Titre: Title:	Cost-effectiveness Analyses of Agricultural Beneficial Management Practices to Improve Water Quality Under Current and Future Climate Conditions
Auteur: Author:	Mohamed Khalil Zammali
Date:	2020
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Zammali, M. K. (2020). Cost-effectiveness Analyses of Agricultural Beneficial Management Practices to Improve Water Quality Under Current and Future Climate Conditions [Mémoire de maîtrise, Polytechnique Montréal]. PolyPublie. https://publications.polymtl.ca/5523/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/5523/
Directeurs de recherche: Advisors:	Elmira Hassanzadeh, & Karl-Erich Lindenschmidt
Programme: Program:	Génie civil

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cost-effectiveness Analyses of Agricultural Beneficial Management Practices to Improve Water Quality Under Current and Future Climate Conditions

MOHAMED KHALIL ZAMMALI

Département des Génies civil, géologique et des mines

Mémoire Présenté en vue de l'obtention du diplôme de Maîtrise en sciences appliquées

Génie Civil

Décembre 2020

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cost-effectiveness Analyses of Agricultural Beneficial Management Practices to Improve Water Quality Under Current and Future Climate Conditions

Présenté par **Mohamed Khalil ZAMMALI**

en vue de l'obtention du diplôme de Maîtrise ès sciences appliquées a été dûment accepté par le jury d'examen constitué de :

Ahmad SHAKIBAEINIA, président

Elmira HASSANZADEH, membre et directrice de recherche

Karl-Erich LINDENSCHMIDT, codirecteur de recherche

Françoise BICHAI, membre

DEDICATION

Je dédie ce travail à:

Toute ma famille pour leur soutien et encouragements

Mes encadrants Dr. Elmira Hassanzadeh et Dr. Karl-Erich Lindenschmidt pour les directives et tout ce qu'ils m'ont enseigné

Antoine, Andrea, Bilel,Cindi Barry, Elisabeth, Hanen, Hazem, Jad ,Maha, Sarah-Claude, et Ulrich

ACKNOWLEDGEMENTS

I would like to sincerely thank my supervisors, Dr. Elmira Hassanzadeh and Dr. Karl-Erich Lindenschmidt for their guidance, patience, and their support throughout all stages of my masters. This project would not have been possible without their encouragement and valuable mentorship that I deeply appreciate.

I would like also to express my gratitude to Etienne Shupena-Soulodre for his help and expertise the past two years. His feedback was important in big sections of this thesis.

I would like to extend my acknowledgement to Dr. Ali Nazemi for his encouragement and positive opinion every time I presented my work.

I would like to express my gratitude for Polytechnique Montréal and Environment and Climate Change Canada.

I want to take this opportunity to also thank my colleagues, Sarah-Claude, Ali, Andrea and Matheo, for their support.

Finally, I want to extremely thank my family for their incredible support, encouragement, and patience.

RÉSUMÉ

Les polluants provenant des sources non ponctuelles sont parmi les principaux contaminants des eaux dans de nombreux bassins versants dans le monde entier. En particulier, le ruissellement excessif de nutriments dû aux activités agricoles majeures est à l'origine de la dégradation de la qualité de l'eau dans plusieurs bassins versants en Amérique du Nord. L'une des solutions les plus utilisées pour améliorer la qualité de l'eau dans ces régions est de mettre en œuvre des pratiques de gestion agricole bénéfiques (PGB). La préparation d'un plan efficace de gestion de la qualité de l'eau dépend de l'efficacité des PGB et de leurs coûts de mise en œuvre. Cependant, une évaluation complète des PGB agricoles n'est pas disponible à différentes échelles spatiales. En outre, l'efficacité des PGB est fréquemment étudiée dans des conditions climatiques historiques; tandis que le changement climatique est susceptible d'avoir un impact négatif sur la dynamique des nutriments et l'efficacité des PGB.

Cette étude présente de nouvelles séries d'analyses pour évaluer le coût et l'efficacité des PGB agricoles dans des conditions climatiques historiques et changeantes et pour proposer une série des PGB optimales dans des conditions futures incertaines. Ces analyses sont effectuées dans le bassin versant de la rivière Qu'Appelle (QARB). Ce dernier est situé dans la région des prairies canadiennes. En bref, un modèle de qualité de l'eau existant a été amélioré et utilisé dans cette étude pour estimer les éléments nutritifs, à savoir l'azote total (TN) et le phosphore total (TP), avant et après la mise en œuvre d'un ensemble de PGB. De plus, un module d'estimation des coûts est développé pour estimer le coût de mise en œuvre des PGB à l'échelle des affluents et des bassins versants. En se basant sur ce modèle, la performance de toutes les combinaisons possibles de PGB est évaluée et les résultats sont fournis dans des "Matrices de prise de décision" qui contiennent les coûts et les impacts des PGB sur le TN et le TP dans les affluents du QARB. En conséquence, des combinaisons optimales de PGB, qui sont très efficaces et correspondent à des faibles coûts de mise en œuvre, ont été identifiées à l'échelle des affluents et des bassins versants dans les conditions climatiques historiques.

De plus, des approches descendantes et ascendantes sont utilisées pour l'évaluation de l'impact du changement dans les conditions climatiques sur la performance des PGB. Pour atteindre ce but, un large intervalle de changements de température et de précipitations annuelles à long terme est pris en compte et les valeurs correspondantes sont introduites dans le modèle de qualité de l'eau pour comprendre la sensibilité du TN et du TP aux changements des conditions climatiques. De plus, le même intervalle est utilisé pour analyser la performance de combinaisons optimales de PGB précédemment trouvées dans des conditions climatiques historiques. En outre, des projections des températures et des précipitations moyennes basées sur 20 modèles de circulation générale (MCG) sous deux profils représentatifs d'évolution de concentration (RCP 4.5 et RCP 8.5) sont utilisées pour trouver des combinaisons optimales de PGB dans le future. À cette fin, l'évolution des combinaisons PGB optimales sous des épisodes futurs alternatifs est identifiée. Enfin, les performances de ces PGB optimales sont analysées à l'aide des projections de chaque modèle climatique individuels.

Nos résultats ont montré que l'efficacité des PGB et leur coût de mise en œuvre varient d'un affluent à l'autre. De plus, la rétention et la conservation des zones humides figuraient parmi les pratiques les plus efficaces pour réduire l'apport de nutriments; cependant, leur coût de mise en œuvre était extrêmement élevé. En revanche, les PGB liées aux enclos à bétail, comme la construction d'étangs de rétention, figuraient parmi les PGB les moins coûteuses avec un niveau d'efficacité modéré. Dans cette étude, différentes combinaisons de PGB qui peuvent réduire fortement ou modérément l'apport de nutriments dans le QARB avec des coûts relativement faibles ont également été présentées. De plus, les taux d'adoption des PGB par les parties prenantes peuvent considérablement affecter leur efficacité dans cette région. Cela montrait l'importance des parties prenantes et leur inclusion dans les décisions. Les résultats de l'évaluation de sensibilité aux changements climatiques ont révélé que TN et TP étaient plus sensibles aux changements de température qu'aux précipitations. De plus, l'utilisation de PGB précédemment identifiées au cours de la période historique peut ne pas réduire les nutriments si la température annuelle à long terme augmente de plus de six degrés. La conservation des zones humides et la construction d'étangs de rétention figuraient à nouveau parmi les combinaisons optimales de PGB identifiées dans les conditions climatiques futures.

En facilitant la communication entre les parties prenantes, ce type d'analyses peut servir à choisir une combinaison de PGB et prendre des décisions pour améliorer la qualité d'eau dans la région. En effet, ce type d'analyses peut être utiliser pour assister les agriculteurs dans leurs choix de différentes combinaisons de PGB en fonction du budget disponible tout en assurant un taux acceptable de réduction des nutriments. Cela peut également les aider à identifier un plan efficace de gestion de la qualité de l'eau en tenant compte des changements climatiques dans le futur.

ABSTRACT

Non-point source pollutants are among the main contributors to water pollution in many watersheds all over the world. In particular, excessive nutrient runoff from agricultural areas is the main cause of water quality degradation in multiple North America's watersheds. One of the common solutions to improve water quality in these areas is to implement agricultural Beneficial Management Practices (BMPs). Selection of water quality management plans not only depends on the effectiveness of BMPs but also on their cost of implementation. However, a comprehensive assessment of agricultural BMPs is not available across various spatial scales. Moreover, the effectiveness of the BMPs is often assessed under the historical climate conditions; while changes in climate can affect the nutrients dynamics and the performance of BMPs in the future.

This study presents new sets of analyses to assess the cost and effectiveness of agricultural BMPs under historical and changing climate conditions and to propose optimal BMPs under uncertain futures. The analyses were carried out in the Qu'Appelle River Basin (QARB), a typical watershed in the Canadian Prairies. In brief, an existing water quality model was improved and used in this study to estimate the nutrients, namely Total Nitrogen (TN) and Total Phosphorus (TP), before and after implementation of a set of BMPs. Moreover, a cost estimation module was developed to estimate the cost of implementing BMPs at tributary and watershed scales. Based on these developments, the performance of all possible combinations of BMPs were assessed and results were provided in "Information matrices" that summarised the costs and impacts of BMPs on TN and TP in the QARB tributaries. Accordingly, optimal combinations of BMPs, which were highly effective and require low costs of implementation were found at both tributary and watershed scales under the historical climate conditions.

Moreover, top-down and bottom-up approaches were used for BMP impact assessment under changing climate conditions. For this purpose, a wide range of changes in long-term annual temperature and precipitation was considered and corresponding values were fed into the water quality model to understand the sensitivity of TN and TP to changes in climate conditions. In addition, the same range of change in climate was used to analyze the performance of previously

found optimal combinations of BMPs under historical climate conditions. Furthermore, multi-ensemble mean temperature and precipitation projections based on 20 General Circulation Models (GCMs) under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) were used to find optimal combinations of BMPs in the future. For this purpose, evolution of optimal combinations of BMPs under alternative future time episodes were identified. Finally, the performance of these optimal BMPs were analyzed using the projections of individual climate models.

Our results revealed that the effectiveness of the BMPs and their cost of implementation vary from a tributary to another. It was also found that on the one hand, wetland retention and conservation were among the most effective practices in reducing nutrients delivery; however, their cost of implementation was extremely high. On the other hand, cattle corral-related BMPs, such as constructing holding ponds, were among the less costly BMPs with moderate level of effectiveness. In this study, different combinations of BMPs that can highly or moderately reduce nutrient delivery in the QARB with relatively low costs were also presented. It was also found that the rates of BMP adoption by stakeholders can considerably affect nutrient abatement in this region. This indicated the importance of stakeholders and their engagement in the decision-making process. Moreover, the results of climate change impact assessment revealed that TN and TP were more sensitive to changes in temperature than precipitation. In addition, the usage of previously identified BMPs under historical period may not effectively reduce the nutrients if long-term annual temperature increases by more than six degrees. Wetland conservation and constructing holding ponds were again among the newly found optimal combinations of BMPs under future climate conditions.

This type of analyses can facilitate communication of BMP and water quality decisions in the region. In particular, the presented results can assist stakeholders in choosing different combination of BMPs according to their available budget and accepted levels of nutrient reduction. Moreover, it can also help identifying effective water quality management plans under changing climate conditions in the future.

TABLE OF CONTENTS

LIST OF TABLES

*

LIST OF FIGURES

LISTOF SYMBOLS AND ABBREVIATIONS

BMP Beneficial Management Practices

CHP Constructing holding ponds below corrals

CRC Complete corrals relocation

CSD Constructing small storage dams

FCP Flow control practices

FM Fertility management

GCMs Generalized circulation models

GRD Grassing ditches

LAAT Long-term Annual Temperature

LAAP Long-term Annual Precipitation

SD System dynamics

TN Total nitrogen

TP Total phosphorus

QR Qu'Appelle River

QARB Qu'Appelle River Basin

WCN Wetland conservation

WRT Wetland retention

WSA Water Security Agency

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

1.1 Background and problem definition

Agricultural activities, in the forms of cattle farming or annual cropping, have been considered as one of the major sources of pollution in various watersheds across the world. These activities can intensify the amounts of nitrogen and phosphorus in downstream water bodies and degrade water quality conditions (Chapra, 2008; Sun et al., 2012). Implementation of agricultural Beneficial Management Practices (BMPs) is often considered as an effective solution to reduce nutrient delivery and improve water quality in watersheds (Government of Canada, 2019). These BMPs aim to eliminate or reduce the nutrients delivery through e.g., minimizing soil erosion, runoff control, or lessening the pollutants by nutrient management (Agriculture and Agri-food Canada, 2000).

Local stakeholders play a key role in choosing and implementing one or a combination of BMPs in farmlands; therefore, the considered BMPs should be feasible and in line with their business plans and viewpoints (Halbe et al., 2013; Inam et al., 2013; Niazi et al., 2014). Therefore, not only the effectiveness of the practices in improving water quality is important but also their costs of implementation can influence water management decisions (Girard et al., 2015). Such cost-effectiveness analyses of BMPs are often neither available nor are comprehensive enough to show the compound impact of utilizing multiple practices simultaneously across various spatial scales. Moreover, the performance of these practices is often assessed considering the historical characteristics of climate conditions. However, changing climate can affect the nutrients dynamics and water quality conditions in the watersheds (Wilby et al., 2006; Van Liew et al., 2012; Qiu et al., 2019). Thus, the selected BMPs based on historical temperature and precipitation may not be effective anymore in the future.

The impact of climate change on the water quality and the effectiveness of the BMPs can be assessed using two common approaches, namely “top-down” and “bottom-up” (Alodah et al., 2019). In the top-down approach, the outputs of one or ensemble of General Circulation Models (GCMs) are often used and transferred to the scale of interest, which are then fed into water quality models for impact assessment (Hassnazadeh, 2016). However, due to uncertainties associated with climate models and downscaling techniques, high uncertainties exist in the water quality projections, which can influence BMP selection and water management decisions. The bottom-up approach aims to provide a full picture of system performance under possible changes in climate conditions without necessarily applying climate models. Although this approach can facilitate stakeholders' understanding of system stress points and climate conditions that can lead to these situations, they do not provide a notion of their occurrence in the future (Jaramillo and Nazemi, 2018; Nazemi et al., 2020). Thus, due to the advantages and limitations of these individual approaches, their concurrent application is necessary for impact assessment.

1.2 Research objectives

In response to these challenges and to improve water quality management under current and changing climate conditions, the global objectives of this study are to:

(1) develop generic approaches to estimate and present the costs and effectiveness of agricultural BMPs in improving water quality;

(2) evaluate water quality conditions and effectiveness of BMPs under changing climate conditions using "top-down" and "bottom-up" approaches.

These objectives will be pursued in the Qu'Appelle River Basin (QARB), a typical watershed in the Canadian Prairies. The specific objectives of this thesis are as follows: (a) develop a cost estimation module to calculate the cost of implementing BMPs in the QARB; (b) identify optimal combinations of BMPs that can improve water quality with low costs of implementation under historical climate conditions;(c) understand the impact of stakeholders' BMP uptake on the effectiveness of the BMPs in the watershed;(d) assess the impact of climate change on the nutrients and the efficacy of BMPs; and (e) propose BMP combinations that can remain effective in reducing the nutrients under future climate conditions.

1.3 Case study

The QARB, with the area of 52,000 km^2, is located in the Province of Saskatchewan, Canada. The watershed supports drinking water for around the third of the population of the province (Andreichuk, 2017), most importantly for the cities of Moose Jaw and Regina. Mean historical annual temperature and precipitation in the watershed are 2.8°C and 420 mm, respectively (Environment and Climate Change Canada, 2018). The basin contains 12 main tributaries and their total areas range between 260 and 12700 km^2 (Roste and Baulch, 2018). The dominating activities in these tributaries are annual cropping and cattle farming (Kulshreshtha et al., 2012). The cattle population in the tributaries are not even and range between 1000 and 32000 cows, while the cropland areas range between 47 and 2636km^2 (Roste and Baulch, 2018). The quality of water in the QARB tributaries and mainstream, the Qu'Appelle River (QR), has been degraded over the past few decades due the excessive nutrient transport mainly from nonpoint sources to downstream (Boyer et al., 2018).

Although improving water quality management in these tributaries has been essential, it has not been a trivial task due to various reasons such as existence of vast agricultural areas. Most importantly, agricultural producers, that should implement BMPs in farmlands, have different attitudes and viewpoints about water quality and the practices that can reduce nutrients in this region. Therefore, proposing a single or combination of practices without considering these local scale dynamics may not be adopted by landowners; thus will not improve water quality here. Hassanzadeh et al. (2019) performed a series of workshops with agricultural producers in this region. Using a set of qualitative analyses, they identified practices related to fertilizer, wetland, cattle corral, and streamflow management that most of the farmers believed are feasible and can improve water quality here. Further assessment of stakeholders' viewpoints revealed that both costs and effectiveness of these practices are critical information that can influence chance of BMP uptake by farmers (Lindenschmidt et al., 2018). Moreover, since the characteristics of temperature and precipitation in this region have been changing significantly since 1981 (Zhang et al., 2019), understanding the impact of climate change on effectiveness of the BMPs is also important for policymakers and local stakeholders (Bradford et al., 2020).

