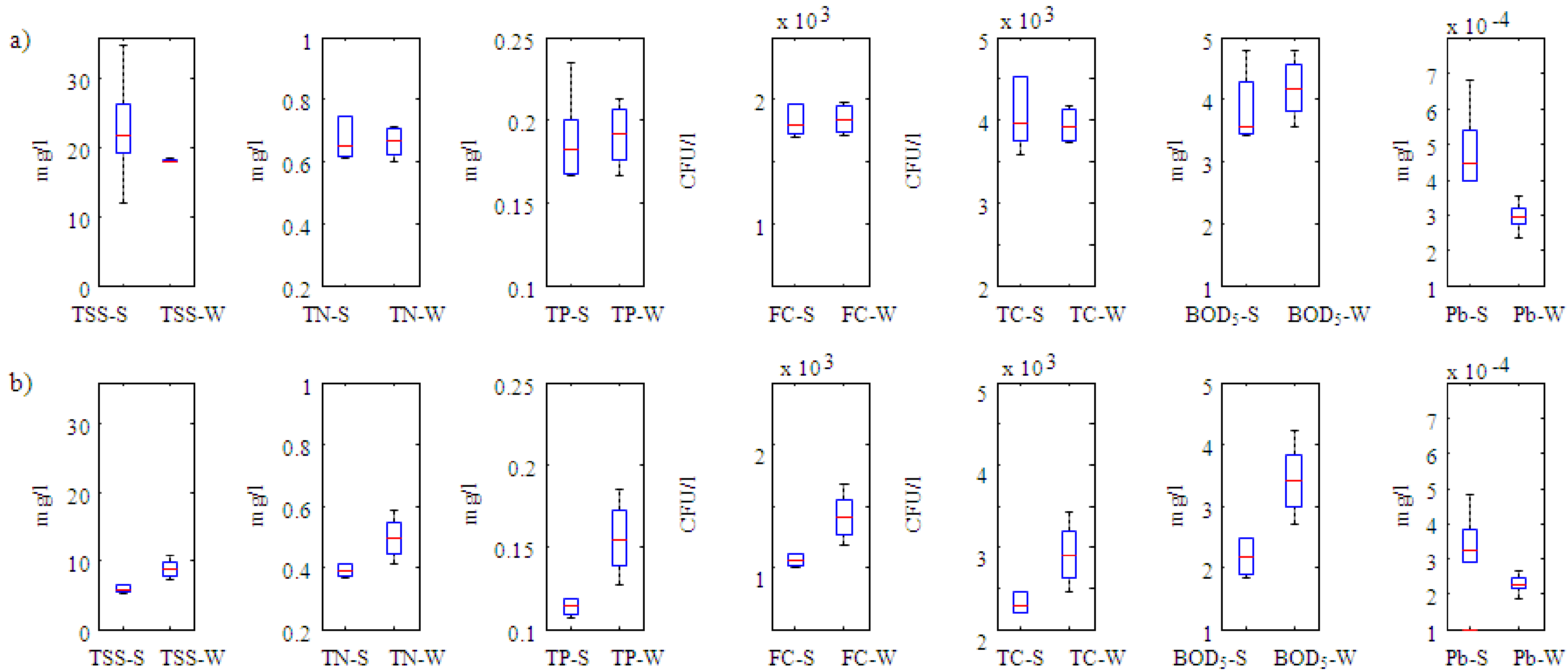

Figure 4.10: Creek water quality prediction for water quality parameters a) with SWP strategies and b) without SWP strategies

It shows significant improvement in water quality due to removal of TSS, FC, TC and comparatively moderate improvement due to reduction in TN, TP, BOD_5, and Pb. In zone 3, $Load_{NPS2}$ was reduced due to VFS and the final pollutant loads (summation of $Load_5$ and $Load_{PPS\_SWM}$) going into the creek water were calculated. The final pollutants in terms of pollutant concentration without VFS and possible pollutant removals after VFS implementation are represented in Figure 4.9. The figure shows improvements (pollutant reduction) in all parameters. It suggests also that better water quality is expected during winter as compared to summer.

Equation 3.10 was used to estimate the changes in the pollutant concentrations in the source water, Figure 4.10 shows changes in pollutant concentrations in the creek. The initial pollutant concentrations, determined by considering the effect of initial SWP strategies around the creek, are as expected higher than the concentrations calculated based on the pollutant removal efficiency of all the proposed SWP strategies. Figure 4.10 also shows reduction in the concentrations for all the parameters. Lower values have been estimated during winter compared to the summer.

Creek water quality assessment has been done using WQI based on fuzzy measure theory (FMT). The weights used in this study are assumed (Table 3.5); however, the model allows user-defined weights as well. The assessment has been done based on monitoring data (Brown, 2009), predicted model initial (base line scenario using the current SWP strategies) and final (using proposed SWP strategies) values. It should be noted that the monitoring data represent a particular day of the month, and not a monthly average concentration. Therefore, a comparison between the monitored and the initial predicted assessment results might show some discrepancies. Appendix L provides the sub-indices values from September 2007 to August 2008 for the monitored, initial and final predicted model data sets. Figures 4.11, 4.12, 4.13, 4.14 and 4.15 exhibit the water quality index for each group: primary, nutrient, microbial, organic and toxic substances, respectively. Figure 4.16 shows overall WQI for summer and winter.

- For primary- WQI group, Figure 4.11 shows that the predicted WQI is independent of the season. Proposed SWP strategies (final conditions) improve water quality. Moreover, each of the three cases, the water quality during summer and winter varies only slightly, especially for the final condition where it is always *excellent*. For monitored data, during summer the WQI was *excellent* but varied from *very good* to *excellent* during winter. In the case of initial conditions, WQI varied from *good* to *excellent* in the summer and was always *excellent* during winter.

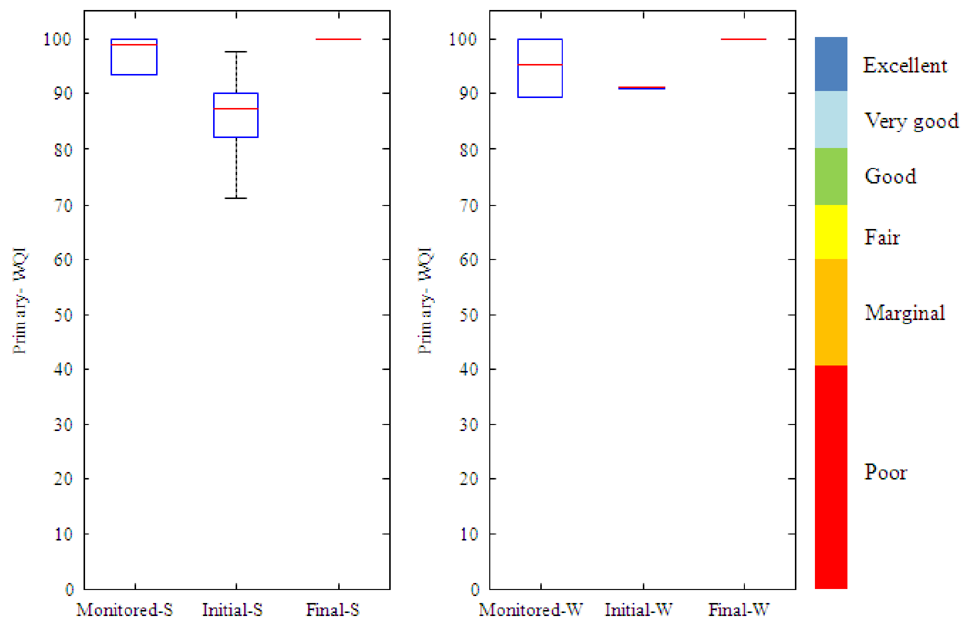

Figure 4.11: Seasonal primary-WQI

- For the nutrient- WQI group (Figure 4.12), the monitored WQI shows a large variability from *poor* to *fair* during summer and *poor* during winter. Initial predicted WQI for summer and winter were the same from *marginal* to *fair*. Finally, the predicted final WQI is *good* during summer and varied from *fair* to *good* during winter.
- For the microbial- WQI group (Figure 4.13), the monitored WQI during summer varied from *poor* to *fair* and *poor* during winter, whereas the initial and final predicted WQI was *poor* in all seasons.
- For the organic- WQI group (Figure 4.14), the monitored WQI varied from *poor* to *very good* during summer and *poor* to *good* during winter. Initial predicted WQI was in *marginal* range whereas the final WQI raged between *marginal* to *very good* during summer and was *marginal* during winter.

- For the toxic substance- WQI group (Figure 4.15), the monitored WQI was *excellent* which showed very little improvements after the implementations of selected SWP strategies.