CHAPTER 2 LITTERATURE REVIEW

2.1 BMP impact assessment in agricultural areas

The water quality condition is assessed by measuring multiple indicators to describe the chemical, physical, and biological characteristics of the water. These measurements are performed based on the purpose of use of water: such as water resources designated for drinking purposes or irrigation. Indicators may include bacteria levels, the concentration of microscopic algae and quantities of pesticides, herbicides, and heavy metals (National Marine Sanctuaries, 2020). The water quality can be degraded by two main types of sources: point sources and nonpoint sources of contamination. Point sources, for which the origin is known, are multiple and they include factories, wastewater treatment facilities, and other sources that are clearly discharging pollutants into water sources. Non-point sources, which cannot be traced back to a particular location, include runoff of sediment, fertilizer, chemicals and animal wastes from farms, and construction sites and mines (Safe Drinking Water Foundation). One of the main agricultural activities harming the water quality is the cattle production. This is because in most areas, cattle corrals are located near creeks, from which manure and urines are transported to downstream water bodies, especially during the snowmelt season in Canada (Chen et al., 2017; Hassanzadeh et al., 2019). Another type of farming is annual cropping. Agricultural producers use herbicides, pesticides, and fertilizers to increase crop yield. Such practices, along with leaving crop residues to enhance production generate excessive amounts of nutrients in land. Therefore, during snowmelt or intense rainfall these nutrients will be delivered to freshwater resources, which speeds up the eutrophication process (United States Environmental Protection Agency, 2005). Moreover, wetland drainage is also a common practice in Canada to convert the wetlands into agricultural land (McRae, 2013). In fact, despite their multiple benefits, more than seventy percent of wetlands across Canada have been drained considerably (Ducks Unlimited Canada, 2020). Wetlands are often “sinks” of nutrients and some studies have found positive relationships between catchments’ wetland coverage area and water quality conditions (Brinsion, 1993; Untereiner et al., 2015) in the Prairies. Hence, although draining wetlands might increase agricultural economic benefit, they may contribute to intensifying erosion, sedimentation, and high nutrient runoff in long-term (Yang et al., 2010).

Agricultural BMPs aim to reduce nonpoint source pollutants and have different functionalities such as reducing nutrients entering the land, preventing soil erosion, controlling runoff, increasing nutrient interception, and lessening nutrient delivery (Agriculture and Agri-food Canada, 2000; Beegle et al., 2000; Lam et al., 2011). Moreover, they can be categorized into structural and non-structural BMPs (USDA, 2006; GC, 2019). Structural BMPs are costly and involve building structures such as detention ponds, vegetated biofilters (e.g., swales and filter/buffer strips), and constructed wetlands. Non-structural BMPs are often less costly and include land and nutrient management solutions such as limiting application of pesticides in croplands, growing cover crops, and controlling fertiliser use (United States Environmental Protection Agency, 2006; Liu et al., 2019). The effectiveness of BMPs depend on various factors, most importantly the physiographic and meteorological characteristics of watersheds. Therefore, on the one hand, the proposition of BMPs should be often region specific. On the other hand, it is extremely challenging and sometimes impossible to monitor and evaluate the BMPs performance on small spatial resolutions over time.

BMPs' assessment has become a thriving area of research. Watershed models are frequently used to evaluate the water quality response to multiple BMPs. Some examples include Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), SPAtially Referenced Regression On Watershed (SPARROW), Agricultural Nonpoint Source (AGNPS) (Young et al., 1989), Annualized Agricultural Nonpoint Source (AnnAGNPS) (Bingner et al., 2007), and Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell et al., 2001). These models have been reviewed by Xie et al. (2015) and their limitations in representing the performance of some local practices are discussed. Moreover, application of simplified tools, using complex models as hidden engines with user-friendly interfaces, is suggested to engage local stakeholders in water quality modeling and management. In other studies, emulation of the complex models in another modeling environment is proposed to make models more accessible and relevant and being able to represent diverse BMPs (Razavi et al., 2012; Hassanzadeh et al., 2014; Zandmoghaddam et al., 2019).

As discussed earlier, the costs of BMPs are important, especially from the stakeholders' point of view. Different approaches have been used for this purpose (Liu et al., 2014; Kalcic et al., 2015;

Liu et al., 2019). In brief, Kalcic et al. (2015) considered material and equipment cost, annual costs such as maintenance costs, and income loss. Liu et al. (2014) focused only on the cost of converting croplands to forests. In addition, Arabi et al. (2006) proposed an equation to include costs of construction and maintenance, BMP lifespan and interest rates to estimate total cost of BMPs, which was used by several studies (Park et al., 2014; Liu et al., 2016). However, this method cannot be used to calculate the costs of non-structural BMPs. Although these efforts have been made, there are still challenging is developing BMP cost estimation models. This might not be due to technical aspect and rather it is due to lack of data and the changing prices in the markets due to inflation (e.g. excavation cost).

2.2 Application of System Dynamics approach in water quality modeling and management

System Dynamics (SD) is an approach to simulate the interactions among system components and assess overall system behaviour over time (Forrester, 1961). There are various software packages that support developing models using SD approach (e.g., STELLA, VENSIM). The models built in these environments are flexible as their structures can be easily modified and/or new variables and parameters can be added if needed. For instance, multiple system aspects such as physical processes as well as socio-economic variables can be represented together in SD environments. Such representations can facilitate integrated analyses of complex systems (Sterman, 2010). It is also possible to develop simple models with transparent interfaces in these SD environments, which can be easily learnt and manipulated by stakeholders with different levels of technical background. As a result, these models can be used as a communication platform (Simonovic, 2009; Kelly et al., 2013). Due to these advantages, SD environments have been commonly used for water quantity and quality modeling and management (Malard et al., 2017; Nazari-Sharabian et al., 2019; Madani and Shafiee-Jood, 2020; Jiang et al., 2020). For instance, SD has been used in understanding the impact of climate change on the water quality (e.g., Encalada et al., 2017), and for water quality management (e.g., Mirchiand Watkins, 2013; Liu et al., 2015; Zomorodian et al., 2018).

2.3 Assessing water quality under changing climate conditions

Human activities since the industrial revolution have increased the amount of greenhouse gas concentrations in the atmosphere. This has resulted in changes in the characteristics of climate variables such as temperature and precipitation (Bush et al., 2019; IPCC, 2020). For instance, global warming-trend is nearly doubled in the last 50 years compared to the beginning of the century (IPCC, 2020). In addition, extreme rainfall has become more frequent in the world (World Resources Institute, 2019). In Canada, mean annual temperature has increased by 1.7 °C and the magnitude, duration and frequency of precipitation have changed within the past several decades (Zhang et al, 2019). Changes in climate can have important impacts on the quality of water (Bouraoui et al., 2002; Luis et al., 2018; World Resources Institute, 2019). For instance, increasing temperature in water bodies can accelerate the growth of toxic algal blooms and eutrophication processes (Liu et al., 2015; USEPA, 2020; IISD, 2020). In addition, increase of extreme rainfall conditions can cause soil erosion, augmentation of sediments, and nutrient delivery to freshwater bodies (Donneret al., 2004; Howarth et al., 2006; United States Environmental Protection Agency, 2020). Such changes imply that the effectiveness of BMPs might vary in the future (Wilby ey al., 2006; Van Liew et al., 2012; Qiu et al., 2019). In fact, Wilby et al. (2006) used historical climate data and found that due to changes in the dynamics of non-point sources of pollutants, existing BMPs' efficacy may have been negatively affected due to changing climate.

The GCMs are the most credible tools to project climate conditions. These models solve various equations e.g., related to conservation of mass, energy, and momentum to represent physical processes in the atmosphere, land surface, ocean, and cryosphere (IPCC, 2020). The models also consider different pathways related to socio-economic activities (e.g., population growth) as well as political conditions in the future, which can lead to different emissions of greenhouses gases. Accordingly, they provide projections of climate conditions until the end of twenty first century. Due to the consideration of different equations, initial conditions, assumptions, as well as simplifications, the projections of climate models are not necessarily similar and can be even diverging (Hassanzadeh et al., 2019). Therefore, it is suggested to use an ensemble of GCMs for climate change impact assessment. The spatial scale of these models is coarse as well, typically few hundreds of kilometer squares (e.g., 300 km^2). Therefore, downscaling approaches are used to transfer the GCMs' outputs to relevant scales for water management purposes (Pulido-Velazquez et al., 2014). The top-down approach has been widely used in various regions for climate change impact assessment purposes (Kaste et al., 2006; Jeppesen et al., 2009; Carvajal et al., 2017; Van

Tra et al., 2018; Hengadeet al., 2018). For instance, Ivkovic (2009), Hosseini et al. (2017) and Morales-Marin et al. (2018) have projected increases in temperature and precipitation across various regions and found their potential negative impact on nutrients. While, some other studies analyzed the performance of BMPs in the future using an ensemble of climate models. For instance, Qiu et al. (2020) found that increasing extreme rainfall events will affect the efficacy of agricultural BMPs. Walters and Babbar-Sebens (2016) found that keeping wetlands can be still effective in the United States of America, under all climate projections. However, the projections of future water quality conditions are associated with various sources of uncertainties, stemming from climate models and downscaling techniques, which can also affect BMP impact assessment (Salas et al., 2012; Girard et al., 2015; Alodah et al., 2019; Pandey et al., 2019).

To avoid these model-based uncertainties, bottom-up impact assessment approaches have been used in the literature to represent the system behaviour under a wide range of possible climate conditions (Nazemi and Wheater, 2014; García et al., 2014; Poff et al., 2016; Hassanzadeh et al., 2017; Wilby, 2017; Zandmoghaddam et al., 2019; Hassanzadeh, 2019). The results based on this approach are often displayed using response surfaces, 2-D maps showing the performance of a system under changes in temperature and precipitation (Brown et al., 2011; Poff et al., 2016). Serra-Llobet et al. (2016) used this approach to assess the impact of climate change on the water quality. Similar to the top-down approach, there are limitations in the bottom-up approach, in particular in generation of climate realizations that might not lead to full representation of system vulnerability (Alodah et al., 2019; Nazemi et al.,2020).

The top-down and bottom-up approaches are individually used to study the impact of climate change on the nutrients dynamics and/or the efficacy of BMPs (e.g., Groves et al., 2008; Ivkovic, 2009; Koontz et al., 2014; Ludwig et al., 2014; Walters and Babbar-Sebens, 2016; Hosseini et al., 2017; Morales-Marin et al., 2018; Van Tra et al., 2018; Qiu et al., 2020; Mukundan et al., 2020; Qiu et al., 2020). While bottom-up approach can be used to portray system’s sensitivity to possible changes in temperature and precipitation, the top-down approach can be used to indicate likely climate conditions and system vulnerabilities under future projections (Hassanzadeh, 2019).

Therefore, the application of both approaches is suggested for impact assessments (Fulco et al., 2013;Wheater and Gober, 2015).

CHAPTER 3 ORGANIZATION OF THE WORK

Successful water quality management plans include a combination of structural and non-structural practices that are cost-effective, can sufficiently reduce nutrients, and are "culturally and socially acceptable" to local stakeholders (UNECE, 2009; Girard et al., 2015). Achieving this plan requires comprehensive analyses of BMPs, which is currently lacking. In response to current research gaps and objectives, this thesis aims to provide a set of analyses for BMP impact assessment, with a greater goal of proposing water quality management plans for the QARB under current and future climate conditions. These efforts are presented Chapters 4 and 5. Based on these chapters, the thesis findings are discussed and concluded in Chapter 6. The brief description of these chapters are as follows.

Chapter 4 proposes a generic approach to evaluate the costs and effectiveness of agricultural BMPs to improve water quality. For this purpose, several BMPs related to cattle corrals and annual cropping in the QARB are considered in the analyses. The SD-Qu'Appelle, existing water quality model for the QARB was used and improved in this study to estimate nutrients before and after implementation of the BMPs. Improvements included dynamic estimations of effective watershed areas with and without considering wetlands. Moreover, a new economic estimation module is developed and added to this model to estimate the costs of implementing BMPs at the tributary and watershed scales. Information matrices, which exhibit the costs and impacts of BMPs on water quality conditions at the tributary scale are presented so that stakeholders be able to choose single or combination of BMPs based on their available budget and target levels of reductions in nutrients. A set of optimal combinations of BMPs that can reduce nutrients considerably with relatively low costs at the large watershed scale are also provided. Finally, the effectiveness of proposed BMPs are analyzed considering different rates of BMP adoption by stakeholders in the region.
This manuscript was submitted to the *Journal of Environmental Management* (Impact Factor: 5.66) in 2020. Moderate revisions are requested.

Chapter 5 evaluates the impact of climate change on the nutrient export and the effectiveness of set of BMPs in the QARB and proposes optimal BMPs under future conditions. For this purpose, a wide range of changes in temperature and precipitation is considered and their corresponding values are fed to the water quality model, used in Chapter 4, to investigate the possible changes in nutrients in the QARB tributaries under changing climate conditions. Moreover, the effectiveness of a set of BMPs, claimed to be optimal under historical climate conditions, is assessed under these changing climate conditions. Accordingly, new sets of optimal combinations of BMPs are found for alternative future episodes under average projections from 20 climate models and two future representative climate pathways. Finally, the uncertainties in effectiveness of the identified combinations of BMPs is analyzed based on the outputs of individual climate models.

Chapter 6 discusses the findings and highlights the contribution of this work. In addition, the limitations of this project and suggestions for future developments are provided in this chapter.

CHAPTER 4 ARTICLE 1: A GENERIC APPROACH TO EVALUATE COSTS AND EFFECTIVENESS OF AGRICULTURAL BENEFICIAL MANAGEMENT PRACTICES FOR WATER QUALITY MANAGEMENT

Mohamed Khalil Zammali[a], Elmira Hassanzadeh[a,b], Etienne Shupena-Soulodre[c], Karl-Erich Lindenschmidt[b]

[a] *Department of Civil, Geological and Mining Engineering, Polytechnique Montreal, 2500 Chemin de Polytechnique, Montreal, QC, H3T 1J4, Canada*

[b] *Global Institute for Water Security, University of Saskatchewan, 11 Innovation Blvd, Saskatoon, SK, S7N 3H5, Canada*

[c] *Water Security Agency, 2365 Albert St #420, Regina, SK, S4P 4K1, Canada*

This chapter was submitted to the *Journal of Environmental Management*.

Contribution of the Master student

The master student modified the performance of existing water quality model, initially developed by Elmira Hassanzadeh. In addition, the master student developed the cost modules to estimate the cost of BMP implementation. Etienne Shupena-Soulodre provided ideas and several data to calculate the operational costs. The candidate carried out the analyses and drafted the manuscript. All co-authors commented and edited of the manuscript.

Abstract

Nutrient export from agricultural areas is among the main contributors to water pollution in various watersheds. Agricultural Beneficial Management Practices (BMPs) are commonly used to reduce excessive nutrient runoff and improve water quality. The successful uptake of BMPs not only depends on their effectiveness but also on their costs of implementation. This study conducts a set of cost-effectiveness analyses to help stakeholders identify their preferred combinations of BMPs in the Qu'Appelle River Basin, a typical watershed in the Canadian Prairies. The considered BMPs are related to cattle and cropping farms and were initially selected by agricultural producers in this region. The analyses use a water quality module to estimate the impact of implementing BMPs on nutrient export, and the costs module to estimate the cost of implementing BMPs at tributary and watershed scales. Our results show that BMPs' effectiveness, total cost of implementation and costs per kilogram of nutrient abatement vary between tributaries. However, wetland conservation has been among the optimal practices to improve water quality across the watershed. It was also found that the rates of BMP adoption by stakeholders can influence the effectiveness of practices in a large watershed scale, which highlights the importance of stakeholder engagement in water quality management. This type of analyses can help stakeholders choose single or a combination of BMPs according to their available budget and acceptable levels of reduction in nutrients.

Keywords: Beneficial Management Practices; Agricultural lands; Water quality management; System dynamics; Cost-effectiveness analysis; Qu'Appelle River Basin

4.1 Introduction

Agricultural activities including annual cropping and cattle farming are widespread and necessary to support socioeconomic developments in various countries (Liu et al., 1998). These activities have; however, led to water pollution in North America due to the discharge of sediments, nutrients, and organic matters into water resources (USEPA, 2020). In particular, excessive nutrients from agricultural areas, most importantly Nitrogen (N) and Phosphorus (P), have greatly contributed to eutrophication and cyanobacterial blooms, causing various socioeconomic and environmental concerns (Sharpley et al., 2013; Kehoe et al., 2015; King et al., 2015). Considering the ongoing agricultural activities and increasing amount of non-point source pollutants worldwide (SC, 2014), there is an urgent need to manage nutrient exports to improve water quality and support sustainable developments in the future (Giri et al., 2012).

One of the common methods to abate nutrients in agricultural zones is to implement Beneficial Management Practices (BMPs) in farmland. These practices have different functionalities ranging from reducing nutrients directly entering the land and minimizing soil erosion to lessening delivery of sediments and/or dissolved nutrients to streams (USDA, 2006; AAFESD, 2015; GC, 2019). However, these BMPs are often not fully adopted by local agricultural producers and their rate of implementation is constrained by multiple factors. For instance, local stakeholders including agricultural producers and policymakers often doubt the effectiveness of different BMPs in terms of improving water quality at the local and regional scales (Arabi et al., 2007). In addition to such concerns, BMPs' costs of implementation and maintenance are highly important (Wuite et al., 2007). Limited knowledge about these factors can affect the viewpoints and attitude of stakeholders to uptake BMPs (Hassanzadeh, 2019). Therefore, presenting the costs and effectiveness of BMPs in improving water quality at different scales is a primary step to facilitate decision-making processes and improving water quality management in agricultural areas.

Several studies have focused on estimating the costs and economic benefits of BMPs (e.g., Pattison-Williams et al., 2018). While such assessments provide a general view on the importance of practices, they involve high level of uncertainty due to consideration of monetary values to show the benefits of environmental systems, which cannot be easily identified. There have been studies on estimating the costs as well as "effectiveness", instead of economic benefits of BMPs, in terms of their impact on water quality conditions. However, these studies have been limited to evaluating either BMPs related to annual cropping such as effective usage of fertilizer (e.g., Thomsen et al., 2010; Jeffrey et al., 2014; Crabbé et al., 2014; Atisa et al., 2014) or cattle farms such as relocation of cattle wintering sites (e.g., Wuite et al., 2007; Shukla et al., 2011; Panagopoulos et al., 2011; Bruce et al., 2017). Therefore, comprehensive analyses of costs and effectiveness of BMPs related to both agricultural activities as well as when and where they can be implemented together are not available. Furthermore, there are some limitations related to spatial scale of existing studies. On the one hand, most of the current studies have focused on the cost-effectiveness analyses of BMPs at the watershed scale; thus, based on the large spatial scale analyses, BMPs were proposed to be implemented at the farm scale. Such assessments can lead to selection of non-optimal BMPs at the local scale (Bruulsema et al., 2008; Panagopoulos, 2011; Gurnell et al., 2015).On the other hand, some studies have focused on the analyses of site-specific BMPs, the application of which might not be neither feasible nor effective across the entire watershed (Wuite et al., 2007; Geng et al., 2019; Baulch et al., 2019).Thus, it has been suggested to perform both regional and site-specific analyses to find reasonable management practices (Liu et al., 2019). On top of these issues, since successful implementation of BMPs requires an active engagement of stakeholders in decision-making processes, BMP analyses should be simple enough that can be understood and discussed by people with different levels of technical backgrounds.

This study proposes a generic approach to analyze and present the costs and effectiveness of multiple combination of BMPs related to annual cropping and cattle farms, to improve water quality at the tributary (local) and watershed scales. The study focuses on the Qu'Appelle River Basin (QARB) in Saskatchewan, which contains large crop and cattle producing farm and is under pressure due to poor water quality conditions (Hall et al., 1999). Therefore, it is aimed to find multiple sets of BMPs that have the lowest total cost of implementation but are most effective across different spatial scales. To the best of our knowledge such analyses than can help policymaking have not been presented in the literature, in particular, for the Canadian Prairies. The structure of the paper is as follows: Section 4.2 and 4.3 provide an overview of the study area and explanation of the water quality and economic evaluation models, respectively. Section 4.4 presents the cost-effectiveness analyses and selection of BMPs according to different criteria. The paper is concluded in Section 4.5.

4.2 Case study

The QARB is located in the south of Saskatchewan, Canada. The basin drains a total area of approximately 52000 km^2(Dixit et al., 2000). Twelve major tributaries, included in this study were shown in Figure 4.1. The two largest tributaries are Moose Jaw River, and Wascana Creek. Mean annual temperature and precipitation in this watershed are 2.8°C and 420 mm, respectively (GC, 2020). The Qu'Appelle River (QR) is the mainstream in this watershed, for which the main part of water comes from the Qu'Appelle River Dam and Gardiner dam on the South Saskatchewan River. The QR supplies water for about 33% of the population in the province (Hassanzadeh et al., 2014). The dominant activities in the basin are crop and cattle production, which generate large amounts of N and P, transported towards the QR (Boyer et al., 2018). Cattle are often wintered in concentrated areas (e.g., corrals) near waterways, where the large amounts of nutrients can accumulate and degrade water quality (DRFA, 2020). Swarbrick et al. (2019) found that the lakes of the QARB have a highly eutrophic status due to the elevated nutrient influx from the regional agriculture.

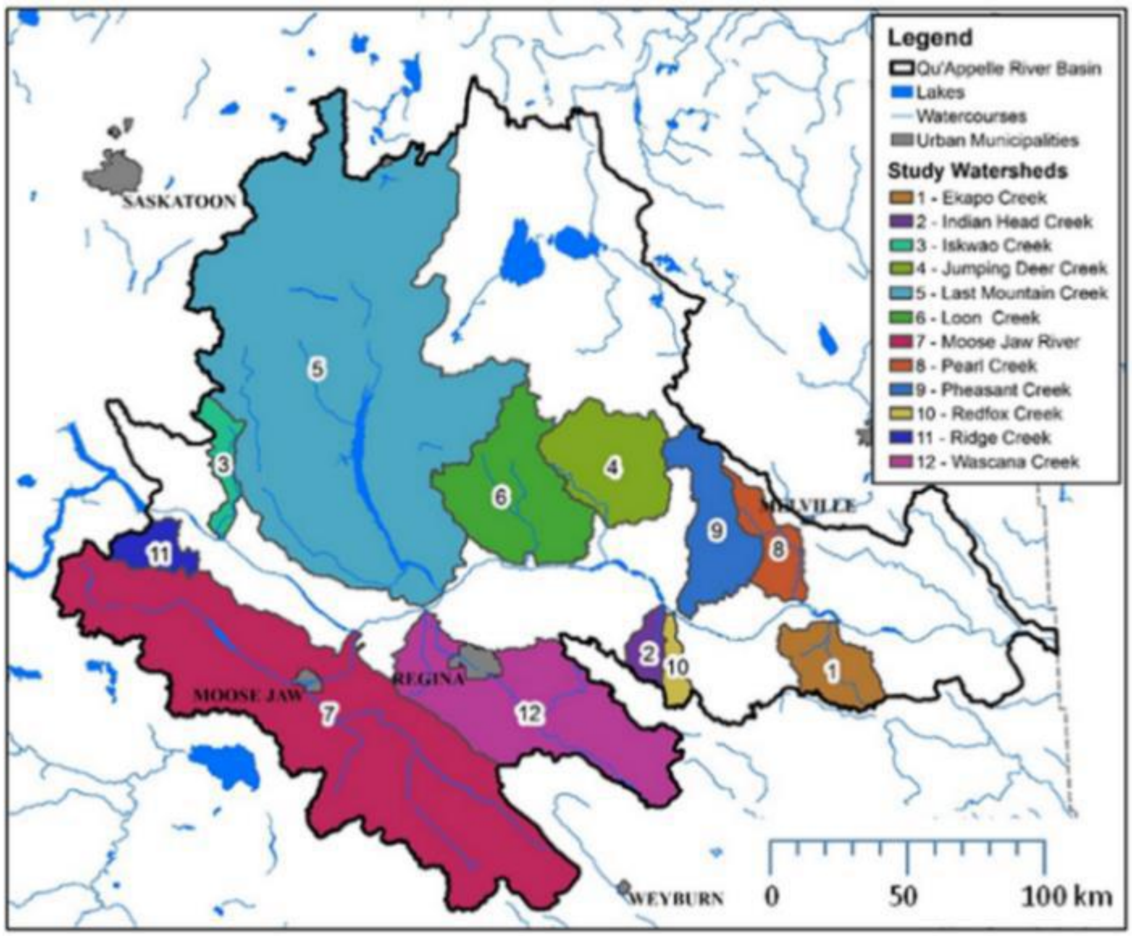

Figure 4.1 The main 12 tributaries in the QARB in the Province of Saskatchewan, Canada (map obtained from the WSA in Saskatchewan).

Figure 4.2 summarizes the total and effective (contributing) areas as well as cropland, current and drained wetland coverage areas and cattle (mother cow) population for the QARB tributaries. These numbers were obtained from Roste and Baulch (2017) and confirmed by experts from the Water Security Agency (WSA) of Saskatchewan. As shown in Figure 4.2, the animal population, cropland and effective drainage areas are proportional to the total area in most of the tributaries. Canola and spring wheat are the most commonly grown crops in this region. Rates of fertilizer, ranging from

102 to 107 kg/ha, are typically used to increase crop yields (Roste and Baulch, 2017). Similar to other prairie basins, the QARB contains hundreds of thousands of small size wetlands, which do not regularly contribute to the main river system network (Fang et al., 2010). As in much of the northern Great Plains, crop producers here have drained parts of these wetlands (see the green bars in Figure 4.2) to increase the cropland area and crop productivity (Dahl, 1990). Apart from economic benefits, draining wetlands can have adverse impacts such as reducing ecosystem productivity, escalating flood damages, and increasing water pollution in downstream reaches (Fang et al., 2010; DUC, 2011; Brunet al., 2012; Dumanski et al., 2015; Pattison-Williams et al., 2018).

Water quality in the QARB has been under pressure over the past few decades. The pollutants stem from agricultural and industrial activities and effluents from major cities. Some BMPs, such as relocation of corrals to non-contributing areas or restoring some of the drained wetlands have been implemented already in the QARB to improve water quality (WSA, 2003). However, the rates of implementing BMPs have been slow and do not meet the requirements to solve the water quality problems. Since local stakeholders play a key role in implementing BMPs, Hassanzadeh et al. (2019) performed a qualitative analysis to understand stakeholders' viewpoints about a series of BMPs that can improve water quality in this region. According to their study, the top preferred BMPs in the QARB are as follows: Constructing Holding Ponds below corrals (CHP), Complete Relocation of Corrals (CRC), Using Fertility Management (UFM), Constructing Storage Dams (CSD), implementing Flow Control Practices (FCP), Grassing Rivers and Ditches (GRD), Wetland Retention (WRT) as well as Wetland Conservation (WCN). The latter includes restoration of drained wetlands and retention of existing ones. Moreover, agricultural producers, who participated in this study, indicated that economic factors are the most important criteria for selecting or rejecting the implementation of these practices in their farms.

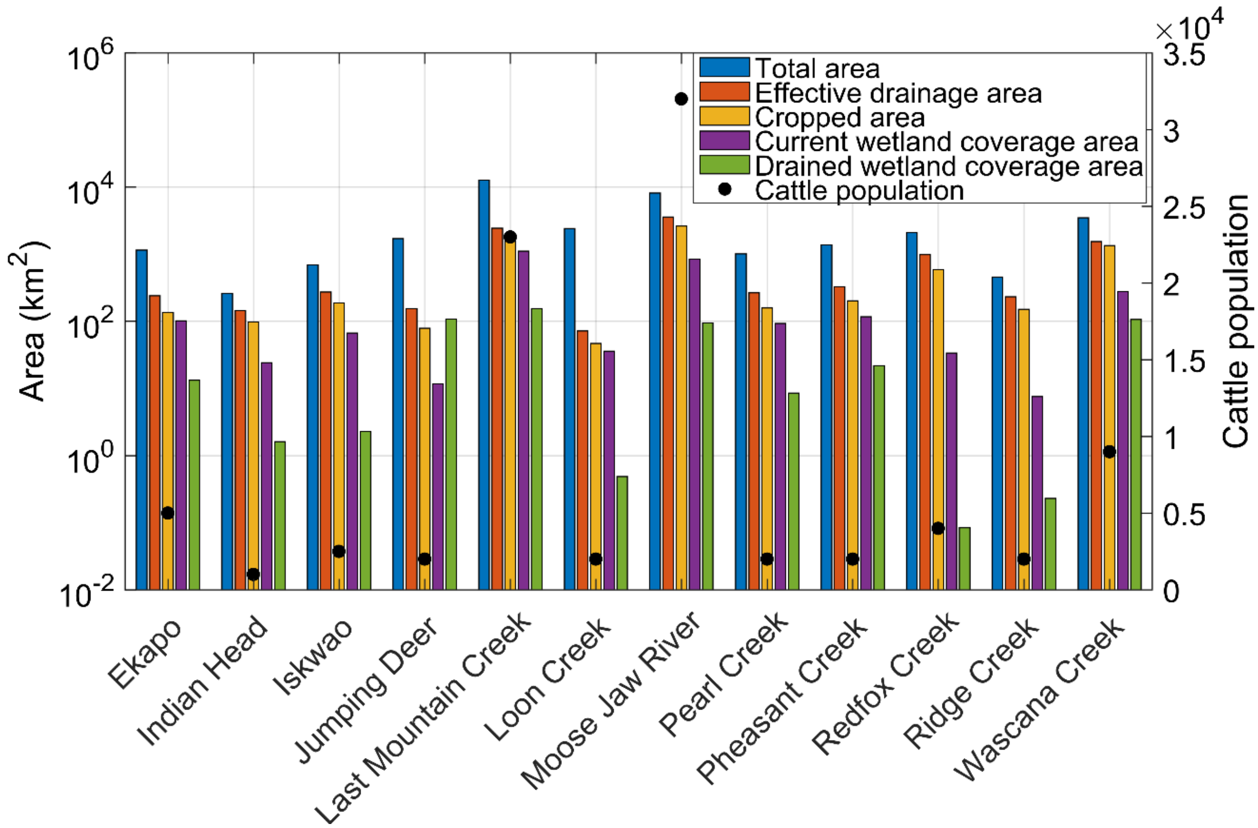

Figure 4.2 Total, effective, and cropland areas, cattle population, as well as current and drained wetland coverage areas in the QARB tributaries. Wetland coverages are estimated from drainage inventories and application of typical historical wetland coverage for the region.

4.3 Methodology

The objective of this study was to analyze the cost of implementation and effectiveness of preferred BMPs on improving water quality in the QARB. For this purpose, an available water quality model, developed by Hassanzadeh et al. (2019), was extended to simulate the nutrient exports from the QARB tributaries under different combination of BMPs. A new module was also developed to estimate the costs of implementing BMPs.

4.3.1 Water quality module

The SD-Qu'Appelle model estimates the long-term annual incremental N and P loads in the sub-catchments of the QARB tributaries. The model was developed by emulating the SPARROW (Schwarz et al., 2006) using the System Dynamics approach (Forrester, 1994), including new components to represent the impact of wetlands and cattle corrals on nutrient export. The structure of this model was shown in Figures A1 to 26 in Appendix A. Input data were the amounts of point and non-point source pollutants, climatic conditions, properties of land, as well as characteristics of rivers and lakes. Accordingly, Total N (TN) and Total P (TP) exports from each tributary were estimated by summing the incremental loads from each sub-catchment. The performance of the model in representing observed TN and TP exports from the QARB tributaries was deemed acceptable (Hassanzadeh et al., 2019). Simulations showed that the amounts of nutrients leaving tributaries mainly depend on the number of corrals, cropland area and applied rates of fertilizer. Therefore, the amounts of nutrients leaving tributaries vary among tributaries. In this model, the impact of BMPs on water quality was represented by a series of coefficients and mathematical relationships that were adopted from the literature (e.g., for reduction of nutrients entering the land due to UFM), results of local experiments in the Prairies (e.g., for impact of CSD), as well as based on consultations with WSA (e.g., for CRC). For more information on the water quality model, please refer to Hassanzadeh et al. (2019).

Due to the key role of wetlands in this region, an improvement was made in the existing model to better represent the impact of wetland related BMPs on nutrient exports. In brief, in the former model, it was assumed that retaining or draining wetlands do not have any impacts on the effective area of watersheds and therefore, the model could not properly represent the long-term impact of wetland retention on nutrient delivery. However, in the current version, this issue has been addressed. For this purpose, the positive impact of retaining wetlands was presented by considering the negative impact of wetland drainage. The more the wetlands are drained, the larger will be the watershed effective area in long term (e.g., in a 30-year period), and consequently the higher will be nutrient exports. Therefore, the model updates the watershed effective area anytime wetland related practices were chosen individually or along with other BMPs. For instance, to show the impact of WRT, first a new effective area corresponding to wetland drainage was calculated by assuming that such activity can increase the effective area up to 75% of the total watershed area in long term. Second, the amount of nutrients corresponding to this new effective area were estimated, which showed the consequence of draining all wetlands i.e., not retaining them. Considering the WCN, it was assumed that existing wetlands would be retained, and drained wetlands would be restored in the future. Therefore, new effective areas corresponding to this BMP were calculated considering reductions in the effective drainage areas based on the restored wetland coverage. Due to existence of enormous number of wetlands in this region, we believe that the assumption related to changes in contributing areas because of WRT and WCN is valid over a long period. This dynamic estimation of effective area is important to better represent the impacts and costs of wetland-related practices when they are combined with other BMPs.