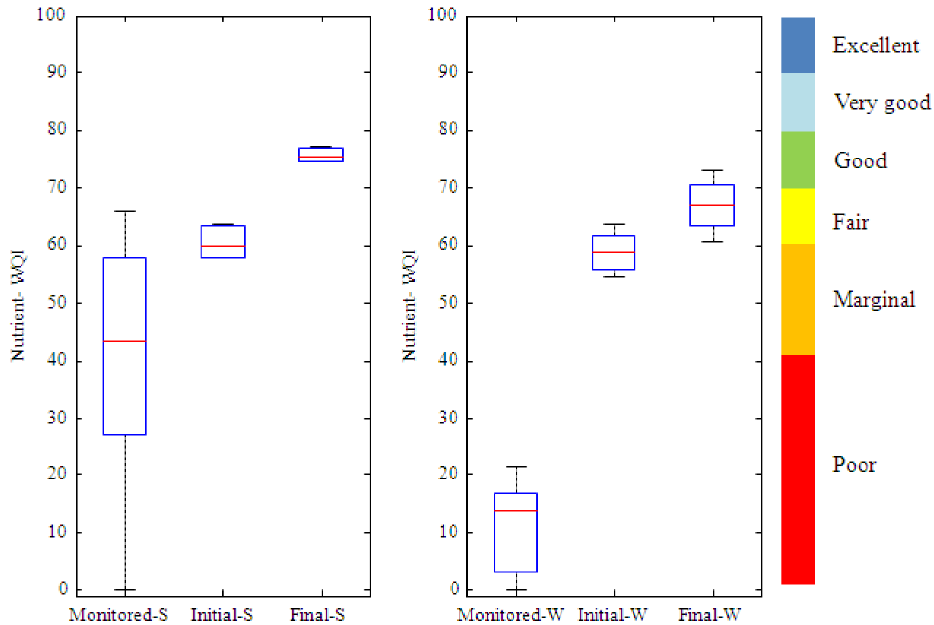

Figure 4.12: Seasonal nutrient-WQI

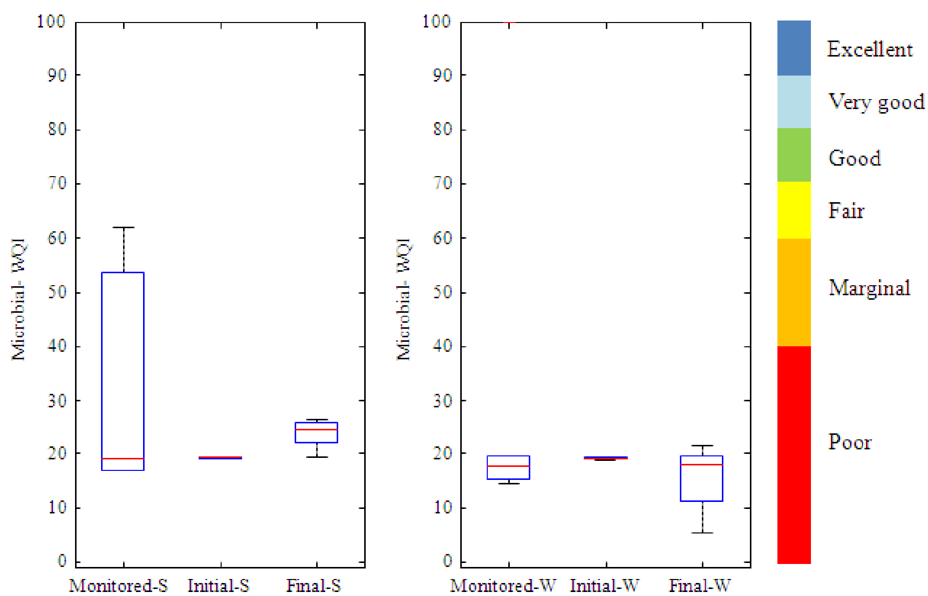

Figure 4.13: Seasonal microbial-WQI

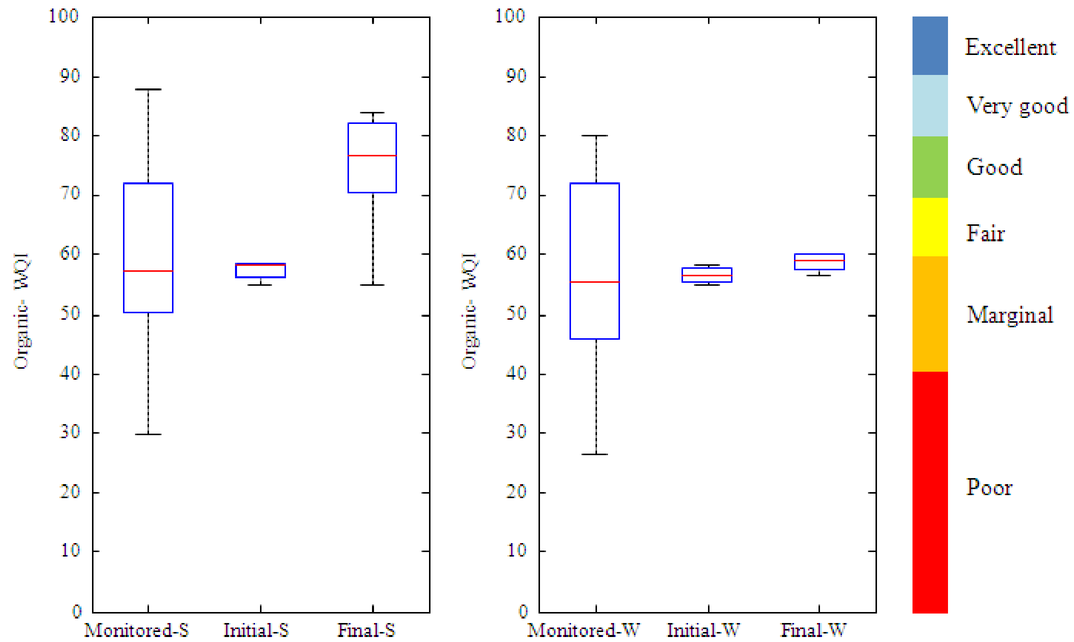

Figure 4.14: Seasonal organic-WQI

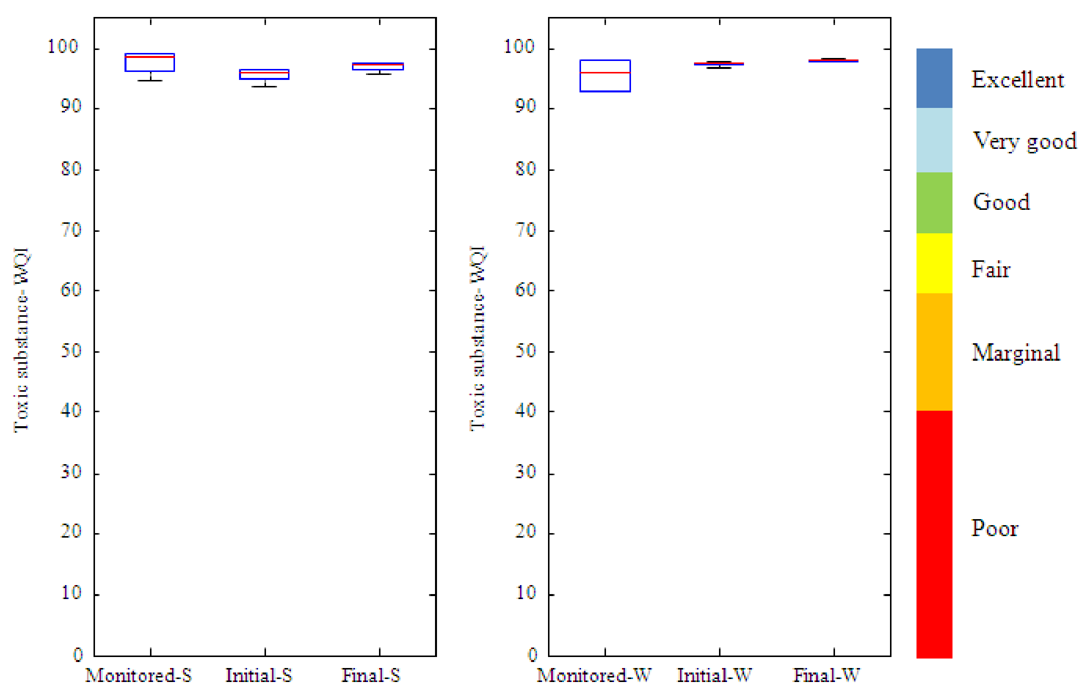

Figure 4.15: Seasonal toxic substance-WQI

* The WQI for monitored data varies from *good* to *very good* during summer months and from *marginal* to *very good* during winter. In case of predicted initial value, the WQI is in the *good* range during both seasons. Predicted final WQI was *very good* in both seasons.

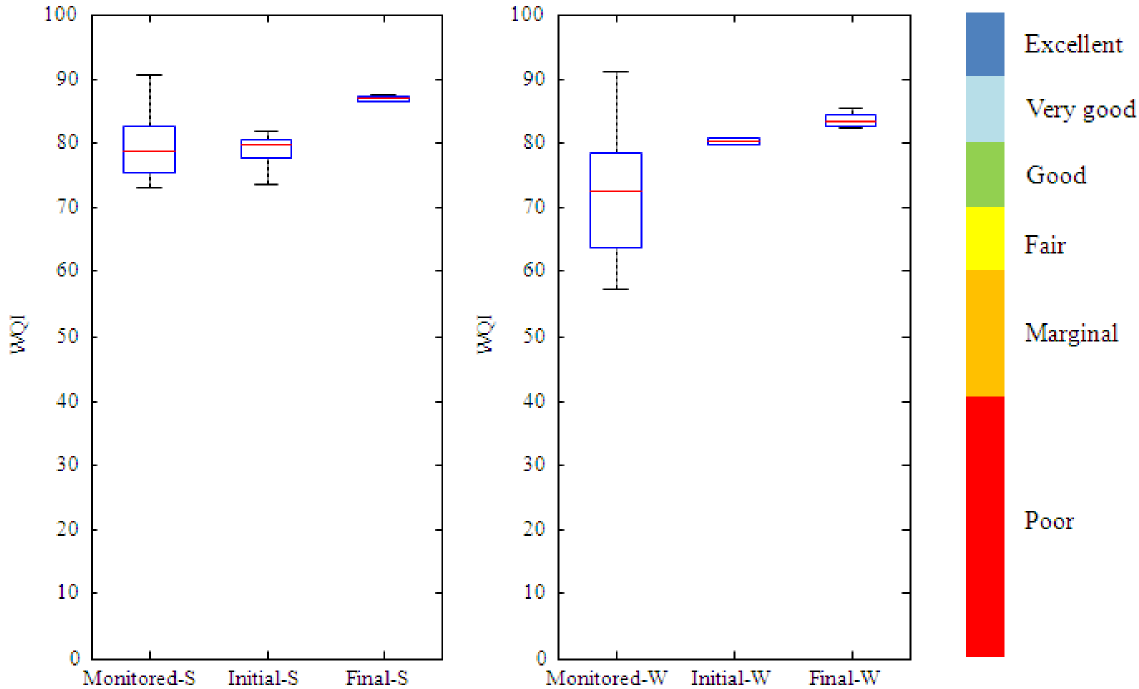

Figure 4.16: Seasonal overall WQI

Three factors including incoming pollutant flow rate, EC and creek water flow rate are affecting water quality. Incoming pollutant flow rates have two contradicting effects: 1) increase in the transport of pollutants due to erosion; 2) dilution of concentration. Dilution due to a higher flow rate can lead to lower concentration whereas higher erosion can increase the pollutant concentration. Similarly, higher creek water flow rates reduce the pollutant concentration through dilution. It usually takes time to change the existing pollutant concentration in the creek water as the flow rates in the receiving bodies are much higher as compared to incoming pollutants loads. For the monthly WQI assessment, identical monthly EC derived from the annual EC has been used for each month due to lack of monthly data. Therefore, for a better comparison between results of initial and final conditions, a yearly WQI has also been derived.

4.3.2 Predicted WQI–a yearly variation

Yearly simulations have been performed to predict the water quality indices from 2008-18 based on the monitored data (September 2007). Results for the initial and final conditions have been presented in Figure 4.17 for primary- WQI. The results predicted gradual degradation of WQI over time for initial conditions (with current SWP strategies) and improvement of WQI for the final conditions (with proposed SWP strategies).

The yearly WQI improvement for primary, nutrient, microbial, organic and toxic substance WQI along with overall WQI are presented in Table 4.7. Table 4.7 shows WQI improvement of highest 8.09%, 16.84%, 12.40%, 3.63%, 0.97% and 5.39% for primary, nutrient, microbial, organic, toxic substance and overall WQI respectively. Therefore, the selected SWP strategies are more effective for controlling nutrient pollutant than microbial, primary, organic and toxic substance respectively.

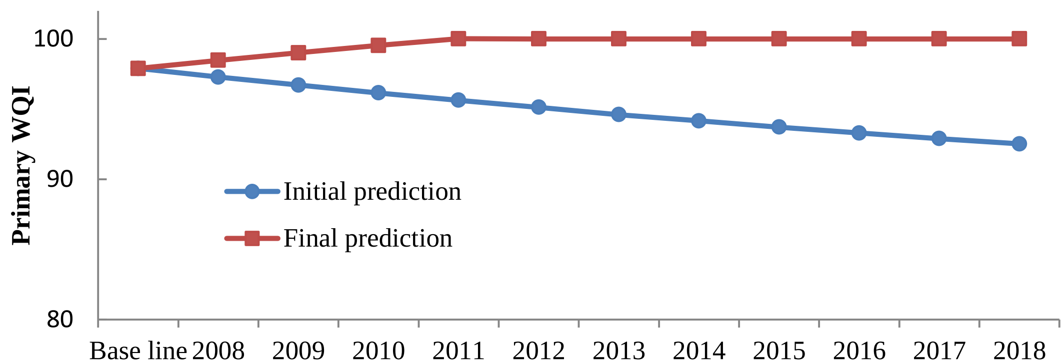

Figure 4.17: Primary WQI prediction (FYs 2008-18)

4.3.3 Sensitivity analysis

A sensitivity analysis to assess the robustness of the model was performed. Sensitivity analysis is the process of estimating the degree to which the output of a model changes as values of input factors are changed. It can help to 1) identify the input factors that have the most influence on model output, 2) identify the processes which have the greatest influence on model output, and 3) quantify the change in output caused by uncertainty and variability in the values of input factors. Various methods exist for sensitivity analysis. These methods include the scatter plot, partial and rank correlation coefficients, multivariate regression, and contribution to variance and probabilistic sensitivity analysis. In this case, sensitivity analysis was performed for different land uses and for determining most important SWP efficiency parameter. Land use sensitivity analysis was done by assuming specific land use scenarios while SWP efficiency part was done with spearman rank correlation. Land use sensitivity will help decision-makers to take adequate actions to protect source water in case of land use variation, specially an increase of urbanisation around source water as it is the tendency around major cities in Canada.

Table 4.7: Percentage of WQI improvement for five WQI group and for overall WQI (FYs 2008-18)

Year	Primary- WQI	Nutrient- WQI	Microbial- WQI	Organic- WQI	Toxic substance- WQI	WQI
2008	1.23	1.98	1.59	0.44	0.11	0.63
2009	2.37	3.80	3.01	0.83	0.21	1.25
2010	3.52	5.58	4.38	1.22	0.31	1.94
2011	4.58	7.21	5.60	1.57	0.40	2.58
2012	5.12	8.76	6.74	1.91	0.49	3.03
2013	5.70	10.39	7.92	2.26	0.58	3.49
2014	6.21	11.79	8.92	2.56	0.67	3.90
2015	6.71	13.16	9.88	2.85	0.75	4.30
2016	7.18	14.43	10.76	3.12	0.82	4.67
2017	7.65	15.68	11.62	3.39	0.90	5.04
2018	8.09	16.84	12.40	3.63	0.97	5.39

Land use impact has been analyzed by comparing the present land use conditions with five fictitious scenarios: fully agricultural, pasture, livestock, forests and urban type 1 land use. Model has been simulated to assess WQI from 2008-2018 for the six scenarios with the same initial condition (present land use and SWP strategies for 2007) and without any proposed SWP strategies. Figure 4.18 shows that the water quality will be the worst in case of ‘urban type 1’ land use. For 100% agricultural land use, the WQI will deteriorate but still better than urban type 1’. If all the land is used for pasture or livestock, the WQI will be better compared to the baseline WQI. As expected, changing to forest land use will also lead to improved water quality in Page Creek. The WQI values for forest land use showed a slow improvement as flow rate of the creek water is very high compared to the incoming pollutant flow rates. Figure 4.19 showed that an implementation of the proposed SWP strategies can improve the water quality; even if all the land use is only ‘urban 1’. The base line in Figure 4.19 refers to the case study area with proposed SWP strategies.