4.3.2 Economic evaluation module

A generic economic evaluation module was developed to estimate the costs of implementing one or a combination of BMPs. Figure 4.3 shows the structure of this module. The structure of this model for all the tributaries are showed in Figures A27 to A36 in Appendix A. In brief, the model uses simple empirical equations to estimate the operational costs over a 30-year period. The key variables and required data were obtained from the literature, government records based on previous usage of BMPs, as well as consultation with local experts and water managers at the WSA. The empirical equations used to estimate the costs of BMPs at sub-catchment and tributary scales were summarized in Table 4.1 and explained below. All costs were annualized. One-time capital costs were annualized over a 30-year period. Similar to the water quality module, the impact of wetland related BMPs on altering effective areas was considered to estimate the cost of implementing these practices. For instance, if wetlands were continued to be drained, the effective tributary area and nutrient delivery would be increased in long term; therefore, more practices (and higher budget) would be needed to improve water quality.

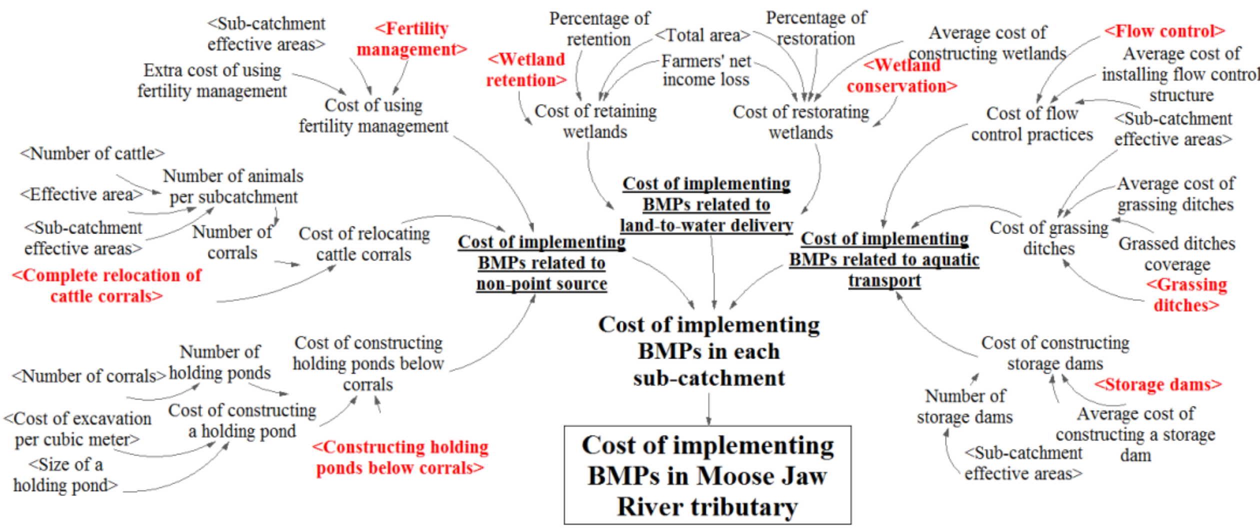

Figure 4.3 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in the Moose Jaw tributary.

CHP: Equation 4.1 was used to estimate the cost of CHP by considering the number of holding ponds to be built per sub-catchment effective area and the average cost of excavating a pond. The number of holding ponds was assumed to be equal to the number of corrals in the sub-catchment effective area. The number of corrals in each sub-catchment effective drainage area was calculated by estimating the number of animals per effective drainage area and considering that on average each corral, includes 200 cows. The cost of excavation was estimated by assuming that the volume of a holding pond was about 3980 m^3 (DED, 2017). The excavation cost was assumed to be $\$4/m^3$, which was a reasonable estimate based on prices in the local market proposed by excavation companies. Implementation of this BMP would often be sufficient to retain nutrients from corrals and improve water quality in downstream creeks.

CRC: The cost of CRC in each sub-catchment was estimated using Equation 4.2, which considers an average cost for an operation of relocation and the number of corrals in the sub-catchment effective drainage area. The cost of CRC (i.e., $140K annualized over 30 years) included the costs for engineering consulting, preparation of the new site, permanent shelter, permanent windbreak, as well as water and electricity at the new site. These costs were found based on the local market prices in Saskatchewan. The estimated cost of CRC varies across Canada, e.g., about $109K in Alberta (Wuite et al., 2007). It should be noted that new sites for accommodating corrals are often chosen based on comprehensive environmental risk assessments e.g., analysing the topography, soil characteristics, and hydrological conditions (Alberta Agriculture and Forestry, 2015). In addition, the operations of corral relocation require an approval issued under the authority of The Agricultural Operations Act. Thus, it is supposed that by relocating corrals to new sites, which are in non-contributing areas, the nutrients from corrals would not reach the mainstream anymore; therefore, this practice can improve water quality in downstream water bodies. As a result, relocation of corrals which nulls the necessity of CHP and these two practices cannot be implemented simultaneously.

UFM: As agricultural producers often use regular fertilizers to increase land productivity, fertility management techniques can be used to reduce downstream nutrient loading. This suite of practices includes a wide range of solutions such as variable rate application, split application, and reductions in application rate. While this topic has been studied (e.g., Simonne and Hutchinson,2005; Lui et al., 2019), net costs or efficacy of these practices is poorly understood. For the purposes of this study, it was assumed that these practices cost farmers a net \$10/acre/year and an efficacy of4.2% if the cropland represents 100% of the effective drainage area in a tributary. The cost of this practice was calculated by considering the cropland area in the sub-catchment effective area and the extra cost related to UFM (see Equation 4.3).

CSD: Although there is a relationship between the size of small dams and their impact on reducing nutrients (Tiessen et al., 2011), only one size of storage dams,15.7 acre-foot, was considered here for the sake of simplicity. This is a common size for small storage dams in the Prairies. In consultation with the WSA, it was assumed that one dam per 5.4 km^2 of effective drainage area can be implemented, similar to Tiessen et al. (2010). The cost of implementing one dam was assumed to be equal to \$100K annualized over 30 years, which includes the cost of construction and the engineering design. Equation 4.4 was used to estimate the cost of CSD considering their average cost of construction and the number of dams per sub-catchment.

FCP: This BMP consists of an earthen berm with a culvert in constructed ditches. Such a structure is commonly used throttle flows from wetland drainage and reduce downstream peaks. FCP can improve water quality and reduce downstream velocities to control soil erosion and reduce sediment delivery. Equation 4.5 was used to estimate the costs associated with the implementation of FCP. In brief, the average cost of installing a single structure is about $3K annualized over 30 years based on common practice in eastern Saskatchewan. This practice is usually implemented at a density of one structure for every km^2 of the effective drainage area.

GRD: Equation 4.6 was used to estimate the cost of implementing this BMP. It was assumed that the ditches cover one acre per quarter section (160 acres) of effective drainage area. Thus, the percentage of coverage area for ditches was assumed to be 0.006% of the sub-catchment effective drainage area. Moreover, it was assumed that seeding 1 acre of ditches would cost about $100 annualized over 30 years. This cost includes purchase of material, as well as payments for labour and equipment. In addition, the opportunity cost (or loss of income revenue) for annual croppers that can accrue from growing crop in the grassed area ($78/year/acre) was included in the calculations. This practice has been implemented in other regions, e.g., in Virginia, USA, where its effectiveness in reducing sediment erosion has been observed (Lang et al., 2016).

WRT: The cost of retaining wetlands includes the opportunity cost for annual croppers that can accrue from growing plants in drained wetland areas. Two commonly seeded crops, namely canola and spring wheat, were used to calculate the farmers' income loss if wetlands are retained instead of being drained. The values for calculation of net incomes for crops were obtained from the Saskatchewan crop guides (MAS, 2020). An average income for the years between 2016 and 2019 was considered in this study. Equation 4.7 was used to estimate the cost of retaining existing wetlands, which is about 78 $/acre/year. This BMP has been implemented in other Canadian Provinces. For instance, the cost of WRT was estimated to be between 91 and 169 $/acre in Ontario (DUC, 2011). The cost of wetland drainage in Saskatchewan was estimated by Dollevoet et al. (2008) to be between $72/acre and $435.45/acre depending on the size of the riparian area and other specific conditions. In another study, the opportunity cost for farmers considering retention or restoration of riparian areas was estimated to be around $8/acre and up to $219/acre (Jeffrey et al., 2014).

WCN: Equation 4.9 was used to calculate the cost of WCN by summing up the cost of retaining the existing wetlands and restoring the drained ones. Restoration of the small palustrine marsh type wetlands in this region is usually accomplished by construction of an earthen plug which replicates original spill elevation of the wetland. The cost of restoring the drained wetlands was calculated by considering the cost of constructing wetlands and farmers' net income loss, similar to WRT. The cost of constructing a wetland includes the excavation cost of $500 and a cost for technologist investigation equal to $600 annualized over 30 years. Using Equation 4.8, the cost of restoring a wetland was estimated to be about 3440 $/acre and calculated for a 30-year lifespan. This practice was commonly applied in other Canadian regions. For instance, the cost of wetland restoration in Ontario is 3791 $/acre for a 30-year lifespan (DUC, 2011) and is about 2000 $/acre for 10 years of lifespan in Saskatchewan (Hershmiller et al., 2014).

Table 4.1 Equations used to estimate the costs of implementing BMPs per tributary in the SD-Qu'Appelle model, where n represents the total number of sub-catchments per tributary.

$Cost\ of\ CHP\ (\$) = \sum_{i=1}^{n} Average\ cost\ of\ constructing\ one\ holding\ pond \times Number\ of\ holding\ ponds\ in\ sub-catchment\ effective\ area_i$	(4.1)
$Cost\ of\ CRC\ (\$) = \sum_{i=1}^{n} Average\ cost\ of\ relocating\ one\ corral\ \times Number\ of\ corralsin\ sub-catchment\ effective\ area_i$	(4.2)
$Cost\ of\ UFM\ (\$) = \sum_{i=1}^{n} Extra\ cost\ of\ using\ slow\ release\ fertilizer\ on\ average \times Cropland\ area\ in\ sub-catchment\ effective\ area_i$	(4.3)
$Cost\ of\ CSD\ (\$) = \sum_{i=1}^{n} Average\ cost\ of\ constructing\ one\ dam \times Number\ of\ storage\ dams\ insub-catchment\ effective\ area_i$	(4.4)
$Cost\ of\ FCP\ (\$) = \sum_{i=1}^{n} Average\ cost\ of\ installing\ oneflow\ control\ strcuture \times Number\ of\ structures\ insub-catchment\ effective\ area_i$	(4.5)

Table 4.1 Equations used to estimate the costs of implementing BMPs per tributary in the SD-Qu'Appelle model, where n represents the total number of sub-catchments per tributary (cont'd).

$Cost\ of\ GRD\ (\$) = \sum_{i=1}^{n} Average\ cost\ of\ grassing\ one\ ditch \times Percentage\ of\ ditch\ coverage\ area\ per\ sub-catchment\ effective\ area_i \times Sub-catchment\ effective\ area_i$	(4.6)
$Cost\ of\ WRT\ (\$) = \sum_{i=1}^{n} Net\ income\ loss\ \times\ Wetland\ coverage\ area_i$	(4.7)
$Cost\ of\ restoring\ wetlands\ (\$) = \sum_{i=1}^{n} (Net\ income\ loss + cost\ of\ construction) \times Drained\ wetland\ coverage\ area_i$	(4.8)
$Cost\ of\ WCN (\$) = Cost\ of\ retaining\ wetlands\ +\ Cost\ of\ restoring\ wetlands$	(4.9)

4.4 Results and discussions

The SD-Qu'Appelle model was run under all possible combinations of noted BMPs, i.e., single implementation, and application of 2, 3, …, and 6 practices simultaneously, leading to a total of 143 scenarios. Figure 4.4 presented a summary of analyses in this study. In brief, single and joint impact of BMPs across tributaries were evaluated and optimal BMPs at the tributary and watershed scale were identified. Finally, the impact of stakeholders' chance of adopting BMPs on reaching water quality targets was assessed.

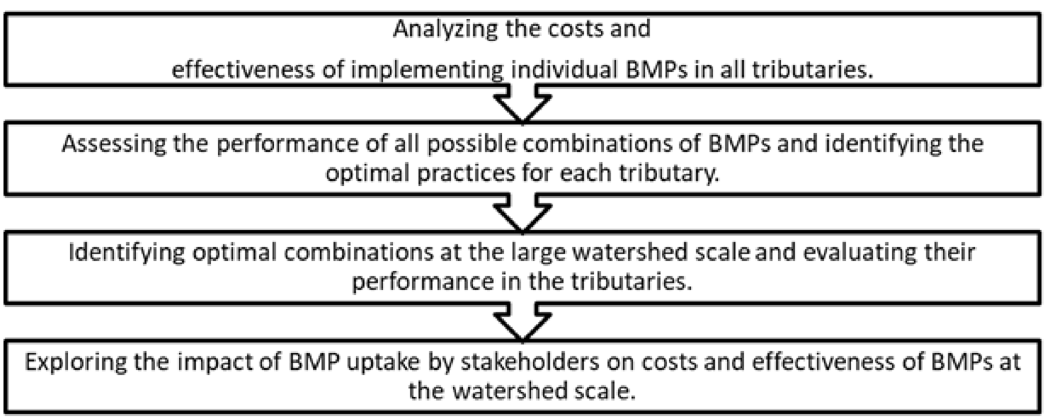

Figure 4.4 Flowchart showing the cost-effective analyses performed in this study.

4.4.1 Implementation of single BMPs

The total (absolute) cost of implementing individual BMPs as well as their associated percentage of reduction in long-term annual average TN and TP vary within and among tributaries (see Figure 4.5). This variation stems from inherent characteristics of tributaries e.g., land, climate, and stream flow conditions, as well as the number of animals, fertiliser application rates. As it can be seen, wetland related practices can significantly (in some tributaries by more than 100%) reduce nutrient exports. This is logical because as noted earlier, to represent the impact of WRT, negative impacts of draining wetlands and consequently augmentations in the effective area in long term were considered. The impact of WRT was therefore calculated based on the relative difference between nutrients under drained wetland conditions (i.e., considerably large effective area) and corresponding nutrients under existing wetland coverage area (i.e., current effective area).Such high changes in nutrients as a result of retaining/draining wetlands were also available in the literature .For instance, it was found that draining wetlands in the Black River sub-watershed in Ontario, Canada can increase TN and TP by about 260% and 860%, respectively (Ducks Unlimited Canada; 2011; Yang et al., 2016). Similarly, Pattison-Williams et al. (2018) showed that an increase by 145% in TP may occur if 100% of the wetlands in the Smith Creek watershed, Saskatchewan were lost. While full implementation of wetland BMPs requires the highest total cost, corral related BMPs were relatively less costly and could moderately reduce TN (by ~26%)in the QARB. Other practices such as FCP, UFM and GRD presented the lowest total reduction of nutrients.

Considering the tributaries, WCN can reduce TN by 56% but it is considerably costly ($148.4K), while CHP can have a comparable effectiveness in reducing TN for just $5.3K (96% less cost) in Ridge Creek. In contrast, in the Moose Jaw River, CHP cannot reduce TN by more than 25%, while WCN can reduce TN by more than 100% but with a higher total cost. Across many of the small tributaries, corral related BMPs can significantly reduce total loads at a lower total cost than wetland related BMPs. This result is likely due to their small wetland coverage and small effective areas. Given the uncertainty in watershed processes, these results might be best viewed as relative ranking/comparison of BMPs rather than an absolute prediction of nutrient abatement.