A sensitivity analysis was performed based on pasture and livestock land use variations with and without proposed SWP strategies. The impacts of livestock land use are provided Figures 4.20 and 4.21. Similarly, the impacts of Pasture are shown in Figures 4.22 and 4.23.

A simulation-based sensitivity analysis is performed with spearman rank correlation for PCAP, storm water management ponds and VFS efficiency models to identify important input factors in case of each of these SWP strategies. Figure 4.24 shows the tornado graphs for SWP strategies including PCAP, storm water management and VFS. These graphs highlight important design parameters that significantly affect the efficiency of these SWP strategies.

Figure 4.24 shows that retention time (RT) is the most important parameter for the storm water management efficiency, followed by media depth, vegetation level and water depth. For VFS efficiency (Figure 4.24), the manning's *n* is the most important parameter. It is important to remember that a storm water pond is very different from a VFS. The width of a VFS is the second most important parameter followed by the slope. The percentage of parameter contribution are presented in Table 4.8.

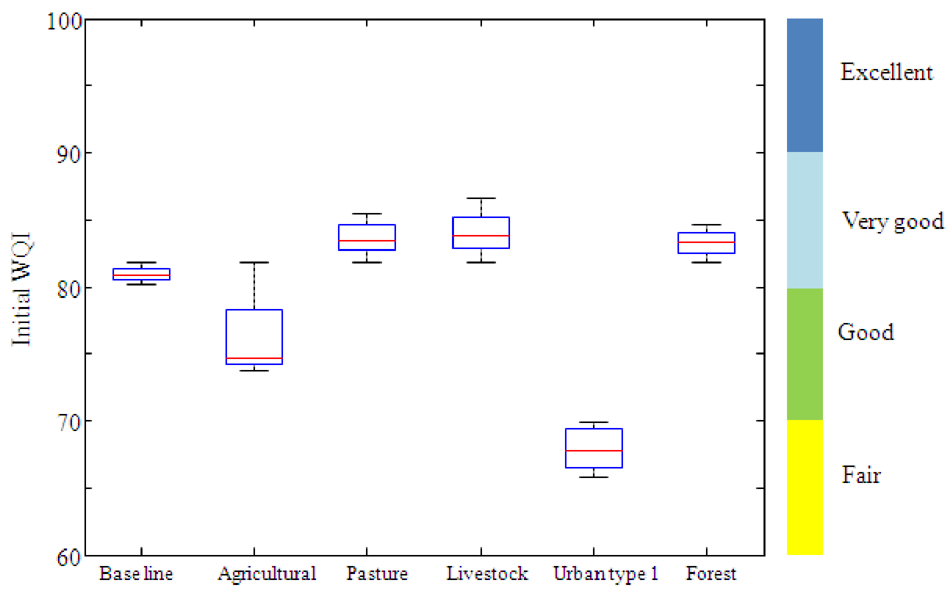

Figure 4.18: Impact of land use on WQI without SWP strategies

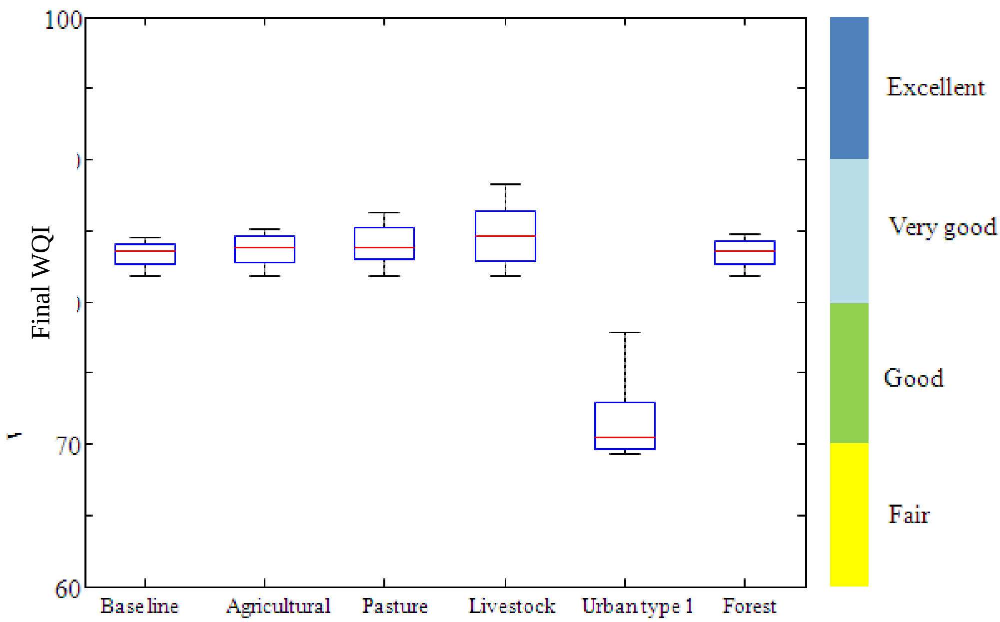

Figure 4.19: Impact of land use on WQI with SWP strategies

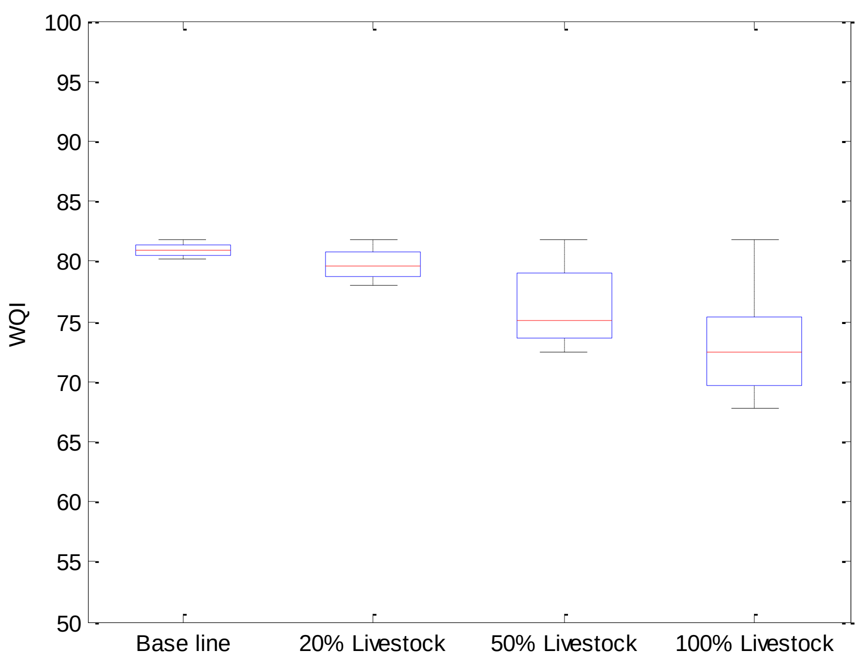

Figure 4.20: Impact of livestock land use on water quality for initial condition

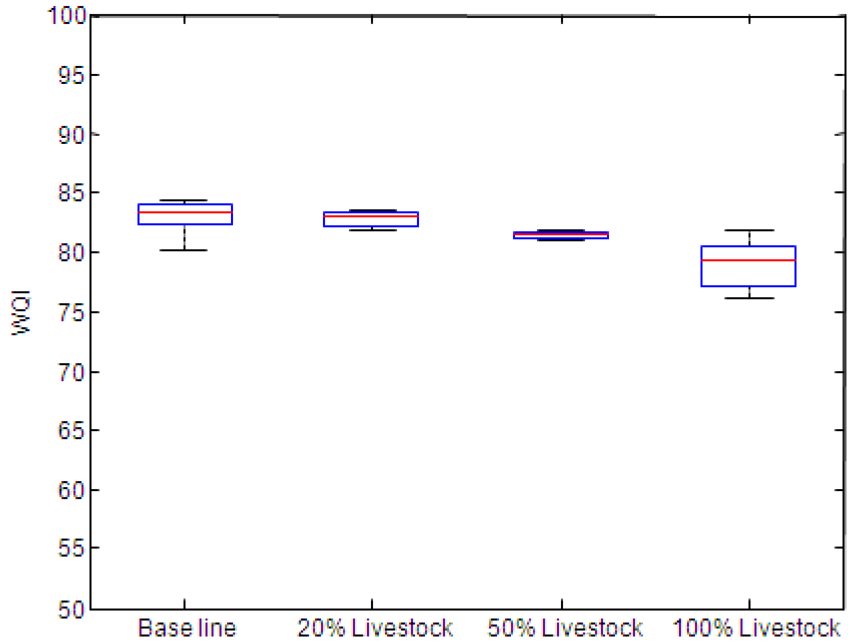

Figure 4.21: Impact of livestock land use on water quality with proposed SWP strategies

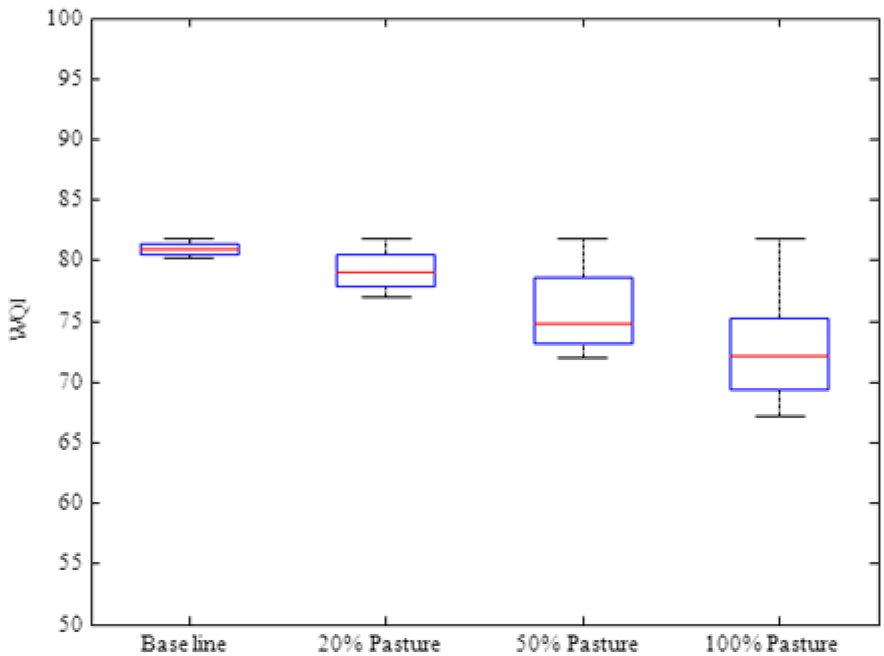

Figure 4.22: Impact of pasture land use on water quality for initial condition

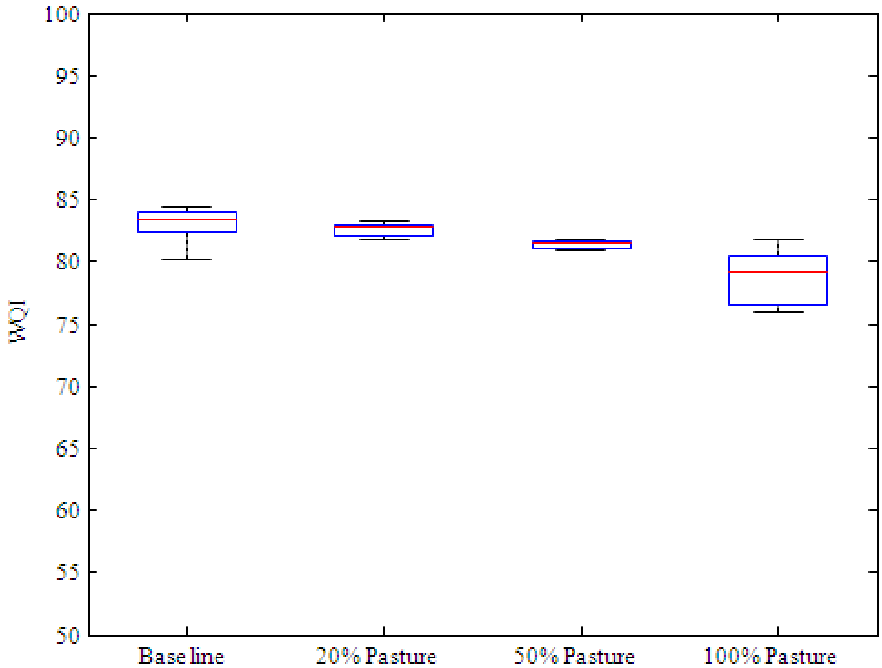

Figure 4.23: Impact of pasture land use on water quality with proposed SWP strategies