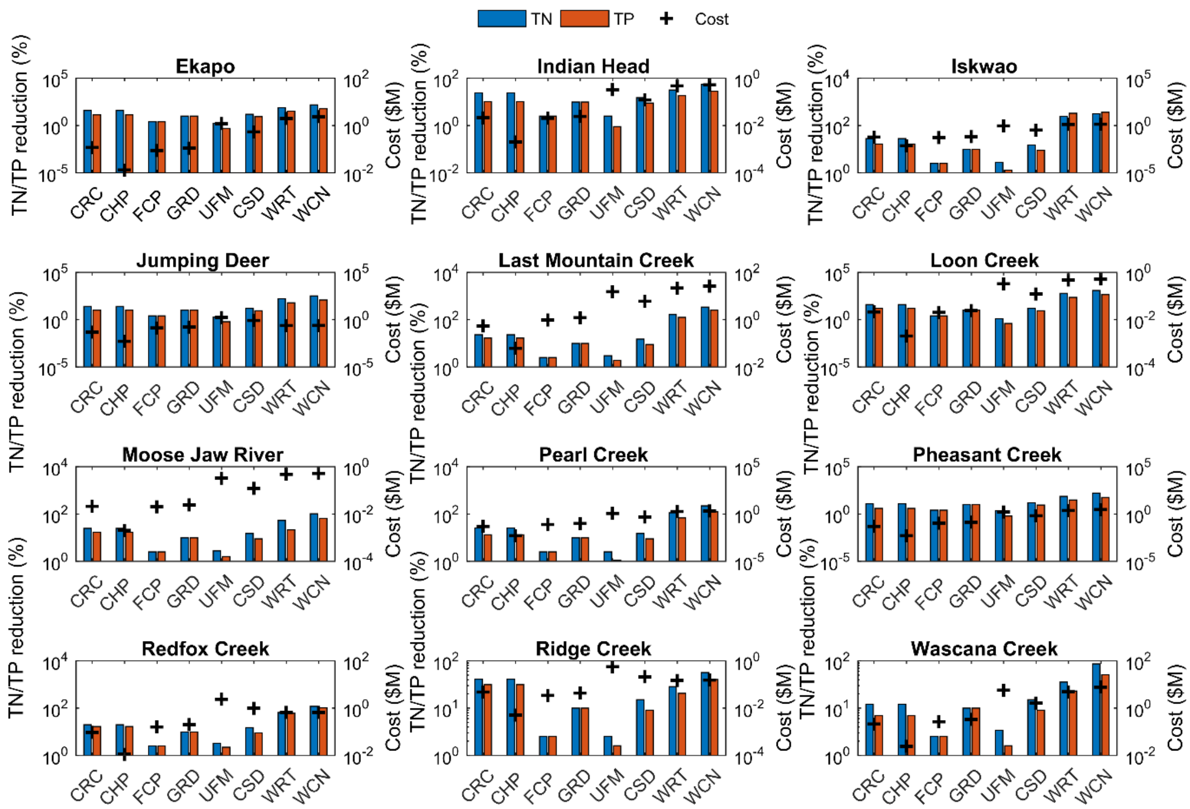

Figure 4.5 Percentage of long-term annual average reduction in TN and TP as well total costs (averaged over 30 years)associated with the implementation of each BMP in the tributaries.

The presented absolute costs in Figure 4.5 provided a general idea about the budget that should be allocated to improve water quality management in the tributaries and in the QARB as a whole. In addition, relative costs (costs per kilogram of nutrient abatement) were calculated to represent the worth of allocating such budgets to each practice. The relative cost is a proxy often used by policymakers in this area to compare BMPs. Although wetland related BMPs have an extremely high absolute cost, since they are effective, they present a low relative cost (~ $200 per kg of N removal). Corral-related BMPs had the lowest total cost (e.g., $3/kg for CHP). The UFM, FCP, and CSD showed the highest relative cost per kg of N removal. Relative costs for removal of TP followed a similar pattern as of TN.

The analyses in this section highlighted the need to assess BMPs for each tributary instead of prescribing the same BMPs for all tributaries in a large watershed and assuming that the effectiveness and costs of the practices would be the same across the entire basin. Moreover, as individual BMP can affect nutrient delivery in different ways and it is common to use a set of practices in agricultural areas, it is critical to evaluate the performance of combination of BMPs, which can be applied simultaneously, to maximize nutrient abatement in a watershed.

4.4.2 Information matrices and optimal BMPs at the tributary scale

All possible combinations of BMPs were simulated and cost-effectiveness analyses were tabulated in a series of "information matrices". The matrices were provided in 6 panels corresponding to 6 different combinations of BMPs. As an example, here the matrices for the Moose Jaw tributary were shown in Figure 4.6. In each panel, the implemented BMPs in the analyses were shown by dark grey cells in each row (see 1st to 8thcolumn from the left), and their impact on TN and TP and associated total cost of their implementation at the tributary scale were shown in three columns from the right. The ranges for percentages of change in nutrients and the costs of implementing BMPs were shown with color bars. As an example, the top left information matrix presents the results for implementation of single BMP, similar to what has been shown in Figure 4.6 for Moose Jaw, showing that conserving the wetlands (1st row from the top) and retaining wetlands (2ndrow from the top) are the most effective with the highest total cost in comparison to the rest of BMPs in this tributary. The top right panel in the figure shows combinations of two BMPs. Six of these combinations can reduce TP by around 70% and TN by more than 100% (see top 6 rows). The absolute costs of implementing 5 of them is less than $20M (see top 5 rows). In fact, the lowest-priced combination is implementing FCP and WCN with a total cost of $16.9M. This combination is optimal from both improvements in water quality and economic aspect. Some combinations might cost less than $1M, but their effectiveness would be also less too e.g., CHP and GRD would cost only about $856K but cannot reduce more than 32% in TN.

In addition to providing all possible options, optimal sets of BMPs in each tributary were also identified based on their relative cost per abatement of nutrients. Table 4.2 shows these optimal BMP combinations for the Moose Jaw River tributary. As expected in all cases, at least one wetland-related BMP e.g., WRT, appeared due to its effectiveness in eliminating more than 100% of the N relative to current loading to downstream. For instance, the combination of WCN, along with GRD and CHP is among all BMP scenarios as its relative cost is around $86 per kg of N removal and reduces TN by 139% in this tributary. These BMPs can also reduce TP by 85% for $414 per kg of P removed.

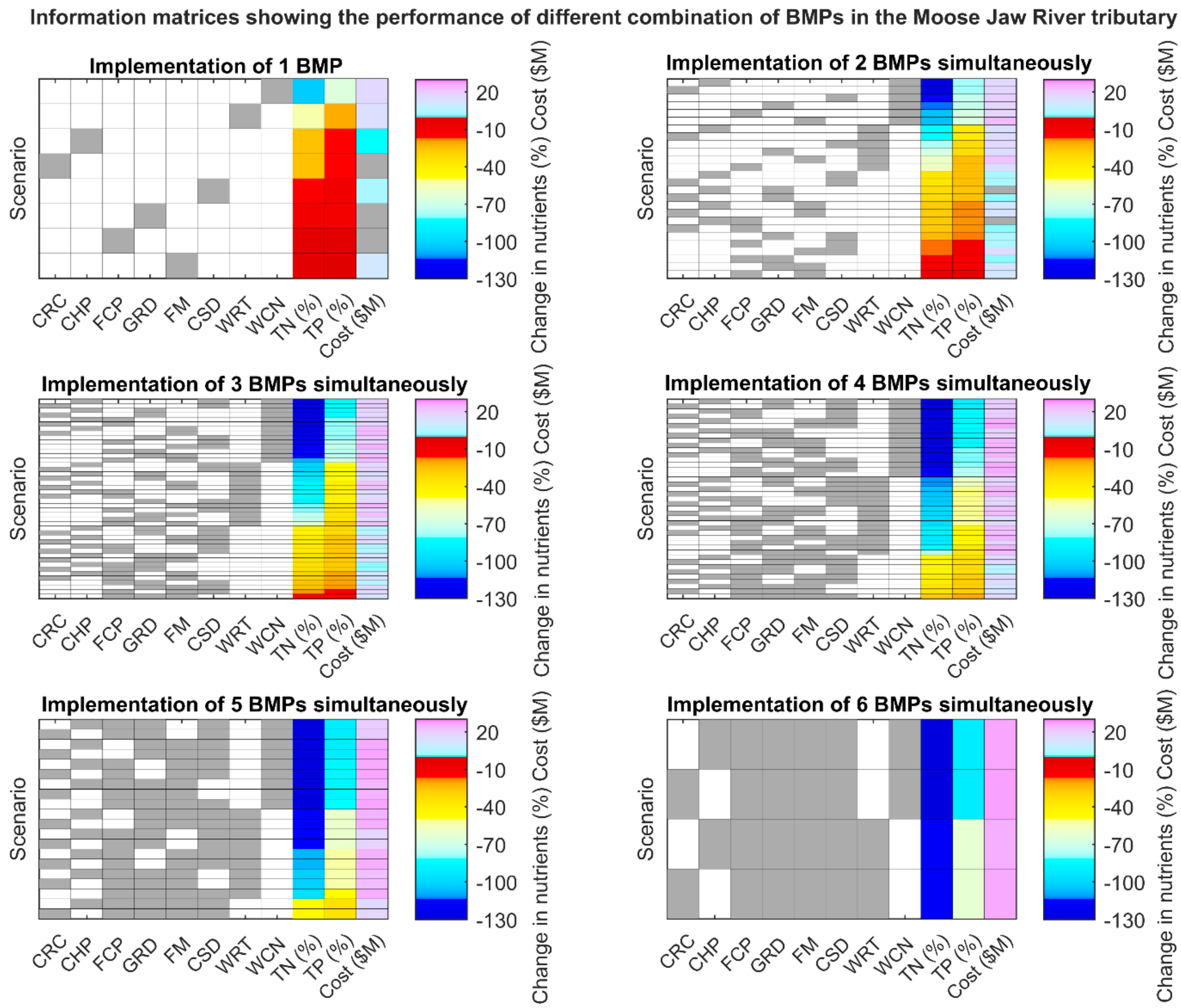

Figure 4.6 Six information matrices, corresponding to implementing different combination of BMPs simultaneously in the Moose Jaw River tributary. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

Information matrices along with optimal BMP combinations are available for the rest of tributaries – see Figures A37 to A47, and Table A1 in the Supplementary Material. It can be observed that the cost and effectiveness of BMP combinations vary among tributaries. For instance, retaining wetlands can be sufficient to improve water quality significant in the tributaries that the wetlands were not heavily drained (see rows 3 to 8 in Table A1). While in other tributaries, both retaining and restoring wetlands, as well as constructing ponds were needed due to existence of high animal population and large drained lands in these tributaries (see the 1st and 2nd rows in Table A1). The cost of implementing BMPs depended mainly on the size of tributaries. For example, WRT in Last Mountain costs 3000% more than Loon Creek and ensures lower abatement rate. Such analyses can assist stakeholders exploring the impact and cost of a wide range of BMPs within and among tributaries.

Table 4.2 Optimal combinations of BMPs, selected based on their relative cost of implementation per abatement of nutrients in the Moose Jaw River tributary.

Number of applied BMPs	Optimal combination of BMPs	Changes in TN (%)	Cost per kg of TN abatement ($/ kg)	Changes in TP (%)	Cost per kg of TP abatement ($/ kg)	Total cost of implementation ($M)
1	WCN	-103	112	-65	541	16.5
2	WCN, GRD	-113	105	-73	505	17.0
3	WCN, GRD, CHP	-139	86	-85	414	17.1
4	WRT, FM, GRD, CHP	-112	108	-58	521	17.3
5	WCN, CSD, GRD, FCP, CHP	-151	91	-91	440	19.6
6	WCN, CSD, FM, GRD, FCP, CHP	-153	120	-92	578	26.2

4.4.3 Optimal combinations for varying abatement targets at the watershed scale

Optimal BMP combinations were also explored for different nutrient abatement targets at the scale of QARB. For this purpose, we identified all combinations of BMPs with the lowest total cost of implementation that correspond to high reduction (more than 100%) and moderate reduction (between 30% and 100%)in nutrients on average across all tributaries. The results for these scenarios were respectively shown in the top and bottom rows of Figure 4.7. Moving from left to right, the maps show the percentages of reduction in TN and TP as well as total cost of implementing BMPs in individual tributaries. Implementation of WRT and GRD, corresponding to high reduction scenario, can lead to an expected decrease of 160% for TN and 100% for TP across all tributaries with low costs. The individual rates of changes in TN and TP, and total costs of implementing these BMPs were shown in the top row. The highest and lowest reductions in nutrients were observed in the Loon Creek and the Ridge Creek, respectively. The total cost of implementing these BMPs varies among tributaries and the highest cost corresponds to the Moose Jaw River, one of the largest tributaries in the watershed.

Implementing GRD, CHP and CSD together can result in moderate reductions in the nutrients on average across QARB. The highest and lowest rates of nutrient reduction were found in Ridge Creek and Pheasant Creeks, respectively. The highest cost of implementing these BMPs belongs to the Last Mountain Creek tributary, which is the largest tributary in the basin. It should be noted that there are other BMP combinations that are more effective than this set, e.g., joint application of CRC, GRD, FCP, UFM, and CSD, however, their total cost is significantly higher. Indeed, it can be also inferred that moderate nutrient abatements can be achieved in the QARB without the need to pay for wetland-related practices.

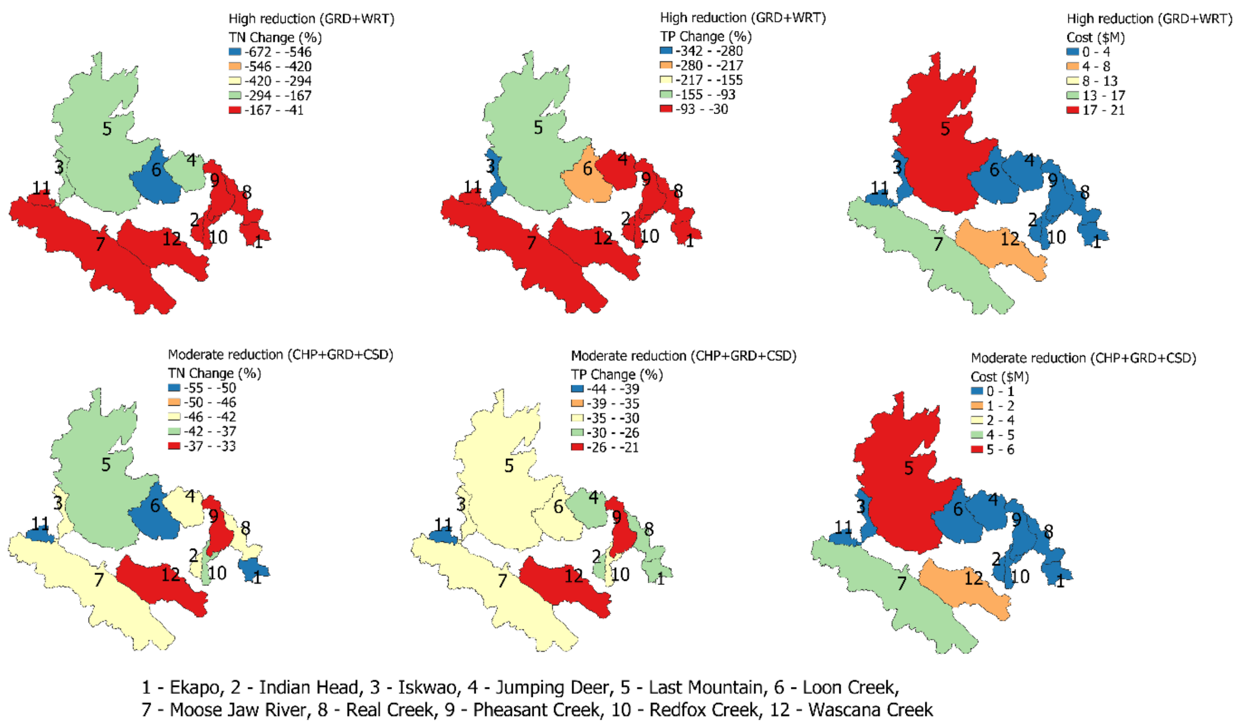

Figure 4.7 Ranges of abatements in TN and total costs of implementation for combination of BMPs with the lowest total cost of implementation for the highest (top row) and moderate (bottom row) rates of reduction in nutrient across the QARB, respectively.

4.4.4 Impact of BMP uptake by stakeholders

In the former sections, the costs and effectiveness of BMPs at tributary and watershed scales were presented assuming that when BMPs are chosen, they would unanimously be implemented by all agricultural producers in the region. However, all stakeholders might not necessarily be willing to adopt these BMPs due to various reasons, indicated in Bradford et al. (2020). Therefore, the costs and effectiveness of BMPs may shift and estimated target levels might not be achieved. In this section, we focused on analyzing the performance of previously identified sets of BMPs corresponding to high and moderate reductions in nutrients, if they are not fully adopted by stakeholders. The results of these analyses were shown in Figure 4.8, which contains 2 panels corresponding to two levels of nutrient abatements. The ranges of changes in TN, TP and costs were provided in the right columns. In each row, the dark grey, light grey, and white cells correspond respectively to a 100%, 50%, and 0% chance of BMP implementation by stakeholders, respectively. For example, a 50% chance of adoption for CHP means only 50% of farmers, instead of all of them, would implement this BMP in their farms.

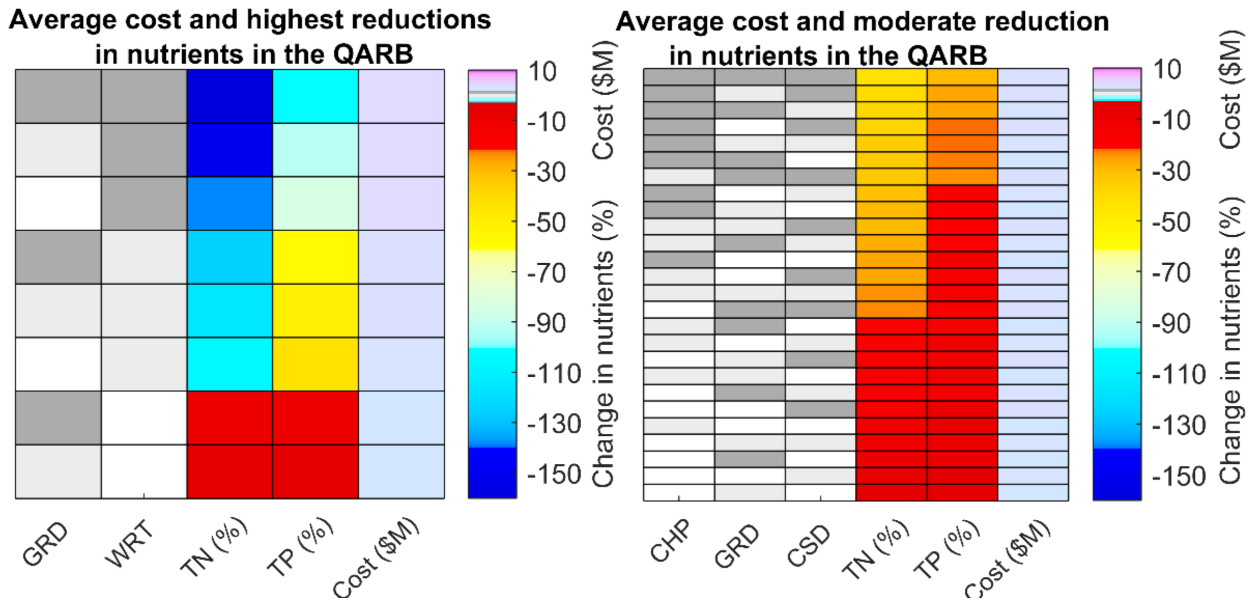

Figure 4.8 Expected reduction in TN and TP and associated total cost of implementing BMPs considering no adoption (white cells), full (dark grey) and partial (light grey) adoption of BMPs by stakeholders in the QARB.

As previously mentioned, and here shown in the top row and left panel, if WRT and GRD are adopted unanimously by all stakeholders, TP can be reduced by around 100%on average across the QARB. The percentage of abatements in TP can decrease significantly from 100%to about 50%, if half of the stakeholders instead of all of them implement these BMPs (see the 5throw in this panel). This is an important observation, revealing the role of stakeholders in improving water quality in the region. There are still other combinations of BMPs that even if are not fully adopted by all stakeholders, they can still reduce nutrients (see for instance the 3rd row from the top). Similar observations were made for BMPs that lead to moderate reduction around 43% for TN and 30% for TP, respectively across the QARB tributaries (see the top row in the right panel of Figure 4.8). Here, if the same BMPs were adopted by half of the producers, TN would be reduced by only 23% and TP by 16%, which was considered relatively non effective in this study. Therefore, a collaboration of more than 50% of stakeholders in implementing these BMPs are required to achieve targeted reduction rates in water quality conditions.

4.5 Conclusions

This study proposes a generic approach to analyze the costs and effectiveness of agricultural BMPs, related to cattle and crop farms, with a greater goal of proposing practices that can improve water quality. For this purpose, the impact of BMPs on nutrient exports as well as their costs of implementation at the tributary and watershed scales were estimated using the water quality and economic evaluation models. The changes in TN and TP as well as the total cost of implementing all possible combinations of BMPs at the tributary scale were summarised in a set of information matrices. These matrices can be used to facilitate discussions of stakeholders and policymakers about BMPs. Accordingly, the optimal combinations of BMPs at the tributary as well as watershed scales were found based on two different criteria i.e., practices with the lowest total cost of implementation and most positive impact on water quality, as well as considering their relative cost per kg of nutrient abatement. Such analyses can assist in selecting combinations of BMPs based on the available budget and targeted levels of water quality improvements. Finally, as stakeholders might not be willing to implement the considered BMPs unanimously, the costs and effectiveness of BMPs corresponding to different chances of BMP uptake were also analyzed.

This study has several implications for QARB. In brief, corral related BMPs can moderately reduce nutrients loads at a more cost-efficient manner than other BMPs. Wetland-related BMPs are costly but highly effective. Therefore, their relative cost per removal of nutrients were reasonable. The costs and potential nutrient abatement by BMPs vary among tributaries due to their different characteristics such as climate, land, and streamflow conditions as well as number of animals and fertilizer application. Moreover, our analyses shed light on the role of stakeholders on the final costs and effectiveness of BMPs at the tributary and watershed scales. It was found that at least more than 50% of the stakeholders should implement the proposed BMPs to achieve the targeted improvement in water quality conditions. This issue has been often under-represented in the literature.

Although the presented analyses were generic, there were some limitations in this study that must be taken into account for local decision-makers. For instance, while wetlands are one of the key features of this watershed, limited data records about the historical, current, and drained wetland coverage area, their locations, as well as vegetation cover was available. For instance, our study showed that the cost-effectiveness analyses of BMPs and the selection of optimal BMPs were sensitive to the considered wetland coverage areas. Moreover, the exact number of animals and corrals near the creek were not available for this basin. Therefore, considered assumptions in this regard can affect the analyses. Moreover, the results of our analyses focused on the impacts of BMPs in long term i.e., 30-year period whereas the effectiveness of the BMPs can vary seasonally as well as in shorter durations (Woznicki et al., 2012; Baulch et al, 2019). Therefore, an assessment of BMPs in finer temporal resolution is essential. For this purpose, more field-based research is also required to monitor and measure the effectiveness of BMPs in the tributaries of the QARB. In addition, our analyses were based on the assumption of stationarity in the climatic conditions (Milly, 2008). However, recent studies show that the characteristics of temperature and precipitation would change in this region (e.g., see Morales-Marín et al., 2018). Therefore, it is recommended to assess the impact of climate change on water quality as well as costs and effectiveness of BMPs. It should be also noted that there are uncertainties related to the estimation of BMPs' costs, as all-encompassing literature and data records to validate our results were not available. With that said, our estimated costs of applying BMPs were in acceptable ranges considering previous operations in other places in Canada. Nevertheless, as the utilised model structure is quite extensive, it is relatively easy to revise the input data and/or update the equations to improve the model accuracy. Regardless of the limitations, this study presents a set of analyses that are not only useful for local stakeholders but also for assessing the impact of BMPs in other basins. Moreover, this study showed the importance of engaging local stakeholders in decision-making processes to increase their chance of BMP adoption to improve the water quality at the watershed scales.

Acknowledgement

This project was funded by the Environment and Climate Change Canada Environmental Damage Fund (417544-1323-8000), as well as the Programme PIED of Polytechnique Montréal. The authors would like to thank the Saskatchewan Water Security Agency for supporting this project.

CHAPTER 5 ASSESSING THE EFFECTIVENESS OF AGRICULTURAL BENEFICIAL MANAGEMENT PRACTICES UNDER CHANGING CLIMATE CONDITIONS

5.1 Methods and materials

5.1.1 Optimal combinations of BMPs

In this chapter, the QARB was divided into 3 different zones. Zone 1 covers three upstream tributaries of Moose Jaw River, Iskwao and Ridge Creeks. Zone 2 corresponds to middle stream tributaries i.e., Wascana Creek, Last Mountain tributary and Loon Creek. Zone 3 covers all the 12 tributaries in the QARB. A simple schematic of the QARB in Saskatchewan is presented in Figure 5.1, where the tributaries are shown with rectangles and the mainstream (QR) is displayed by a dark blue arrow.

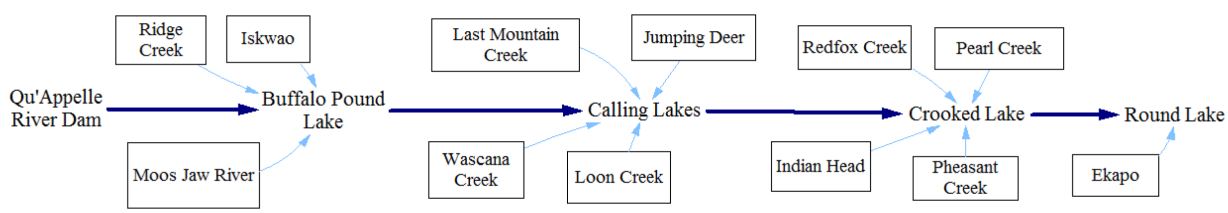

Figure 5.1 A simple schematic of the QARB in Saskatchewan, Canada, where rectangles show the main tributaries, dark and light blue arrows shows the mainstream (QR), and rivers reaching the mainstream, respectively.

Zammali et al. (2020) performed a set of cost-effectiveness analyses and among 143 (all possible) combinations of noted BMPs, they identified sets of practices that together can considerably reduce nutrients with low costs of implementation in the QARB. Table 5.1 shows these combinations for three zones. In Zone 1, the combination of CHP, WRT, CSD and FCP were identified as optimal, as they can potentially reduce TN and TP by 151% and 85%, respectively with the operational cost of $21M. In Zone 2, WRT and GRD were identified as optimal combinations that can reduce TN and TP by 141% and 99%, respectively with total cost of implementation estimated by $27M. The combinations of WCN and GRD were selected as the optimal combination that can eliminate TN and TP with cost of implementation less than $59M in Zone 3. In most of the cases, WCN alone was the costliest but could reduce TN and TP more than using all the rest of BMPs simultaneously. In addition, using combinations of BMPs that include wetland related practices may result into nutrient reduction by more than 100%. This can be explained by the fact that the impact of WRT was incorporated in the model in a way that it reflects the reversed impact of wetland drainage. Therefore, changes in nutrients when these BMPs are implemented were estimated considering the potential TN and TP that could have been delivered to downstream over the years if wetlands would have been drained.

Table 5.1 Total, effective drainage, and cropland coverage areas, number of cattle and the optimal combinations of BMPs in the three Zones of the QARB.

Zone	**Tributaries**	**Total area (km^2)**	**Effective drainage area (km^2)**	**Cropland area (km^2)**	**Number of cattle**	**TN before implementation of the BMPs (ton/year)**	**TP before implementation of the BMPs (ton/year)**	**Optimal BMP combinations**	**Number of cattle**
Zone 1	Ridge Creek, Iskwao Creek, Moose Jaw River	9337	4597	3448	36500	129	24	WRT, CHP, GRD, CSD	36500
Zone 2	Last Mountain, Wascana,Loon Creeks	18635	5906	4430	34000	161	26	WRT, GRD	34000
Zone 3	All tributaries	35619	12836	9627	86608	349	64	GRD, WCN	86500

These optimal sets of BMPs were identified using the Long-term Annual Temperature (LAAT) and Long-term Annual Precipitation (LAAP) and assuming that these climatic conditions remain unchanged in time. However, over the past few decades, the LAAT and LAAP in the QARB have been increased by 1.9 °C and 7%, respectively (ECCC, 2020). Considering an ensemble of CMIP5 models under RCP 2.6 and RCP 8.5, Zang et al. (2019) predicted increases of LAAT between 1.9 °C and 6.5 °C and increases in LAAP between 6% and 15% by the end of this century in the Prairies. Other studies projected higher increases in precipitation (Mailhot et al., 2012) and high temperature values (Jeong et al., 2016) for this region. Moreover, an average increase in temperature and precipitation by 200% and 9%, respectively, was expected for this region by the end of the century (ECCC, 2020). In other studies, an average increase in LAAT between 3°C and 4.5 °C and in LAAP between 6% and 9% was projected. However, reductions in LAAP based on individual models were also reported (Moose Jaw Climate Data by Atlas Canada, 2020).

The main objectives of this chapter were to (1) assess the nutrient export in the QARB zones under all possible climate conditions; (2) evaluate the effectiveness of previously identified optimal BMPs under changing climate conditions; and (3) find new ensembles of practises that can still improve water quality in the QARB zones with low costs in the future. For this purpose, bottom-up and top-down climate change impact assessments were used and explained below.

5.1.2 Impact assessment approaches and procedure

Bottom-up approach: Feasible ranges of -1°C to +8.5°C for LAAT and -15% to +40% for LAAP were considered for vulnerability assessment. These ranges are wide enough as they cover the climate projections for the Canadian Prairies (e.g., see Zhang et al., 2019). Considering an increment of 0.5°C for temperature and 5% for precipitation, the entire range of climate change surface included 240 combinations (20×12). The generated LAAP and LAAT under these combinations were fed to the SD-Qu'Appelle to estimate the TN and TP in each of the QARB zones, without considering any BMPs. Moreover, the effectiveness of previously found optimal BMP combinations, shown in Table 5.1, was assessed. For this, percentages of change in TN and TP in the QARB zones were estimated by comparing the nutrients considering the implementation of BMPs under each of specific climate conditions (out of 240 combinations) and the nutrient values under historical climate, when no BMPs were implemented.

Top-down approach: Bias-corrected and spatially-downscaled precipitation and temperature projections for 20 GCMs at a 25 km × 25 km grid scale were obtained from https://www.nccs.nasa.gov/services/climate-data-services. The projections under RCPs 4.5 and 8.5 over the period of 2025-2095 served in impact assessment. The projections of climate models varied considerably. As an example, for the same tributary, projected LAAT based on models ranged between 4 °C to 8 °C. Moving time episodes each containing a 30-year period i.e., 2025-

2054, 2026-2055, …, 2066-2095 were considered in the analyses to identify adaptation practices over time. LAAP and LAAT values under 20 GCMs and 2 RCPs for each of these 42 episodes were estimated by averaging model-based daily values over the thirty-year periods and fed to the SD-Qu'Appelle model. In order to find optimal sets of BMPs under future climate, the costs and effectiveness of all BMP combinations were analyzed in each future time episode given the expected projections of LAAP and LAAT under 2 RCPs. Accordingly, the performance of newly found optimal BMPs in each time episode was analyzed under the outputs of individual climate model and RCP to understand their extend of effectiveness in the future.

5.2 Results

5.2.1 Vulnerability in the QARB zones without considering BMPs

The estimated TN and TP leaving the QARB zones under the possible ranges of change in LAAT and LAAP were illustrated in Figure 5.2. The figure showed that the amounts of nutrients in all zones were more sensitive to augmentations than reductions in temperature and precipitation. Moreover, the changes in nutrients are more sensitive to variations in temperature than precipitation; however, their compound impact can be significant, see the top-right corner of panels. Furthermore, comparison between the two rows show that for the same temperature and precipitation conditions TP is more sensitive to changes in climate conditions than TN. Similar to Zone 3, the two other zones showed the same percentages of changes in TN and TP and the maximum increase in TN for all of the zones is around 400% and TP around 2000%. However, the magnetite of TN and TP loads are different and are higher in Zone 2 than Zone 1 and this is because two of the 3 largest QARB tributaries are located in Zone 2.

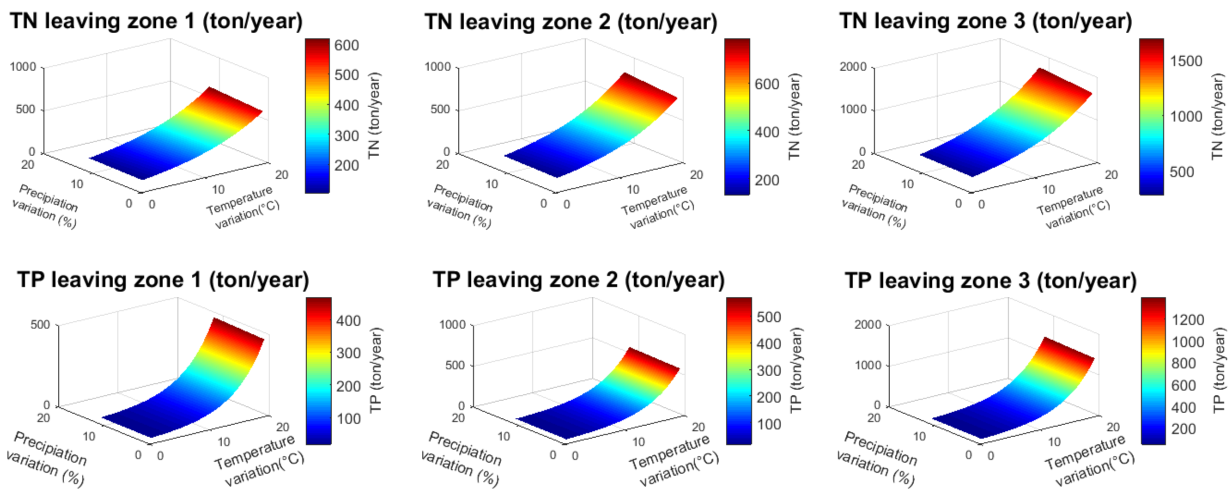

Figure 5.2 Long-term annual average TN and TP leaving QARB zones under a possible range of changes in LAAT and LAAP, without considering any BMPs.

5.2.2 Vulnerability in the QARB zones considering the existing optimal BMP

Relative changes in TN and TP in the QARB zones were estimated by considering the difference between nutrients after implementation of previously identified optimal BMPs under each climate conditions and the nutrients during the historical climate and no usage of BMPs. Moreover, temperature and precipitation projections of 20 GCMs under RCPs 4.5 and 8.5 were mapped on these panels with solid lines to illustrate the future climate paths.