Table 4.8: Percent parameter contribution for SWM pond, VFS and PCAP efficiency

SWP strategy	Parameter percent contribution
SWM pond	Water depth- 0.63 Retention time- 75.71 Vegetation level- 4.73 Media depth- 18.93
VFS	Manning's n- 50.81 VFS width- 42.29 Slope- -6.90
PCAP	Cover crop- 45.67 Crop rotation- 47.21 Soil water content- 1.53 Dry bulk density- -5.59

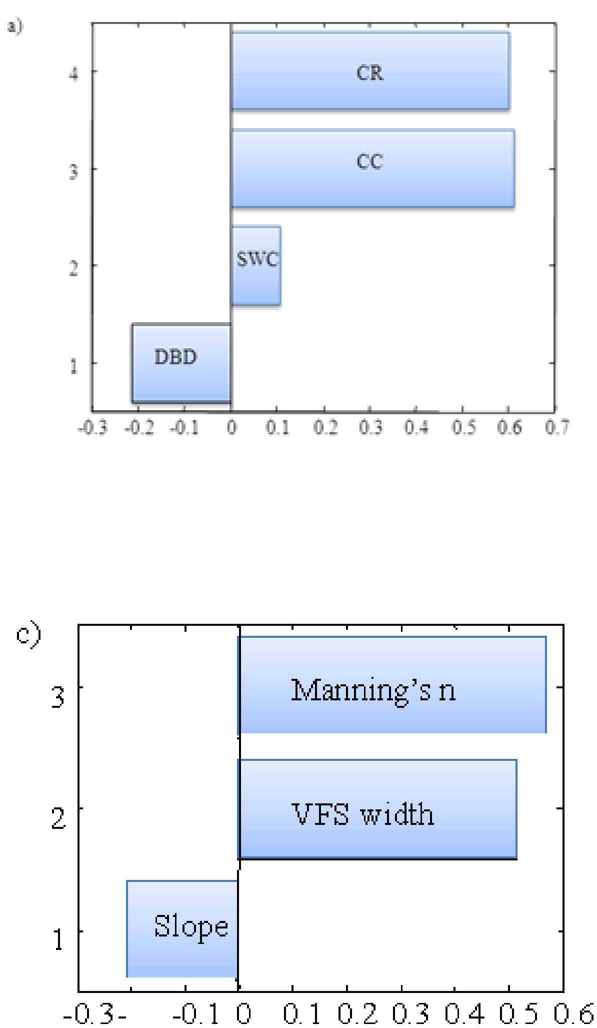

Figure 4.24: Tornado graphs describing the contribution of various design parameters in the removal efficiency of selected SWP strategies a) PCAP, b) SWM pond, and c) VFS

4.3.4 Comparison of proposed WQI with NSF-WQI

For the monitored data, the proposed overall WQI results are compared with NSF-WQI (Brown *et al*., 1970). The NSF-WQI values are obtained from online calculator[6] for TSS, phosphorous, FC and BOD_5. The same, parameters were also used in the proposed model to estimate overall WQI using steps 4, 5 and 6 (Figure 3.1) only. Figures 4.25 compares monthly WQI variations estimated using proposed WQI and the NSF-WQI. The pattern is very similar in both assessment models, as reflected by high R^2 value in Figure 4.26, where the proposed WQI

[6] http://www.water-research.net/watrqualindex/index.htm

values are plotted against NSF-WQI. The proposed WQI is predicting worse surface water quality compared to NSF-WQI, as more weight is given to parameters in the proposed model, that govern drinking water quality whereas the NSI-WQI distributes the weighting more evenly to all parameters.

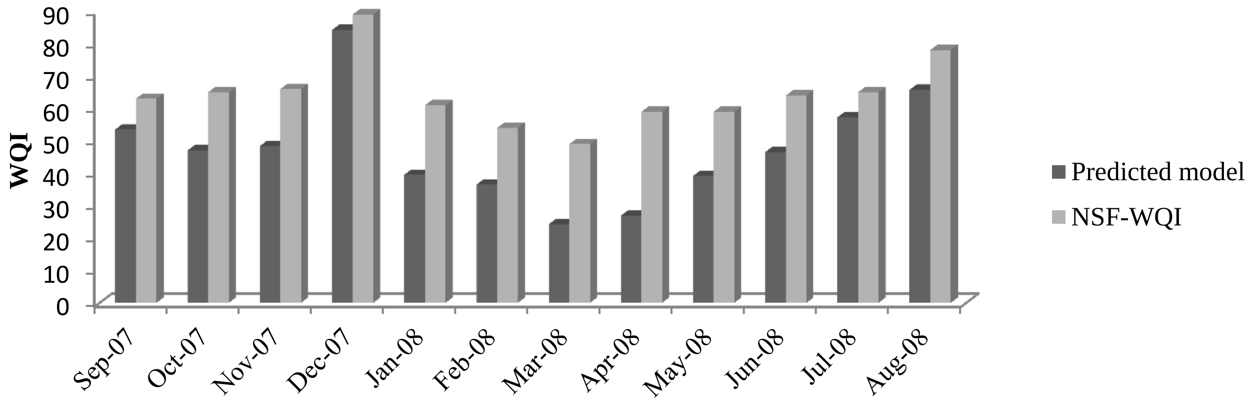

Figure 4.25: Monthly variations predicted by proposed WQI and NSF-WQI

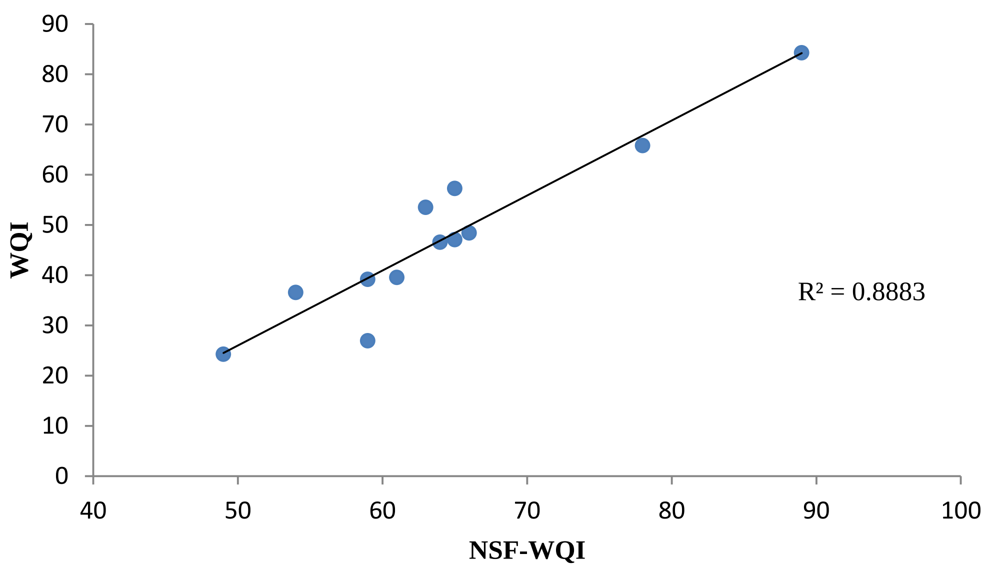

Figure 4.26: NSF-WQI vs. proposed WQI

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

Source Water Protection (SWP) is an important step in a multi-barrier approach that ensures safe drinking water to the consumers in a cost effective manner. The management of source water is a complex undertaking and requires tools to help decision makers at different levels of the governments (Federal/ Provincial/ Municipal) to coordinate and make informed decisions. Most of the existing models are exceedingly complex, data intensive, and found not be useful for decision makers with limited or no technical expertise. Moreover these models mainly focus on specific water quality issues (e.g., microbial, nutrients, aesthetics) and don't provide an assessment of water quality, which is a key for making resource allocation and capital investment decisions by the related agencies.

A comprehensive literature review has been performed on various aspects of this interdisciplinary research. The main focus of the review is on source water protection strategies that includes agricultural practices (e.g., cover crop, crop rotation), storm water management ponds (e.g., dry detention ponds, storm water wetlands, bioretention areas, wet detention ponds, sand filters and grass swales), fencing and vegetated filter strips have been provided in the context of possible pollutant load reduction. The proposed model based on a conceptual framework links selected SWP strategies to the improvement in water quality index (WQI), a surrogate for water quality.

The analysis based on developed model is performed in six steps. The first step estimates the pollutant loads based on land use export coefficient approach. In case of pasture and livestock land use, the numbers of animals are used to estimate the pollutant load for each parameter. The second step estimates the percentage of pollutant reduction based on removal efficiency of the selected SWP strategies using fuzzy rule-based models. Step 3 estimates pollutant concentration using steady-stead mass balance approach over pre-defined time duration. Step 4 transforms the calculated concentrations of the water quality parameters into unit less sub-indices. In Step 5, the water quality parameters are classified as Primary, Microbial, Organic, Nutrient and toxic substances water quality indices. Finally in Step 6, an overall WQI is derived from these water quality groups using fuzzy measures theorem. The WQI provides water quality assessment of a receiving water body using a scale $\in$ [0 100], where 0 refers to the *worst* and 100 refers to the *best* quality water.

The developed model has been applied to a case study of Page Creek water in Clayburn watershed (BC, Canada). The Page Creek sub-watershed is mainly an agricultural and farming area. For summer months, the estimated WQI based on the monitored data suggested that quality ranges from *good* to *very good*. Contrarily, during winter months it ranges from *marginal* to *very good*. Monthly and yearly analyses are carried out using different scenarios of changing land use with implementation of SWP strategies. An improvement in the water quality of Page Creek can be attributed to specific arrangement of SWP strategies (as proposed in this study). Monthly analysis showed improvements in Page Creek water quality for both summer and winter months (*very good*). PCAP and vegetated filter strip are found to be more effective for removal of TSS, while storm water management ponds are more effective for the removal of both TSS and coliforms (microbial indicators). Yearly analysis (FYs 2008-18) predicts water quality degradation (from v*ery good* to *good*) if no actions are taken, however, if the proposed SWP are implemented, the water quality will either improve or remain in *very good* condition. The proposed SWP strategies improve source water quality approximately by 8.1%, 16.8%, 12.4%, 3.6%, 1% and 5.4% for primary, nutrient, microbial, organic, toxic substance and overall WQI respectively.

A sensitivity analyses shows that if the land use is of 'urban type 1' (i.e., highway/ roads) and/or 'agricultural', the adverse impact on water quality will be paramount. However, land uses such as pasture or livestock can also adversely affect the water quality, especially if no precautionary measures are taken. As expected, the use of forests found to be the best land use with minimal impact on source water quality. The key parameters that contributed to the removal efficiency of SWM pond, VFS and PCAP efficiency are retention time (~76%), manning's n (~51%) and crop rotation (~47 %), respectively

5.2 Limitations and Recommendations

The main thrust of this research is to develop a simple model that require basic data and can be adapted by decision-makers and engineers as a decision support tool. As data availability is a major issue in planning and management of watersheds, simple assumptions (such as steady state mass balance, export coefficient, water quality indices) have been found useful to predict water quality improvement based on selected SWP strategies. Proposed model has following limitations:

- Numerous studies are investigated from the literature to estimate the pollutant loads from a specific land use and estimate the efficiency of SWP strategies. However, these studies vary significantly in terms of their experimental setups and ambient conditions.
- For monthly analysis, the average yearly EC (kg/ha/yr) is used by dividing with twelve. This implies that for each month the EC remains the same however there can be significant variations due to land use (e.g., impacts of agricultural practices, antecedent conditions and climatic and weather variations).
- In the case of unavailability of EC values, the model uses pollutant concentrations based on values reported in the literature. Extrapolation from these concentrations can lead to uncertainties in the estimates of pollutant loads.
- For PCAP efficiency only cover crop and crop rotation are incorporated as effective agricultural practices. However, conservative tillage can also be included.
- Many assumptions are made for missing data in case of Page Creek case study. For example, the number and type of livestock animal are assumed due to unavailability of information.
- The focus of this research was on pollutants, which negatively affect water quality in the receiving water body. However, the water quality is also a function of factors like dissolved oxygen, which is not included in this study.
- Factors related to snow melting temperature, snow water equivalent, antecedent ground conditions, saturation and porosity of soil, etc. are not studied in this research.

Based on this research, we recommend the following for future research:

- Develop a database for monthly EC values for different pollutants and different types of land uses; however site specific EC values are preferable where possible
- Perform uncertainty analysis using probabilistic or fuzzy-based approaches
- Perform cost-benefit analysis for the selected SWP strategies
- Integrate the model with a GIS platform to make recommendations for potential land use in a specific watershed

- Verify the model predictions for a case study that has a long-term data available to evaluate the performance.
- Modify and apply the model for other possible land uses (e.g., mining) using relevant pollutant export coefficients
- Validate removal efficiency for different SWP strategies as function of design parameters using laboratory or pilot studies.

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APPENDICES

Appendix A: Available Canadian regulations regarding SWP strategies in three provinces (Ontario, Alberta, and British Columbia)

Management	Province Name	Regulation	Identification of SWP strategies
Land Management	Ontario	Conservation Land Act (1990) Crown Forest Sustainability Act (1994) Crown Timber Act (1990) Forestry Act (1990) Conservation Authorities Act (2006) Lakes and Rivers Improvement Act (1990) Greenbelt Act (2005) Planning Act (1990)	▪ 'Conservation of forest' to achieve land management for ensuring better water quality. ▪ Restriction in development within 130 m of significant and 30 m from other 'wetlands' so that wetlands can perform their hydrological function. ▪ 'Riparian areas' are mentioned as a mean of water quality improvement. ▪ Land management is declared as a SWP strategy. ▪ Agricultural land conservation for ecosystem preservation. ▪ Proper 'planning' of a area after preserving natural lands for SWP.
	Alberta	Alberta Forest Conservation Strategy (1997) Wetland Management in the Settled Area of Alberta (1993) Water Act (2000)	▪ 'Forests' are identified as an effective mean to have clean water. ▪ 'Wetland' management is highly encouraged to protect water quality. ▪ Integrated approach with proper planning with land and water resources.
	British Columbia	Water Act (2007) Forest and Range Practices Act (2002) Forest and Range Practices Act (2004) Forest and Range Practices Act (2009) Drinking water protection Act (2001) Environmental and Land Use Act (1996)	▪ 'Vegetation' is stated as a mean to have stable stream channel. ▪ 'Forests' are also considered as effective protection way of watershed management. ▪ 'Wetlands and riparian areas' are stated as a buffer for ecosystem. ▪ Provincial and local govt. strategies are recommended for land management to have safe water. ▪ Land use relation with source water is stated. ▪ Close relation between ecological conservation with land use is declared.

Management	Province Name	Regulation	Identification of SWP strategies
Agricultural and farming management	Ontario	Pesticides Act (2009) Nutrient Management Act (2002a, 2002b, 2002c) Environmental Protection Act (1990)	▪ 'Monitoring' of pesticides in surface water by leakage and restriction of washing with pesticides contaminated water. ▪ Animals are restricted near surface water. ▪ 'Vegetative buffer' is recommended before nutrient application. ▪ Setback maintenance for all type of nutrient application near surface water is stated.
	Alberta	Environmental Protection and Enhancement Act (1993a, 1993b)	▪ Setback from source water is recommended to apply pesticides and herbicides. ▪ Careful management in handing pesticides especially for storm water. ▪ Limited application by aircraft is suggested.
	British Columbia	Water Act (1996) Environmental Management Act (2008a) Forest and Range Practices Act (2004) Integrated Pest Management Act (2004) Environmental Management Act (2007)	▪ Restriction for livestock watering for prevention of contamination of water. ▪ Setback distance is recommended for domestic, agricultural composting, farming composting, incineration, and gazing animal areas. ▪ Setback distance is recommended for fertilizer application for sivilculture treatment. ▪ Regulation on the selection of pesticides. ▪ Better pesticides management to protect water course. ▪ In case of poultry and slaughter, 10 mg/l is the maximum permissible for fat, oil or grease release.
Storm water management	Ontario	Environmental Assessment Act (1996) Environmental Protection Act (2007)	▪ Non-structural programs and best management practices are encouraged. ▪ Regular 'monitoring' in case of extreme weather events. ▪ Effective 'drainage design' and planning is stated.
	Alberta	Environmental Protection and Enhancement Act (1993a, 1993b)	▪ 'Drainage design' is announced to perform. ▪ No substance can be discharged which is harmful.
	British Columbia	Environmental Management Act (2004b)	▪ Careful storage of petroleum chemicals is declared.
Municipal management	Ontario	Environmental Protection Act (1990) Environmental Protection Act (1994) Environmental Protection Act (1998a, 1998b)	▪ Installation of a landfill requires regular surface water 'monitoring', leachate determination. ▪ Turbidity, dissolved oxygen, temperature and the hydrology of the site should be monitored. ▪ Setback distance for leaf composting. ▪ Cannot dump more than 100 liter of mineral oil. ▪ Disposal without adequate 'treatment' is restricted. ▪ Bern and dykes are encouraged in landfill area for protecting water pollution.

Management	Province Name	Regulation	Identification of SWP strategies
Municipal management	Alberta	Environmental Protection and Enhancement Act (2000) Environmental Protection and Enhancement Act (1996a, 1996b) Environmental Protection and Enhancement Act (2003) Water Act (2007)	▪ Restriction in dumping waste to source water and ice. ▪ Strict design of the landfill. ▪ Leachate should be monitored to maintain the standards.
	British Columbia	Environmental Management Act (2008b) Environmental Management Act (2007)	▪ Setback distance from landfill is declared to maintain. ▪ Restriction in case of changing the direction of stream flow.
Industrial management	Ontario	Environmental Protection Act (1990)	▪ ‘Treatments’ are recommended before dumping.
	Alberta	Environmental Protection and Enhancement Act (2006)	▪ Restriction in dumping waste near surface water.
	British Columbia	Public Health Act (2009)	▪ Restriction in sewage disposal in proper way to avoid contamination in source water.
Vehicle spill management	Ontario	Environmental Protection Act (1998b) Technical Standards and Safety Act (2000) Environmental Protection Act (1990)	▪ Restriction in dumping vehicular spillage more than specific amount.
	Alberta	N/A	
	British Columbia	Environmental Management Act (2004b)	▪ Recreational dumping is restricted.
Road management	Ontario	Environmental Protection Act (1990)	▪ Setback from asphalt pavement construction site.
	Alberta	N/A	N/A
	British Columbia	N/A	N/A

N/A= Not available.

Appendix B: Source water protection strategies under USEPA bulletin

Management sectors	Reference	SWP strategies
Agricultural management	USEPA (2001a)	• 'Yearly soil sampling' to evaluate the exact fertilizer demand of the crop. • Use of 'ammonia nitrogen fertilizer' to get rid of immediate leaching. • Proper 'fertilizer timing', e.g., close time of fertilizer application to the period of maximum uptake time. • Proper calibration of the fertilizer application equipment to ensure the required amount of fertilizer. • Correct placement of the fertilizer ▪ Place near the roots ▪ In case of erosive soil, place the dry fertilizer into the ground in bands. ▪ Never apply the fertilizer to frozen ground on in sloppy areas. • Proper application of the irrigation water ▪ Increase efficiency by using lined ditches, gate pipe, and reuse system. ▪ Shorten the use of gravity controlled irrigation. • Careful fertilizer storage from any source of water. • 'Conservation tillage' to reduce runoff. • Using 'buffer strips or filter strips', e.g., plating dense vegetable near water bodies to filter fertilizers. • Use of 'crop rotation' to minimize fertilizer need. • Use of 'cover crops' to stop wind and soil erosion.
Managing large-scale application of pesticides	USEPA (2001b)	• Careful use of Integrated Pest Management (IPM) with chemical and non-chemical ways, e.g., mechanical, cultural, biological, sanitation and plating pest resistant plants. • Proper pesticide application (proper setbacks and never start the application before any weather event). • Economic and effective use of pesticides by 'crop rotation', proper placement of the pesticides, use split application procedure (Application before and at the plating time), 'spot treatment' • Careful management of the pesticide storage and handling
Managing small scale application of pesticides	USEPA (2001c)	• In case of the large scale- pesticide use manual activities, e.g., spading, hoeing, hand picking weeds and pests, mulching to get rid of pests without pesticides are recommended. • Proper plant management to reduce the need for the pesticides. ▪ Maintain proper drainage and aeration to have the microbes to degrade the pesticides. ▪ Using biological control (e.g., birds and bats).
Farming Management	USEPA (2001d)	• Feedlot management such as by using waste storage lagoons, litter storage structures, clean water divisions, composting and runoff treatment. • Using poultry liner storage which can keep the rainwater runoff from poultry home waste. The water can be further used for agricultural use. • Water diversion especially clean water to keep them away from the pollution. • Use of 'vegetation buffer' for feedlot management. • Proper application of manure with proper placement. • Pasture management such as by 'fencing'.

Management sectors	Reference	SWP strategies
Storm Water or Runoff Management	USEPA (2001e)	• Plant temporary fast-growing vegetation, grasses and flowers to filtrate water. • Covering top soil with 'geotextile or impervious covers'. • Proper 'planning' to minimize directly connected impervious areas (Connect runoff from roofs and sidewalks). • Placement of concrete grid pavement placed on a sand or gravel base with a void area filled with pervious materials. • Effective structural 'design' to control runoff. • Use of 'grass swales'. • 'Buffer strip' which is made of three zones is recommended. The main parts are- ▪ Four or five rows of trees closest to the source water. ▪ One or two rows of shrubs. ▪ 20/24 foot wide grass zone. • Long rooted vegetation is preferred for buffer strip. • 'Storm water ponds' which can settle the solids and with the help of the wetland vegetation zone contaminants can be removed biochemically. • 'Constructed wetlands' whose main function is similar to storm water ponds is recommended. • 'Swirl type concentrators' which can create circular motion to remove oil, and grease can be used for oily substances.
Managing pet and wild life	USEPA (2001f)	• Clean up and waste disposal. • Bury waste. • Keep the pets away from the water bodies. • 'Long grass' which not only attracts the pets but also infiltrate the contaminate particle is used for managing wild life.
Managing septic systems	USEPA (2001g)	• Proper sitting of septic system ▪ Maintenance of proper setback distances (both horizontal and vertical). ▪ Adequate soil permeability to ensure septic system effluent. • Design and construction consideration. • Annual inspection of the septic tank.
Managing Sanitary Sewer	USEPA (2001h)	• Visual inspection about the proper working of the septic tank system. • Monitoring and maintenance. • Employee training. • Public education. • Eliminating direct pathways to source water.