The results for Zone 1 show that even with implementation of WRT, CHP, GRD, and CSD, TN and TP are still sensitive to changes in temperature and precipitation values (left panels).The highest abatement rates were found under the coldest climate with lowest precipitation rates, whereas the smallest reductions in nutrients correspond to the warmest climate with highest rate of precipitation. It is also observed that if temperature goes above 7°C, the considered combination of BMPs cannot reduce TN anymore. Changes in TP were more sensitive to any alterations in temperature than TN. For instance, TP can increase by more than 600% moving from low to high temperature values. Additionally, the considered BMPs cannot effectively reduce TP if the temperature increases by about 3°C.

As previously noted, WRT and GRD can reduce TN and TP by more than 100% under the historical climate conditions in Zone 2. However, their effectiveness in improving water quality in the future depends on the considered climate conditions as well as the type of nutrients (see middle panel in Figures 5.3 and 5.4). Similar to Zone 1, the highest and lowest abatement rates can be observed under the lowest and highest temperature values, respectively. These BMPs can still be considered effective in reducing TN if increases in temperature remain below 2.5°C. Unlike TN, the BMPs cannot reduce TP if temperature increases by 1°C.

Moreover, simultaneous implementation of WCN and GRD can reduce TN and TP by more than 100% in all the QARB zones under historical climate conditions (see right panels). As explained above, the total elimination of nutrients is a representation of the reversed impact of wetland drainage. However, the effectiveness of these practices is sensitive to changes in temperature conditions. For instance, if temperature increases by more than 2.5°C, these BMPs are not effective anymore in reducing TN and TP in the QARB. Moreover, for every degree above this threshold, the increase in TN and TP can be significant.

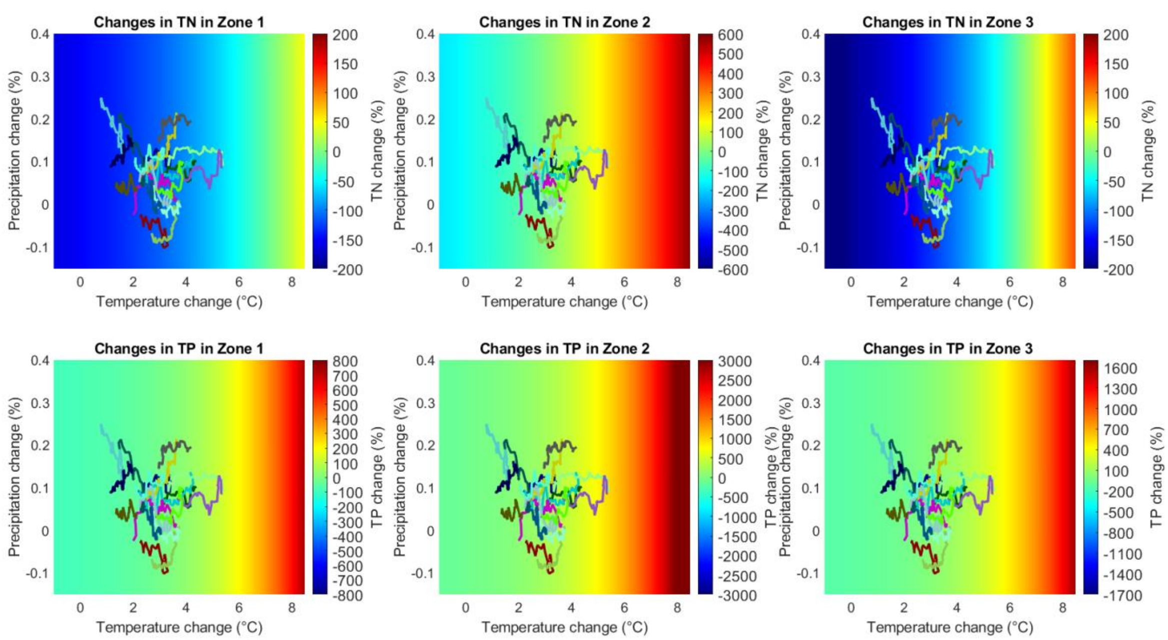

Figure 5.3 Relative changes in TN and TP in the QARB zones, estimated based on nutrients after implementation of BMPs under changing climate conditions and nutrients under historical

climate when no practices were implemented. Solid lines show the projected changes in temperature and precipitation under 20 GCMs and RCP 4.5 over the period between 2025-2095.

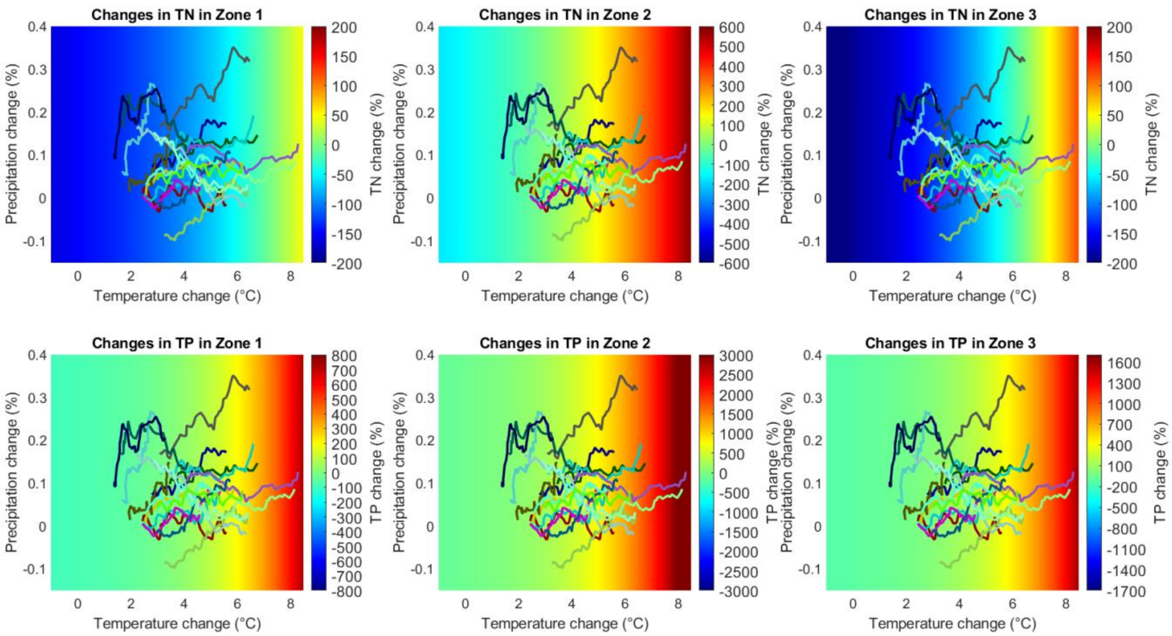

Figure 5.4 Relative changes in TN and TP in the QARB zones, estimated based on nutrients after implementation of BMPs under changing climate conditions and nutrients under historical climate when no practices were implemented. Solid lines show the projected changes in temperature and precipitation under 20 GCMs and RCP 8.5 over the period between 2025-2095.

By increasing TN and TP loads in the QARB, increasing temperature and precipitation affected the BMPs' effectiveness in reducing the nutrients. It is also clear that the effectiveness of BMPs in reducing nutrients depends on the considered climate conditions, as well as the type of nutrients and QARB zones. Considering TN, the optimal combinations for Zones 1 and 3 are expected to be relatively effective in reducing TN under RCP 4.5. However, the same BMPs may become ineffective in these two zones under RCP8.5. Results for the same zones show that the effectiveness of BMPs significantly decreases if increases in temperature go above 2.5°C. The BMPs in Zone 2 become ineffective in improving water quality under the projections of most GCMs considering both RCPs 4.5 and 8.5. This is because two of the three largest tributaries of the QARB are in Zone 2 and they correspond to high amounts of TN and TP loads. Therefore, in order to reduce system's vulnerability, it is essential to identify new combination of BMPs that can effectively reduce the nutrients with acceptable costs under future climate conditions.

5.2.3 Identification of optimal BMPs for the QARB zones under future climate conditions

Mean LAAP and LAAT values averaged over 20 GCMs under RCPs 4.5 and 8.5 were estimated for each of considered time episodes and fed to the SD-Qu'Appelle to find new sets of optimal BMPs in QARB zone in the future. The practices were considered optimal if they could totally eliminate or highly reduce nutrients for the lowest possible cost. The changes in the nutrients were estimated with respect to the historical climate conditions and if no BMPs were implemented. The pathways to adopt BMP combinations over time in the QARB zones under RCP 4.5 and 8.5 were illustrated using solid and dashed lines in the left and right panels of Figure 5.5, respectively. The triangles and circles indicate the starting and ending year for effectiveness of specific BMP combinations. The representation of the management plan in the form of metro cards was inspired from the pathway maps developed by Marchau et al. (2019). The changes in TN, TP, and cost of implementation of each combination of the BMPs identified for Zone 1, Zone 2, and Zone 3 were summarized in Tables B1, B2, and B3 in the supplementary material, respectively.

Our analyses showed that implementation of WCN, CHP, and GRD in Zone 1 can sufficiently reduce TN and TP up to the time episode 2032-2061 under both RCPs (see blue solid and dashed lines in left and right panels of Figure 5.5). Implementation of these two BMPs was not enough to improve water quality after these episodes. Therefore, FCP and CSD were also needed to increase the rate of abetment in nutrients. These new combinations were found to be effective until the episodes 2054-2084 and 2033-2062 under RCP4 and RCP8.5, respectively (see Table B1 in Appendix B). After these time episodes, TP starts to increase instead of being reduced. In addition, it is clear that under RCP 8.5 the optimal practices should be implemented earlier as its projected temperature conditions are higher than RCP 4.5. In fact, the abatement rate for the same combinations of BMPs is lower under RCP 8.5 (see Table B1 for comparison of the values).

In Zone 2 CHP and WCN can significantly reduce TN and TP up to the time episode 2036-2065 under RCP 4.5. Starting from the time episode 2037-2066, GRD was needed, for $1M more, to increase the abatement rate of nutrients. Interestingly the 3 BMPs, along with CSD were essential to reduce the nutrients delivery from the 2025 under RCP 8.5. Moreover, implementation of FCP along with CSD was required from the time episode 2045-2074 to improve water quality under RCP 8.5. Although implementing these 5 BMPs simultaneously can reduce TN significantly they cannot reduce any amount of TP under RCP8.5. In fact, TP amounts would be doubled by the year 2055-2084 under the high emission scenario (see Table B2 in the supplementary material for changes in TN and TP values). TP is highly sensitive to increases in temperature and precipitation which made it challenging to find BMP combination that can reduce it by the end of the century. Finally, it is important to note that the allocated budget to reduce nutrients under RCP 8.5 was estimated to be higher (around $2M more) than RCP 4.5.

WCN and CHP can reduce nutrients sufficiently in Zone 3 up to the time episode 2040-2070 under RCP 4.5. Implementing these practices along with GRD can be considered effective in reducing nutrients up to a much longer period (2050-2079). The latter combination of BMPs was identified as effective in reducing the nutrients under RCP 8.5 up to 2034-2063 episode. However, starting from the episode 2035-2064 TP loads starts to increase even if the BMPs are implemented. In addition to their higher abatement rate, the combinations of BMPs identified under RCP 4.5 are less costly than the combinations of BMPs identified under RCP 8.5. Starting from the time episode 2051-2080, the same cost would be spent under both RCPs ($70M), ensuring total elimination of TN while TP amounts are expected to be doubled under RCP 8.5 but moderately reduced under RCP 4.5 (50% or less of reduction in nutrients). These results correspond to the simultaneous implementation of WCN, CHP, GRD, FCP, and CSD (see Table B3).

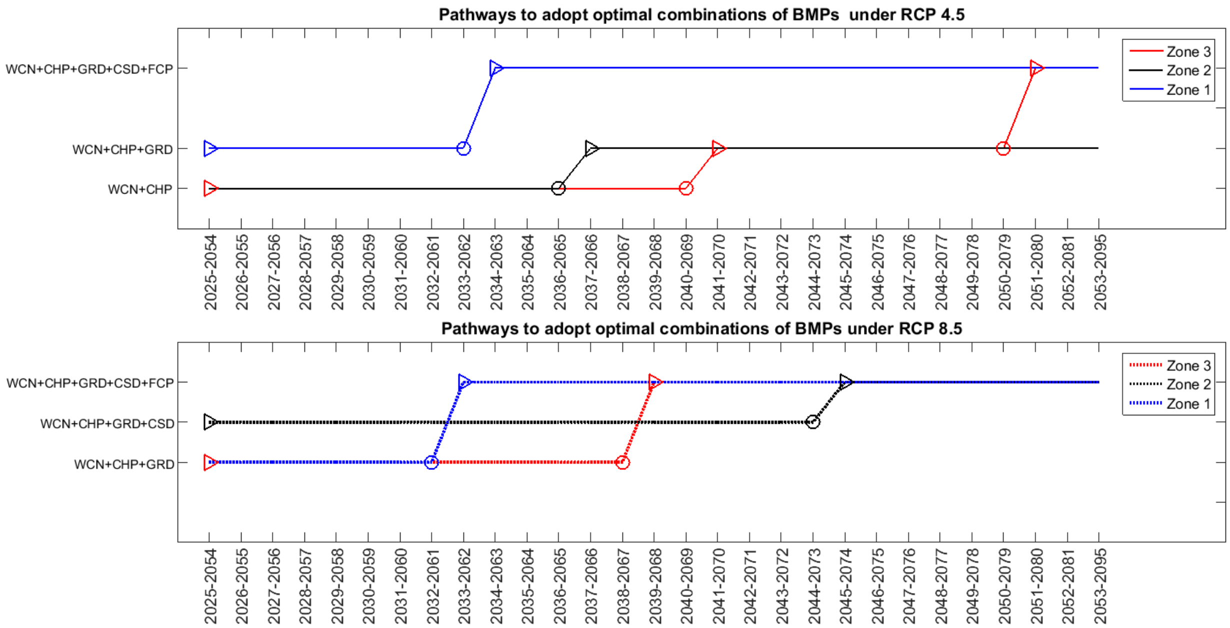

Figure 5.5 Pathways to adopt optimal combinations of BMPs in Zone 1(blue), Zone 2 (black) and Zone 3 (red) over time under RCP4.5 (solid lines) and RCP8.5 (dashed lines). The triangles and circles show the starting and ending episodes for effectiveness of specific BMP combinations.

Overall, CHP and WCN practices repeatedly appeared among the optimal sets of BMPs in the QARB zones to abate nutrients under both RCPs. These two BMPs complement each other in this region in improving water quality. CHP can fairly reduce nutrients, and its cost of implementation is relatively low, whereas WCN corresponds to the highest rates of reduction in nutrients but with the highest cost of implementation. Our analyses show that without conserving wetlands, it is almost impossible to improve water quality under the projected changes in temperature and precipitation since 2025 under both RCPs. This is due to the fact that the GCMs project a minimum of 4 °C increase in the temperature in the future. The combination of WCN, CHP, CSD, GRD and implementing FCP appeared as the most reasonable solution to improve water quality in the future in all 3 zones under both RCPs. Other BMPs did not appear among optimal solutions either due to their low rates of abatement (20% or less of reduction of nutrients) or high costs of implementation. It is also important to emphasize that the identification of the optimal combinations of BMPs depend on both nutrient reduction and cost of implementation. For example, for the first 8 episodes, only WCN and CHP were identified as optimal in Zone 3, which includes all the tributaries, while for Zone 1 in addition to these BMPs GRD was also needed. This choice was made based on the cost-effectiveness analyses: in Zone 1, the cost of implementing GRD is very low and adds sufficient abatement rate. While in Zone 3, $1M had to be added to the total cost of implementation of the combination of BMPs and the abatement rate was not sufficiently high.

Further analyses revealed that identified optimal combinations of BMPs under historical and future climate conditions are not the same. For example, in Zone 3, WCN and GRD were found to be effective in eliminating the nutrients delivery based on historical LAAP and LAAT; while here it was shown that in addition to these practices CHP was also needed to increase the abatement rates under RCP 8.5. Similarly, in Zone 2, WCN replaced WRT in the optimal combinations of BMPs when comparing between the historical and future climate conditions. In general, more effective and costly combinations of BMPs were needed since 2025 to reduce the nutrients delivery in the QARB.

5.2.4 Uncertainties associated with effectiveness of selected optimal BMPs

The presented optimal combinations of BMPs in the previous section were found based on the averaged projections of 20 GCMs. Here, it was aimed to understand the behaviour of selected BMPs under individual projections and RCPs in future time episodes in the QARB zones. Results of these simulations under RCPs 4.5 and 8.5 for Zone 3 were shown in Figures 6 and 7, respectively – see Figures B1, B2, B3, and B4 for Zones 1 and 2. In each figure, 42 panels corresponding to 42 episodes were presented. In the panels, changes in TN and TP after implementation of optimal BMP combinations and considering the mean of projections of LAAT and LAAP of the GCMs were shown with blue and red lines, respectively. Changes in TN and TP using projections of individual climate models were shown with blue and red scatters, respectively. The changes were estimated with respect to the TN and TP under historical conditions and if no BMPs are implemented. Negative changes represent reduction in nutrients while positive changes represent increases in nutrients delivery even if the BMPs are implemented.