Appendix C: Main factors in storm water management

Reference (Type of SWM)	SA/DA, %	Brief system description	Depth, m	RT, hr	Vegetation type
Li and Davis (2009) (Bioretention)	6 or 2	Sandy loam or sandy clay loam : Sand -80% or 45% Silt- 13%or 26% Clay- 7% or 20% pH -7.3 OM- 5.7% or 12.2%	0.5-0.8 or 0.9	6-8	Natural vegetation (e.g., grasses, shrubs, and small trees)
Davis (2007) (Bioretention)	2	Sand-50% Topsoil- 30% Mulch (Shredded hardwood)- 20% Or Mixture of newspaper mass :sand=0.017:1	0.9 or 0.3	24	Grasses, shrubs, and small trees or no vegetation
Hunt *et al.* (2008) (Bioretention)	6.00	Loamy sand: Soil media P-index 6 (low) Silt and clay fraction 5.7% Permeability 0.43 in./h	1.2	24-36	Blueflag iris (*Iris virginica*), cardinal flower (*Lobelia cardinalis*), common rush (*Juncus effusus*) , hibiscus (*Hibiscus spp*.) , red maple (*Acer rubrum*) , sweet pepperbush (*Clethra alnifolia*) , Virginia sweetspire (*Itea virginica*) , wild oat grass (*Chamanthium latifolium*)
Hsieh and Davis (2005) (Bioetention)	N/A	Mulch-5cm Filter- 55-75cm, Soil- 10-30cm, Fine sand-5cm Or additionally vegetative layer- 20-35cm above filter-25-50cm	1.15 or 1.25	6	Not specified
Hathaway *et al*. (2009) (Dry and wet pond)	0.64 to 4.67	Vegetation-grass Sunlight-high or lor	N/A	48	Natural trees around the pond
Passeport *et al.* (2009) (Bioretention)	3.20	80% state 15% sand 5% topsoil Underlying soil-loamy clay or sandy loam: P-index-5 or 8 Humic matter-0.18%	0.75 or 1.05 (0.45[1] or 0.75[1])	Longer duration for ISZ	Bermuda grass cover
Scholz and Yazdi (2009) (Combined detention and infiltration system)	2.88	Layer 1- 0.05m gravel; Layer 2- 0.15 to 0.25m gravel; Layer 3- Geotextile; Layer 4- 0.1to0.2 m of mixture; Layer 5- plastic liner	0.3 -0.5	0.17	*S. Viminalis* is used as plantation

Reference (Type of SWM)	SA/DA, %	Brief system description	Depth, m	RT, hr	Vegetation type
Middleton and Barrett (2008) (Sand filter with extended detention basin)	1.33	Sand filter followed by extended detention basin	0.78[1]	72	No vegetation
Muthanna *et al.* (2007) (Bioretention)	4.75	10 cm gravel (bottom) 55 cm sandy loam: 92.7% sand 2.6% clay 4.7% silt pH-6.88 OM-8.7% 10 cm Mulch (pH-5.5) 15cm freeboard	0.9	0.83	*Lythrum salicaria.*, *Iris pseuacorus*, *Vinca minor* and *Hippophaë rahmnoides* with small shrubs, evergreens and perennials.
Hsieh *et al.* (2007 a, 2007b) (Bioetention)	4-5	2% mulch (mixed of grass and vegetation) 20.5%, Soil I 77.5 % Sand II	0.95	1-2	Not specified
	4-5	29.3% homogeneous media (3 kg mulch, 3kg soil IV, 6 kg sand) 56.1%, Sand II 14.6 % Soil IV			
Lucas and Greenway (2008) (Bioretention)	N/A	80cm sandy loam, 80cm loamy sand 20cm pea gravel with loamy sand	0.75-0.80 (0.15-0.20[1])	12-18	Swamp Foxtail Grass (*Pennisetum alopecurioides*) and Flax Lily (*Dianella brevipedunculata*), and two woody shrubs, Banksia (*Banksia integrefolia*), and Bottlebrush (*Callistemon pachyphyllus*).

SA/DA= surface area of the BMPs/ Drainage area; RT= retention time; OM= Organic matter; N/A= Not available; ISZ= Internal storage zone (with media); Depth= Media depth; Soil I= Sandy loam: sand-71%, clay-17%, silt-12%, pH-6.7, OM-4.4.%; Sand II = Sand-95%, clay-3%, silt-2%, pH-7.1, OM-0.15%; Soil IV = Sandy loam: sand-71%, clay-14%,; silt-15%, pH-7.1, OM-3.5%; 1- Water depth

Appendix D: Common formulations for water quality indices (WQI)

Index	Parameter, unit	Sub-index, SI_i	W_i	Aggregation formulation	Range
NSF-WQI (Brown *et al.*, 1970)	DO, %	142 experts draw curves for raw data and assigned a value ranging from 0 (worst) to 100 (best) and final curves were obtained with the weighting curves for each parameter	0.17	$\sum_{i=1}^{N} SI_i W_i$	0-25 = very bad
	FC, MPN/100ml		0.16		26-50 = bad
	pH		0.11		51-70 = regular
	BOD_5, ppm		0.11		71-90 = good
	Nitrates, ppm		0.10		91-100 =excellent
	Total Phosphates, ppm		0.10		
	Temp., °C		0.10		
	Turbidity, NTU/ JTU		0.08		
	Total suspended solids, ppm		0.07		
O-WQI (Dunnette, 1979; Cude, 2001)	Temp., °C	1, a		$\sqrt{\frac{N}{\sum_{i=1}^{N} \frac{1}{SI_i^{2}}}}$	10-59 = very poor
	DO, %	1, 2			60-79 = poor
	BOD_5, mg/l	2			80-84 = fair
	pH	2			85-89 = good
	Ammonia +Nitrate nitrogen, mg/l	2			90-100= excellent
	Total phosphorus, mg/l	1, b			
	Total solids, mg/l	2			
	FC, #/100ml	2			
PW-WQI (Pesce and Wunderlin, 2000)	DO, mg/l	4		$\frac{\sum_{i=1}^{3} SI_i}{3}$	0= minimum quality
	Con, µS/cm				100= maximum quality
	Turbidity, NTU				

Index	Parameter, unit	Sub-index, SI_i	W_i	Aggregation formulation	Range
CPCB-WQI (Sarkar and Abbasi, 2006)	DO, %	3	0.31	$\sum_{i=1}^{N} SI_i W_i$	<38 =bad to very bad 38–50 =bad
	BOD_5, mg/l	3	0.19		50–63 = medium to good
	pH	3	0.22		63–100 = good to excellent
	FC, MPN/ 100ml	5	0.28		
River pollution index (RPI) (Liou *et al.*, 2004)	DO, mg/l BOD_5, mg/l Ammonia nitrogen, mg/l Suspended solids, mg/l Turbidity, NTU Temp., °C. FC, MPN/100ml pH Toxicity	4		$SI_{temp} SI_{pH} SI_{tox}$ $[\left(\sum_{i=1}^{3} SI_i W_i\right)^{1/3} x\left(\sum_{j=1}^{2} SI_j W_j\right) x(\sum_{k=1}^{1} SI_k)]$ SI_j= sub-index for two particulate parameters SI_k=Sub-index for FC SI_i=sub-index for last three parameter	Value varies from 0-64.8 and are divided into non-polluted, lightly-polluted, moderately-polluted, and grossly-polluted
U-WQI (Boyacioglu, 2007)	Cadmium, cyanide, mercury, selenium, arsenic, fluoride, nitrate-nitrogen, DO, BOD_5, total phosphorus, pH and total coliform	N/A	N/A	$\frac{\sum_{i=1}^{N} SI_i}{N}$	N/A
S-WQI (Said *et al.*, 2004)	DO, % Con, µS/cm Turbidity. , NTU FC, MPN/100ml Total phosphorus (TP)			$log[\frac{DO^{1.5}}{(3.8)^{TP}(Turb)^{TP}(15)^{FC/10000}+0.14\ (Con)^{0.5}}]$	< 1= poor < 2 =marginal and remediation 3-2= acceptable 3= very good

Index	Parameter, unit	Sub-index, SI_i	W_i	Aggregation formulation	Range
$ISQA^*$	Temp.,°C	3		$SI_{Temp}\ (SI_{TOC} + SI_{SS} + SI_{DO} + SI_{Con})$	0= minimum quality
	TOC, mg/l	3		-	100= maximum quality
	SS, mg/l	3			
	DO, mg/l	3			
	Con, µS/cm	5			
$\mathrm{CCME-WQI}^{**}$	Not fixed	F_1: scope (% of variables that do not meet their objectives at least once) F_2: frequency (% of individual tests that do not meet their objectives) F_3: amplitude (amount by which failed tests do not meet their objectives)		$100-(\frac{\sqrt{F_1^2+F_2^2+F_3^2}}{1.732})$	0-44= poor 45-64= marginal 65-79= fair 80-94= good 95-100= excellent
S-T WQI (Swamee and Tyagi, 2007)	Not fixed	Monotonically decreasing Sub-indices , SI= $(1+\frac{P}{P_c})^{-m}$ Non-uniformly decreasing sub-indices, SI= $\frac{1+(\frac{P}{P_T})^4}{1+3\,(\frac{P}{P_T})^4+3(\frac{P}{P_T})^8}$ Unimodal subindices, SI= $\frac{qr+(n+q)(1-r)(\frac{P}{P_c})^n}{q+n(1-r)(\frac{P}{P_c})^{n+q}}$		$[1-N+\sum_{i=1}^{N} SI_i^{-log_2(N-1)}]^{-1/log_2(N-1)}$	0–0.25= poor 0.26–0.50= fair 0.51–0.70= medium /average 0.71–0.90= good 0.91–1.0= excellent

W_i- Relative weights; DO- Dissolved oxygen ; FC- Faecal coliform; BOD_5- Biochemical oxygen demand for 5 day; Con- Electric conductivity; SS- Suspended solids; CPCB- Central Pollution Control Board ; NTU-Nephelometric Turbidity Units; JTU-Jackson Turbidity Unit; MPN- The Most Probable Number; P- Parameter real value ; P_c-Characteristic value of P (Swami and Tyagi 2000); P_T –Threshold concentration;

1- Polynomial function 2- Exponential function 3- Linear function 4- Step function 5- Logarithmic function

a- 3rd order polynomial function b- 2nd order polynomial function; n, q, r- Exponents (Swamee and Tyagi, 2000) * Catalan water Agency, available at http://aca-web.gencat.cat/aca) ; ** Canadian Council of Ministers of the Environment (CCME), in:

Canadian Environmental Quality Guidelines, CCME, Winnipeg, Canada, 2001

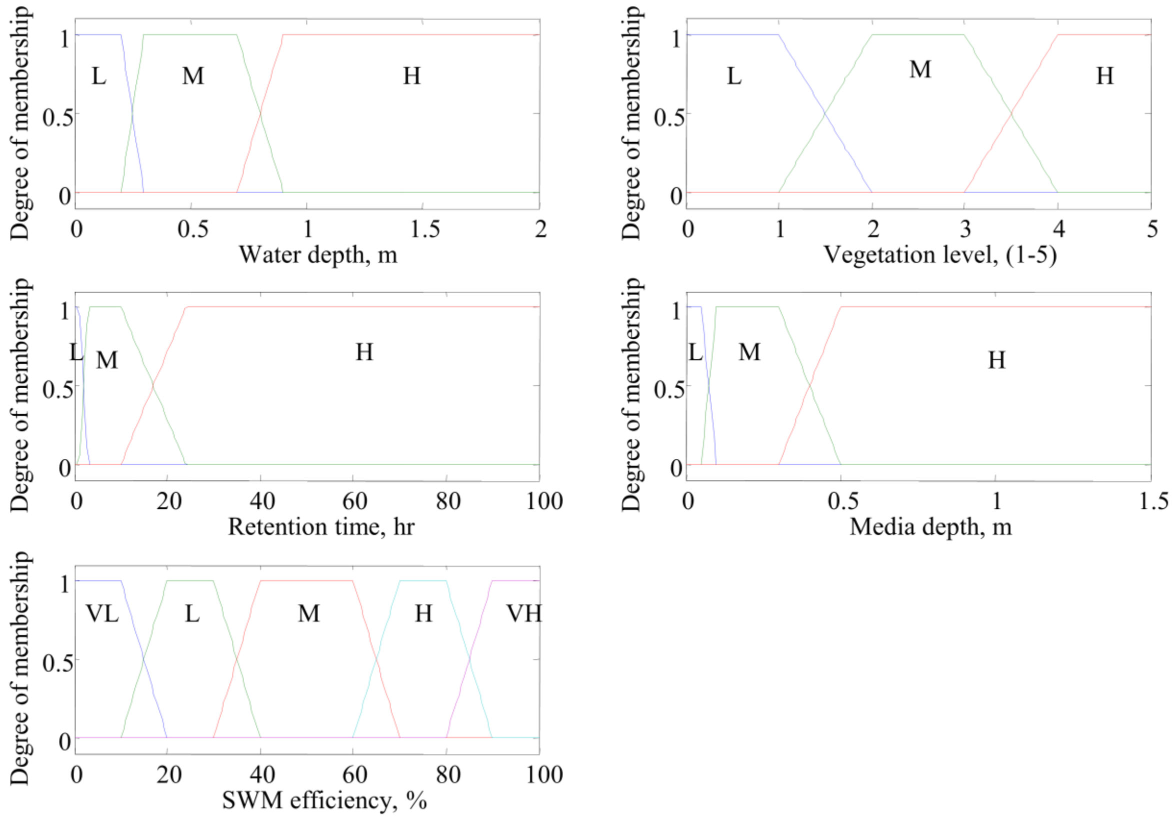
Appendix E: Pollutant load mass generation from manure (ASAE, 2003)

Factors	**Dairy**	**Beef**	**Veal**	**Swine**	**Layer (Poultry)**	**Turkey**
Avg. Size (ABW_k), Kg	640	360	91	61	1.8	6.8
Total manure, kg/day	86	58	62	84	64	47
Total solids, kg /1000kg mass.day[1]	12	8.5	5.2	11	16	12
TN, kg/1000kg mass.day	0.45	0.34	0.27	0.52	0.84	0.62
TP, kg/1000kg mass.day	0.094	0.092	0.066	0.18	0.3	0.23
BOD_5, kg/1000kg mass.day	1.6	1.6	1.7	3.1	3.3	2.1
FC, CFU/1000kg mass.day	16	28	25[a]	18	7.5	1.4
TC, CFU/1000kg mass.day	1100	63	55[a]	45	110	60[a]
Pb, kg/1000kg mass.day	0.000001[a]	0.000001[a]	0.000001[a]	0.000084	0.00074	0.0003[a]

a- assumed value based on the similar type of livestock

1- TSS has been assumed 1/3 of total solids

Appendix F: Membership functions and inference rules for TSS removal using SWM



Rule-set for TSS removal using SWM

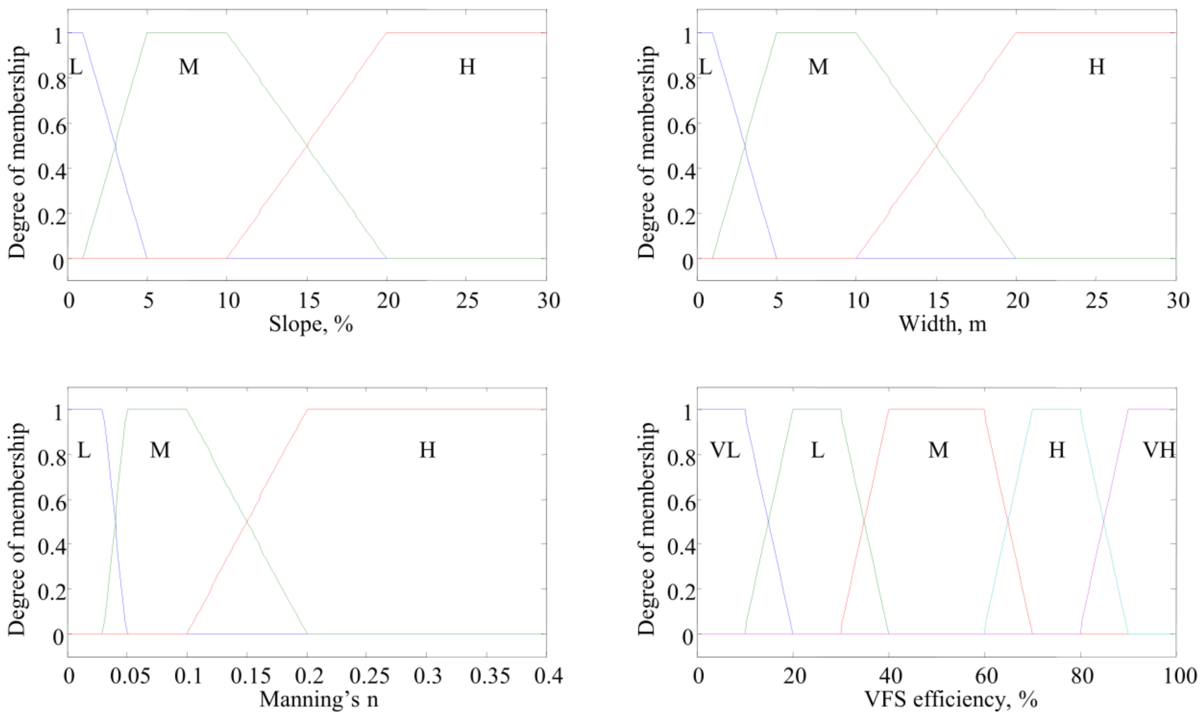
Rule no		**Water depth**		**Vegetation**		**RT**		**Media depth**		**SWM Efficiency**
1	If	L	and	L	and	L	and	L	then	VL
2	If	L	and	L	and	M	and	L	then	L
3	If	L	and	L	and	M	and	M	then	L
4	If	L	and	L	and	M	and	H	then	M
5	If	L	and	L	and	H	and	L	then	L
6	If	L	and	L	and	H	and	M	then	L
7	If	L	and	L	and	H	and	H	then	M
8	If	L	and	M	and	L	and	L	then	L
9	If	L	and	M	and	M	and	L	then	M
10	If	L	and	M	and	M	and	M	then	H
11	If	L	and	M	and	M	and	H	then	H
12	If	L	and	M	and	H	and	L	then	M
13	If	L	and	M	and	H	and	M	then	H
14	If	L	and	M	and	H	and	H	then	H
15	If	L	and	H	and	L	and	L	then	VL

Rule no		Water depth		Vegetation		RT		Media depth		SWM Efficiency
16	If	L	and	H	and	M	and	L	then	VL
17	If	L	and	H	and	M	and	M	then	M
18	If	L	and	H	and	M	and	H	then	H
19	If	L	and	H	and	H	and	L	then	L
20	If	L	and	H	and	H	and	M	then	M
21	If	L	and	H	and	H	and	H	then	H
22	If	M	and	L	and	L	and	L	then	L
23	If	M	and	L	and	M	and	L	then	L
24	If	M	and	L	and	M	and	M	then	M
25	If	M	and	L	and	M	and	H	then	M
26	If	M	and	L	and	H	and	L	then	M
27	If	M	and	L	and	H	and	M	then	H
28	If	M	and	L	and	H	and	H	then	VH
29	If	M	and	M	and	L	and	L	then	L
30	If	M	and	M	and	M	and	L	then	M
31	If	M	and	M	and	M	and	M	then	M
32	If	M	and	M	and	M	and	H	then	H
33	If	M	and	M	and	H	and	L	then	H
34	If	M	and	M	and	H	and	M	then	H
35	If	M	and	M	and	H	and	H	then	H
36	If	M	and	H	and	L	and	L	then	L
37	If	M	and	H	and	M	and	L	then	M
38	If	M	and	H	and	M	and	M	then	M
39	If	M	and	H	and	M	and	H	then	H
40	If	M	and	H	and	H	and	L	then	M
41	If	M	and	H	and	H	and	M	then	H
42	If	M	and	H	and	H	and	H	then	H
43	If	H	and	L	and	L	and	L	then	L
44	If	H	and	L	and	M	and	L	then	L
45	If	H	and	L	and	M	and	M	then	M
46	If	H	and	L	and	M	and	H	then	H
47	If	H	and	L	and	H	and	L	then	VH
48	If	H	and	L	and	H	and	M	then	VH
49	If	H	and	L	and	H	and	H	then	VH
50	If	H	and	M	and	L	and	L	then	M
51	If	H	and	M	and	M	and	L	then	M
52	If	H	and	M	and	M	and	M	then	H
53	If	H	and	M	and	M	and	H	then	H
54	If	H	and	M	and	H	and	L	then	VH
55	If	H	and	M	and	H	and	M	then	VH
56	If	H	and	M	and	H	and	H	then	VH

Rule no		Water depth		Vegetation		RT		Media depth		SWM Efficiency
57	If	H	and	H	and	L	and	L	then	L
58	If	H	and	H	and	M	and	L	then	M
59	If	H	and	H	and	M	and	M	then	M
60	If	H	and	H	and	M	and	H	then	H
61	If	H	and	H	and	H	and	L	then	H
62	If	H	and	H	and	H	and	M	then	H
63	If	H	and	H	and	H	and	H	then	H

SWM- storm water management; RT- retention time; L- low; M- medium; H- high; VH- very high

Appendix G: Membership functions and inference rules for TSS removal using VFS



Rule- set for TSS removal using VFS

Rule no		Slope		Width		n		VFS efficiency
1	If	L	and	L	and	L	then	VL
2	If	L	and	L	and	M	then	M
3	If	L	and	L	and	H	then	H
4	If	L	and	M	and	L	then	L
5	If	L	and	M	and	M	then	H
6	If	L	and	M	and	H	then	VH
7	If	L	and	H	and	L	then	M
8	If	L	and	H	and	M	then	H
9	If	L	and	H	and	H	then	VH
10	If	M	and	L	and	L	then	VL
11	If	M	and	L	and	M	then	L
12	If	M	and	L	and	H	then	L
13	If	M	and	M	and	L	then	L
14	If	M	and	M	and	M	then	M
15	If	M	and	M	and	H	then	H
16	If	M	and	H	and	L	then	M
17	If	M	and	H	and	M	then	H
18	If	M	and	H	and	H	then	VH

Rule no		Slope		Width		n		VFS efficiency
19	If	H	and	L	and	L	then	VL
20	If	H	and	L	and	M	then	L
21	If	H	and	L	and	H	then	M
22	If	H	and	M	and	L	then	M
23	If	H	and	M	and	M	then	M
24	If	H	and	M	and	H	then	M
25	If	H	and	H	and	L	then	M
26	If	H	and	H	and	M	then	M
27	If	H	and	H	and	H	then	H

n- Manning's n; L- low; M- medium; H- high; VH- very high

Appendix H: Mass balance equations for water quality parameters

Model name	Reference	Water quality parameters									
		DO	**Organic nitrogen, N_4**	**Ammonia nitrogen, N_1**	**Nitrite nitrogen, N_2**	**Nitrate nitrogen, N_3**	**Organic phosphorus, P_1**	**Dissolved phosphorous, P_2**	**BOD_5**	**Coliform, E**	**Temp, T**
QUAL2E	USEPA (1985)	$\frac{dDO}{dt}= k_2(DO^* - DO)+(\alpha_3\mu - \alpha_4\rho)A-\alpha_1 L-\frac{k_4}{d}-\alpha_5\beta_1 N_1-\alpha_6\beta_2 N_2$	$\frac{dN_4}{dt}=\alpha_1\rho A-\beta_3 N_4-\alpha_4 N_4$	$\frac{dN_1}{dt}=\beta_3 N_4-\beta_1 N_1+\frac{\sigma_3}{d}-F_1\alpha_1\mu A$	$\frac{dN_2}{dt}=\beta_1 N_1-\beta_2 N_2$	$\frac{dN_3}{dt}=\beta_2 N_2-(1-F_1)\ \alpha_1\mu A$	$\frac{dP_1}{dt}=\alpha_2\ \rho A-\beta_4 P_1-\ \sigma_5 P_1$	$\frac{dP_2}{dt}=\ \beta_4 P_2+\frac{\sigma_2}{d}-\alpha_2\mu A$	$BOD_5=L(1-e^{5k_{BOD}})$ $\frac{dL}{dt}=\ -k_1 L-k_3 L$	$\frac{dE}{dt}=-k_5 E$	
SIMCAT	SIMCAT (2004)	$\frac{dDO}{dt}=\ -k_{BOD}L+k_2(DO^*-DO)$ $DO^*=14.652-0.41022T+0.0079910T^2-0.000077774T^3$									
TOMCAT	Bowden and Brown (1984)	$\frac{dDO}{dt}=\ k_2(DO^*-DO)-\ \frac{dL}{dt}-4.57\frac{dN_1}{dt}$									$\frac{dT}{dt}=\ -k_T(T-T_{air})$
QUASAR	Whitehead *et al*. (1997)	$\frac{dDO}{dt}=\ \tau(C'-DO+WEIR)+P-R-k_4 DO+k_2(DO^* - DO)-4.57k_{NI}N_1-k_{BOD}L$		$\frac{dN_1}{dt}=\frac{1}{\tau}[N_1' - N_1]-k_{NI}N_1$		$\frac{dN_3}{dt}=\ \frac{1}{\tau}[N_3' - N_3]+\ k_{NI}N_1-k_{DENI}N_3$			$\frac{dL}{dt}=\frac{1}{\tau}[L' - L]-k_{BOD}L-k_3 L+k_{AL}Chla$		
MIKE 11	DHI Water & Environment (2005)	$\frac{dDO}{dt}=\ P-R+k_2(DO^* - DO)-k_{BOD}L-\ \alpha_1 k_{NI}[N_1]^{e_4}-k_4$		$\frac{dN_1}{dt}=-k_{NI}[N_1]^{E4} - \alpha_{PHO}P+\alpha_{RES}R$		$\frac{dN_3}{dt}=\ k_{NI}[N_1]^{e4}-k_{DENI}[N_3]^{e6}$			$\frac{dL}{dt}=\ -\ k_{BOD}L-k_3\ L(1-e^{5k_{BOD}})+\ k_{SUS}$		

Appendix I: Predicted value of the parameters for models in Appendix H (USEPA, 1985)

Legend	Parameter name	Unit	Predicted value range	Temperature dependant
k_1	Carbonaceous deoxygenating rate constant	day^{-1}	0.02-3.4	Yes
k_2	Re-aeration rate constant	day^{-1}	0-100	Yes
k_3	Rate of loss of BOD due to settling	day^{-1}	-0.36-0.036	Yes
k_4	Sediment oxygen demand rate (benthic oxygen uptake)	g/ft^2 -day	N/A	Yes
k_5	Coliform die off rate	day^{-1}	0.05-4.0	Yes
k_{BOD}	BOD conversion rate coefficient	day^{-1}	0.23	Yes
α_1	Faction of algal biomass that is nitrogen	mg /mg	0.07-0.09	No
α_2	Fraction of algal biomass that is phosphorous	mg /mg	0.01-0.02	No
α_3	O_2 production /algal growth	mg /mg	1.4-1.8	No
α_4	O_2 uptake per unit of algae respired	mg /mg	1.6-2.3	No
α_5	The rate of oxygen uptake per unit per unit of ammonium –nitrogen oxidation	mg /mg	3-4	No
α_6	O_2 uptake per unit of NO_2 oxidation	mg /mg	1-1.14	No
β_1	Rate constant for biological oxidation of NH_3-NO_2	day^{-1}	0.1-1	Yes
β_2	Rate constant for biological oxidation of NO_2-NO_3	day^{-1}	0.02-0.4	Yes
β_3	Rate constant for hydrolysis of organic nitrogen to ammonia nitrogen	day^{-1}	0.02-0.4	Yes
β_4	Rate constant for the decay of organic-P to dissolved-P	day^{-1}	0.01-0.7	Yes

Legend	Parameter name	Unit	Predicted value range	Temperature dependant
σ_5	Organic phosphorous settling rate	day^{-1}	0.001-0.1	Yes
μ	Algal growth rate	day^{-1}	1-3	No
ρ	Algal respiration day	day^{-1}	0.05-0.5	No

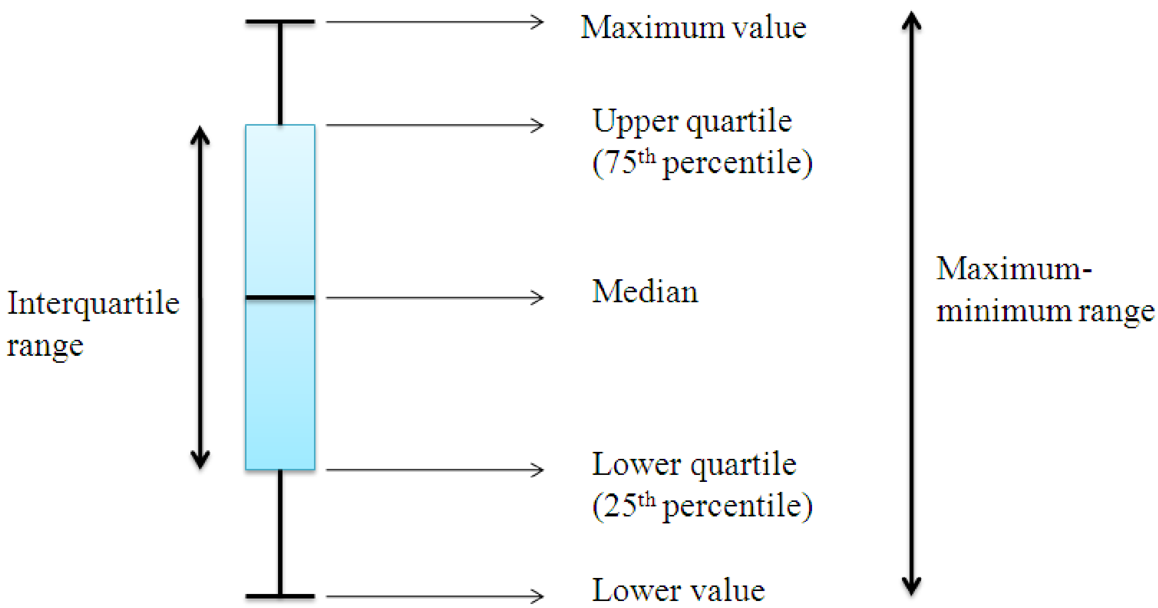
DO^*= Saturated DO, mg/l; L= concentration of ultimate carbonaceous BOD, mg/l; d= Mean stream depth, ft; τ = the travel time or residence time=$\frac{L}{v}$; L is the reach length; v is the water velocity; C'= is the concentration of the solute entering the reach; WEIR= the increase in DO concentration due to a weir or other structure in the reach; P = the rate of (algal) photosynthetic oxygen production; R = rate of oxygen uptake due to algal respiration; k_{NI}= nitrification rate coefficient; e4= Concentration dependence of nitrification; k_f= the decay rate coefficient for fast BOD (BOD); k_s= the decay rate coefficient for slow BOD (BOD); AC = the dry-weight of algal carbon as a concentration; k_{DC} = the rate coefficient for the oxidation of detrital carbon; DC = the concentration of detrital carbon; k_{DENI}= Denitrification rate coefficient; α_{PHO} = the amount of ammonium uptake per 3 unit mass of photosynthetic oxygen production; α_{RES} = the amount of ammonium produced per unit mass of oxygen consumed in respiration; e_6= coefficient characterizing the concentration dependence of denitrification; k_T = the heat transfer coefficient; k_{hyd}= the reaction rate coefficient for hydrolysis; rphtn = the nutrient to carbon ratio for nitrogen for phytoplankton; A= Algal biomass concentration, mg/l; σ_3= Benthos source rate for NH_3-N, mg/ft^2-day; F_1= fraction of algal nitrogen uptake from the available ammonium; σ_2= the source rate of phosphorous from the sediments; T= Temp; N_1'= Concentration of the NH_3-N solute entering the reach; N_3'= Concentration of the NO_3-N solute entering the reach; L'= Concentration of the L solute entering the reach; k_{AL} = Rate coefficient for the increase in BOD due to algal death; Chla= concentration of chlorophyll-a representing the algal (biomass) concentration; k_{SUS}= Rate or re-suspension; T_{air}= Ambient air temperature; e_6= coefficient characterizing the concentration dependence of nitrification; N/A= Not available

Appendix J: Seasonal creek water flow rate prediction with Manning's formulation

Month	Days	Water depth (d), m	Flow area (A=b*d), m^2	Perimeter (P=b+2*d), m	Wetted perimeter (R=A/P), m	Creek flow rate[1] (Q), m^3/s	Creek flow rate, liter/ month
September	30	0.221	0.829	4.192	0.198	0.663	1.72E+09
October	31	0.422	1.583	4.594	0.344	1.833	4.91E+09
November	30	0.700	2.625	5.150	0.510	3.948	1.02E+10
December	31	0.606	2.273	4.962	0.458	3.182	8.52E+09
January	31	0.576	2.160	4.902	0.441	2.948	7.90E+09
February	28	0.466	1.748	4.682	0.373	2.135	5.17E+09
March	31	0.425	1.594	4.600	0.346	1.853	4.96E+09
April	30	0.349	1.309	4.448	0.294	1.365	3.54E+09
May	31	0.288	1.080	4.326	0.250	1.009	2.70E+09
June	30	0.229	0.859	4.208	0.204	0.702	1.82E+09
July	31	0.146	0.548	4.042	0.135	0.340	9.12E+08
August	31	0.143	0.536	4.036	0.133	0.329	8.81E+08

1- $Q=\frac{1}{n}AR^{2/3}s^{1/2}$; n=0.03 (for clean and straight natural channel); s=slope=1/200, b= average width=3.75m

Appendix K: Description of box-and-whisker plot



Appendix L: Sub index value for monitored data, predicted initial and final creek water quality parameter

TSS sub-index	Tem sub-index	TN sub-index	TP sub-index	FC sub-index	TC sub-index	BOD_5 sub-index	Pb sub-index
Monitoring data							
0.9737	1.0000	0.8450	0.4000	0.3883	0.0000	0.5484	0.9910
1.0000	1.0000	0.0000	0.0800	0.3670	0.0000	0.6400	0.9820
1.0000	1.0000	0.3650	0.0000	0.3458	0.0000	0.8000	0.9820
1.0000	1.0000	0.0000	0.3340	1.0000	1.0000	0.7200	0.9730
0.8806	1.0000	0.3000	0.0800	0.3970	0.0000	0.4683	0.5680
0.8673	1.0000	0.0000	0.0000	0.2884	0.0000	0.4569	0.9460
0.5280	1.0000	0.4175	0.0800	0.3057	0.0000	0.2640	0.9280
0.5920	1.0000	0.6350	0.0800	0.5071	0.5995	0.2960	0.9460
0.9205	1.0000	0.6775	0.0000	0.3391	0.0000	0.5027	0.9820
1.0000	1.0000	0.0000	0.0000	0.3381	0.0000	0.7200	0.9640
1.0000	1.0000	0.7200	0.4660	0.3843	0.0000	0.5942	0.9910
1.0000	1.0000	0.8525	0.5320	0.5609	0.7595	0.8800	0.9910
Initial value with present strategies (predicted with the model)							
0.9737	1.0000	0.8450	0.4000	0.3883	0.0000	0.5484	0.9910
0.9006	1.0000	0.8224	0.3618	0.3811	0.0000	0.5485	0.9788
0.8889	1.0000	0.8236	0.3797	0.3826	0.0000	0.5551	0.9754
0.8920	1.0000	0.8302	0.4089	0.3858	0.0000	0.5625	0.9740
0.8928	1.0000	0.8372	0.4405	0.3884	0.0000	0.5698	0.9728
0.8926	1.0000	0.8433	0.4690	0.3908	0.0000	0.5764	0.9711
0.8863	1.0000	0.8484	0.4969	0.3921	0.0000	0.5830	0.9682
0.8764	1.0000	0.8471	0.5014	0.3927	0.0000	0.5861	0.9645
0.8578	1.0000	0.8422	0.4961	0.3915	0.0000	0.5876	0.9620

TSS sub-index	Tem sub-index	TN sub-index	TP sub-index	FC sub-index	TC sub-index	BOD_5 sub-index	Pb sub-index
0.8290	1.0000	0.8316	0.4742	0.3883	0.0000	0.5865	0.9574
0.7767	1.0000	0.8129	0.4306	0.3818	0.0000	0.5819	0.9515
0.6392	1.0000	0.7616	0.2948	0.3660	0.0000	0.5630	0.9386
Predicted final value with proposed SWP strategies							
0.9737	1.0000	0.8450	0.4000	0.3883	0.0000	0.5484	0.9910
0.9904	1.0000	0.8531	0.4433	0.3936	0.0000	0.5647	0.9829
1.0000	1.0000	0.8627	0.4837	0.3992	0.0000	0.5757	0.9807
1.0000	1.0000	0.8715	0.5189	0.4044	0.0000	0.5842	0.9800
1.0000	1.0000	0.8802	0.5537	0.4094	0.0000	0.5923	0.9793
1.0000	1.0000	0.8882	0.5858	0.4144	0.0000	0.6002	0.9782
1.0000	1.0000	0.8966	0.6202	0.4197	0.0102	0.6579	0.9764
1.0000	1.0000	0.9017	0.6425	0.4243	0.0481	0.7036	0.9740
1.0000	1.0000	0.9058	0.6617	0.4283	0.0774	0.7479	0.9724
1.0000	1.0000	0.9078	0.6740	0.4312	0.0930	0.7863	0.9693
1.0000	1.0000	0.9072	0.6788	0.4322	0.0889	0.8205	0.9653
1.0000	1.0000	0.8963	0.6520	0.4267	0.0151	0.8374	0.9563

TSS- total suspended solids; TN- total nitrogen; TP- total phosphorous; FC- faecal coliform; TC- total coliform; BOD_5- 5 day biochemical oxygen demand; Tem-Temperature; Pb-Lead