The figures show that the behaviour of BMPs is not similar under 20 GCMs due to their diverging projections of LAAT and LAAP. Although the performance of BMPs can be degraded under higher projections of LAAT based on few climate models, overall it seems that TN can be effectively reduced in all the time episodes under RCP 4.5 (see all panels of figure 6; abatement rate is between -200% and -100%). In addition, the reduction rate of TP was lower than TN for all the time episodes. In fact, unlike TN, TP loads were expected to highly increase using some GCMs even if the BMPs were implemented. This was expected since TP is much more sensitive than TN and these GCMs are projecting high temperature augmentation in the future.

Similar to the results obtained under RCP 4.5, TN can be still considerably reduced (more than 100% of reduction for all the time episodes) considering the LAAT and LAAP projections by individual climate models under RCP 8.5. In addition, TP can be moderately reduced only up to 2032-2061. After the latter time episode, the abatement rate of TP becomes low until it starts increasing and being doubled by the time episode 2053-2082. It is important to note that the combinations of BMPs identified in this study are expected to be non effective in reducing TP amounts using some of the GCMs from the first time episode.

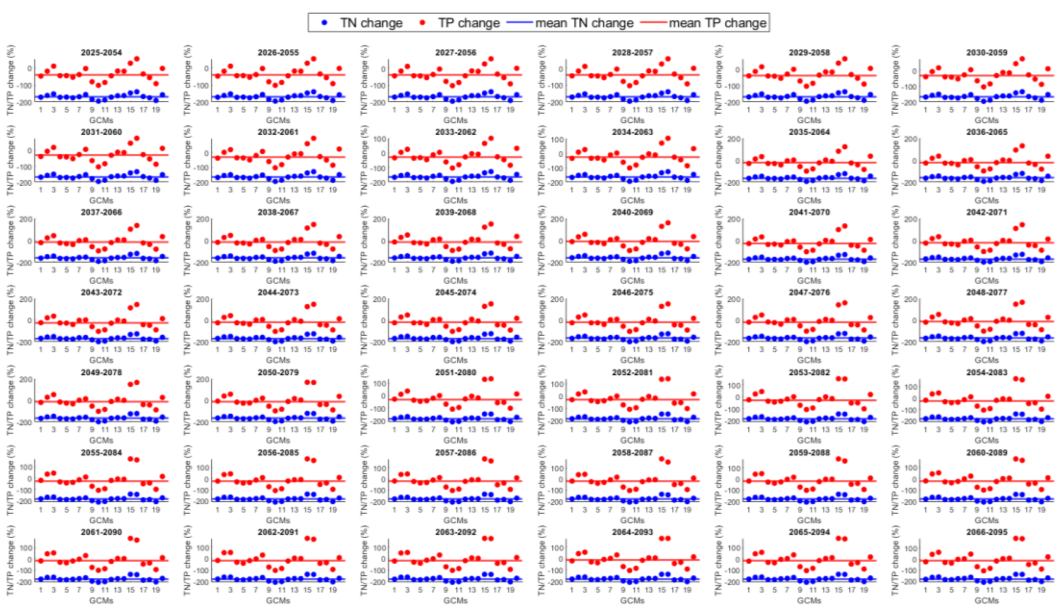

Figure 5.6 Changes in TN and TP after implementation of optimal BMP combinations in Zone 3 under RCP 4.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 4.5 using projections of individual climate models were shown in blue and red scatters, respectively.

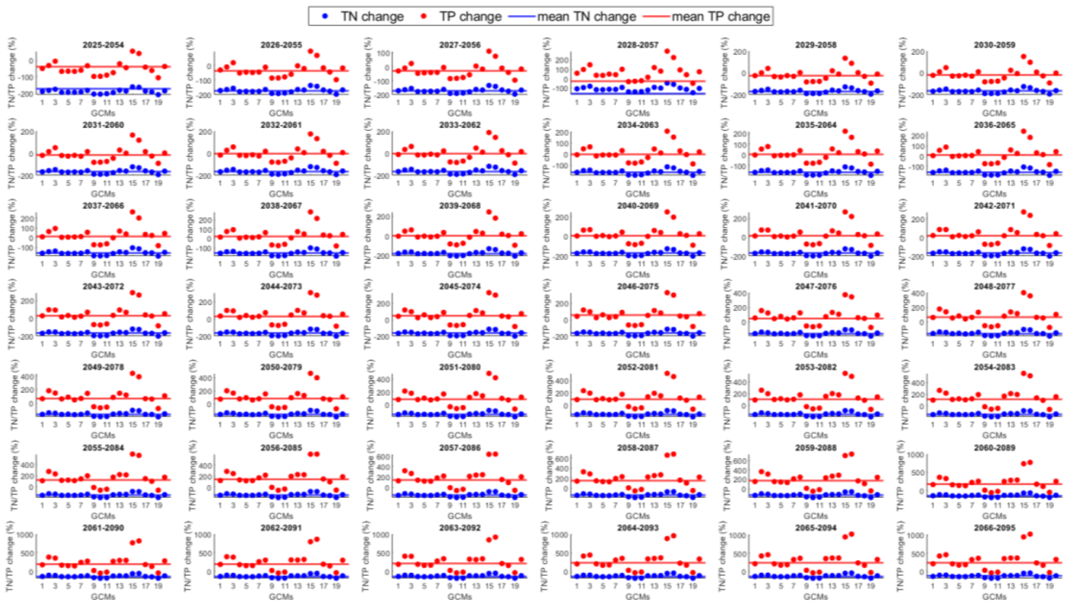

Figure 5.7 Changes in TN and TP after implementation of optimal BMP combinations in Zone 3 under RCP 8.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 8.5 using projections of individual climate models were shown in blue and red scatters, respectively.

Overall, the analyses show that the performance of identified optimal combinations of BMPs varied depending on climate models' projections. Although, they could still effectively reduce the nutrient export especially under RCP 4.5, their effectiveness become questionable under extreme temperature projections. This was somewhat expected based on the results of the bottom-up approach that it would be challenging to find effective BMPs if LAAT increase by more than 6 °C.

5.3 Summary and conclusions

There are a series of limitations in available water quality model related to estimation of both BMPs costs of implementation as well as effectiveness. Most importantly, a series of assumptions have been made related to wetland coverage area, number of animals in corrals, density of implementation of some practices (e.g. CSD and FCP), ditches coverage, sizes of ponds, and prices of some utilities necessary to calculate the cost of BMPs (e.g. the cost of constructing a wetland) that influence the cost-effectiveness analyses and BMP selection (see Zammali et al., 2020). In addition, the estimation of the costs may change in the future due to inflation in the currency. Moreover, the optimal BMPs for the future conditions were constrained to NEX-GDDPCMIP5 climate projections. It is also suggested to include the outputs of CMIP6 models for future impact assessment. In addition, our analyses were based on changes in long-term annual average climate conditions; while in the Canadian Prairies region, multiple studies suggested that some BMPs should be analyzed seasonally due to the high variation of temperature between winter and summer. Therefore, it is recommended to analyze the performance of BMPs on seasonal scale. Regardless of these limitations, this has been the first attempt to holistically assess the performance of stakeholder identified BMPs in the QARB under changing climate conditions. It was showed that indeed such analyses were necessarily as set of BMPs suggested based on historical climate conditions would not necessarily improve the water quality conditions in the future.

CHAPTER 6 CONCLUSIONS

The present study proposes a set of analyses to assess the performance of agricultural BMPs under current and future climate conditions. For this purpose, a cost estimation module is added to an existing water quality model to perform cost-effectiveness analyses of a series of BMPs in the QARB. Information matrices are proposed to present the changes in nutrients, TN and TP, as well as costs of implementation for more than 140 combinations of BMPs at the tributary scale. The advantage of this visualisation of results is that stakeholders can view all possible options in one platform and can choose their favourable practice based on levels of reduction in nutrients and their budget. Therefore, they can be used in water quality management discussions. Further analyses revealed the existence of multiple combinations that can highly/moderately reduce the nutrient exports in the QARB with relatively low cost. In brief, on the one hand, wetland-related BMPs were found as the most effective practices in improving the water quality despite their high cost of implementation. On the other hand, corral-related BMPs, specifically CHP, were found the most inexpensive practices with moderate reduction in the nutrients delivery. Therefore, the combination of these practices can complement each other. It was also found that the stakeholders' chance of BMP adoption can highly affect the effectiveness of the combinations of BMPs at large scale, therefore, their engagement in water quality management is essential.

As water quality conditions are sensitive to changes in climate, and optimal combinations of BMPs were identified based on historical climate conditions, it was necessity to understand their performance in the future as well. For this purpose, first a wide range of changes in temperature and precipitation was considered and their corresponding values were fed into the water quality model for BMP impact assessment. Results revealed that the nutrients are more sensitive to changes in temperature than precipitation and TP is more sensitive than TN to changes in climate conditions. The optimal combinations of BMPs were found effective under moderate increases in temperature. However, high increases in temperature can affect their efficacy in reducing the nutrients. Second, climate projections from 20 different GCMs under 2 RCPs were used to find new sets of optimal combinations over future time episodes each containing a 30-year window. Results revealed that WCN and CHP were among all the optimal combinations of BMPs under both low and high future emission scenarios. The implementation of these BMPs can reduce moderate to high amounts of TN; however, it was challenging to find any BMPs that can reduce TP. Moreover, it was found that usage of these two practices might be enough to reduce nutrients in the next couple of decades; however, as we approach to the end of century and temperature increases, implementation of a larger set of BMPs is required.

Despite the important value of the study, it presents few uncertainties and limitations. Uncertainties are mainly related to data records such as the wetland coverage, animal population, and climate data in the region. Moving from a tributary to another, the intensity of wetland drainage is changing. It was challenging to find any accurate records for the drained land coverage. Previous reports were used and assumptions had to be made through discussions with experts from the WSA in the region to estimate the current and drained wetland coverage that were incorporated in the model. To solve this issue, it is recommended to study satellite pictures to estimate the wetland coverage. Comparisons between old and new pictures can help estimate the intensity of wetland drainage. Similarly, to wetland coverage data, there were no records providing the animal population in the region. The values used in this study were obtained from the report of Roste and Baulch (2018). In this report, the experts of the WSA used data including manure concentration measurements to estimate the number of cows in each tributary. One of the solutions to solve the data records issue is to engage the stakeholders through surveys, preferably online to ensure higher number of participants, to obtain more accurate estimation of the animal population. Additionally, historical and future climate incorporated in the model were obtained from the GCMs which represent uncertainties in their projections. In this study, CMIP5 models were used, while more accurate projections can be obtained from CMIP6 models and be incorporated in the model in the future to reduce the uncertainties related to climate variables. The economic evaluation model was developed based on empirical equations which may affect the accuracy of the results depending on the changes in the prices available in the market but it cannot be considered as major uncertainties. In addition, it is easy to update the inputs of the model when new prices are provided. However, it is recommended to discuss the opportunity cost with the annual croppers, as in previous surveys in the United States of America, the third of the participants mentioned that the estimations made by the government do not accurately represent their income loss (Miller, 2014). With all that said, this study presents generic analyses for BMP impact assessment under current and future climate conditions that can be used for water quality management at watershed scale.

REFERENCES

Agriculture and Agri-food Canada, 2000. Agricultural Best Management Practices. Available at: http://www5.agr.gc.ca/resources/prod/doc/pfra/pdf/Agric_bmp_e.pdf.

Alberta Agriculture and Forestry Environmental Stewardship Division (AAFESD). (2015). Relocation of Livestock Facilities Planning Guide., pp. 1-19. Available at:

https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/epw12912/$FILE/Relocation_of_Livestock_Facilities_Planning_Guide.pdf.

Alodah, A., & Seidou, O. (2019). Assessment of Climate Change Impacts on Extreme High and Low Flows: An Improved Bottom-Up Approach. Water, 11(6), 1236.

Andreichuk, I. (2017). How Climate Change Could Affect the Water Supply of Potash Solution Mining in Southern Saskatchewan (Doctoral dissertation, The University of Regina (Canada)).

Arabi, M., Govindaraju, R. S., & Hantush, M. M. (2007). Watershed Management Tool for Selection and Spatial Allocation of Nonpoint Source Pollution Control Practices. US Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory.

Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment-part 1: Model development. J. Am. Water Resour. Assoc. 1998, 34, 73–89.

Assiniboine Watershed Stewardship Association (AWSA). (2014). Saskatchewan Prairie Conservation Action Plan., pp. 1-51. Available at: https://www.pcap-sk.org/rsu_docs/documents/2015-Aron-Hershmiller---Wetland-Restoration.pdf.

Atisa, G., Bhat, M. G., & McClain, M. E. (2014). Economic assessment of best management practices in the Mara River Basin: toward implementing payment for watershed services. Water resources management, 28(6), 1751-1766.

Authority, S. W., Kulshreshtha, S. N., Nagy, C., & Bogdan, A. (2012). Present and Future Water Demand in Selected Saskatchewan River Basins. Saskatchewan Watershed Authority.

Baulch, H. M., Elliott, J. A., Cordeiro, M. R., Flaten, D. N., Lobb, D. A., & Wilson, H. F. (2019). Soil and water management: Opportunities to mitigate nutrient losses to surface waters in the northern Great Plains. Environmental Reviews, 27(4), 447-477.

Beneficial management practices for decreasing nutrient losses. (2019). http://www.agr.gc.ca/eng/agriculture-and-climate/agricultural-practices/agriculture-and-water/watershed-protection/watershed-evaluation-of-beneficial-management-practices/beneficial-management-practices-for-decreasing-nutrient-losses/?id=1553695465404. (Accessed 20 April 2020)

Bicknell, B.; Imhoff, J.; Kittle, J., Jr.; Jobes, T.; Donigian, A., Jr.; Johanson, R. Hydrological Simulation Program-Fortran: HSPF Version 12 User's Manual; EPA National Exposure Research Laboratory: Athens, GA, USA, 2001.

Bingner, R. L., Theurer, F. D., & Yuan, Y. (2007). AnnAGNPS technical processes.

Bouraoui, F.; Galbiati, L.; Bidoglio, G. Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK). Hydrol. Earth Syst. Sci. Discuss. 2002, 6, 197–209.

Boyer, L., Davies, J. M., Hassanzadeh, E., Marin, L. M., Strickert, G., & Wauchope, M. (2018). Interfacing Stakeholder Involvement into a Surface Water-Quality Modelling System for Water Management and Policy Development. New Trends in Urban Drainage Modelling: UDM 2018, 312.

Bradford, L., Thapa, A., Duffy, A., Hassanzadeh, E., Strickert, G., Noble, B., & Lindenschmidt, K. E. (2019). Incorporating social dimensions in hydrological and water quality modeling to evaluate the effectiveness of agricultural beneficial management practices in a Prairie River Basin. Environmental Science and Pollution Research, 1-17.

Brinson, Mark M. "Changes in the functioning of wetlands along environmental gradients." Wetlands 13.2 (1993): 65-74.

Bruce, S. N. (2017). Economics of Beneficial Management Practices Adoption by Beef Producers in Southern Alberta.

Brunet, N. N., & Westbrook, C. J. (2012). Wetland drainage in the Canadian prairies: Nutrient, salt and bacteria characteristics. Agriculture, Ecosystems & Environment, 146(1), 1-12.

Bruulsema, T., Chen, F., Garcia, F., Ivanova, S., Li, S., Rao, N., & Witt, C. (2008). A global framework for best management practices for fertilizer use. IPNI Concept Paper, 1.

Bush, E., Gillett, N., Watson, E., Fyfe, J., Vogel, F. and Swart, N. (2019): Understanding Observed Global Climate Change; Chapter 2 in Canada's Changing Climate Report, (ed.) E. Bush and D.S. Lemmen; Government of Canada, Ottawa, Ontario, p. 24–72

Carvajal, P. E., Anandarajah, G., Mulugetta, Y., &Dessens, O. (2017). Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—the case of Ecuador. Climatic Change, 144(4), 611-624.

Crabbé, P., Lapen, D. R., Clark, H., Sunohara, M., & Liu, Y. (2012). Economic benefits of controlled tile drainage: Watershed evaluation of beneficial management practices, South Nation river basin, Ontario. Water Quality Research Journal of Canada, 47(1), 30-41.

Dahl, T. E. (1990). Wetlands losses in the United States, 1780's to 1980's. US Department of the Interior, Fish and Wildlife Service.

Department of Economic Development (DED). (2017). Storage pond sizing. Available at: http://agriculture.vic.gov.au/agriculture/dairy/managing-effluent/storage-pond-sizing.

Dixit, A. S., Hall, R. I., Leavitt&, P. R., Quinlan, R., & Smol, J. P. (2000). Effects of sequential depositional basins on lake response to urban and agricultural pollution: a palaeoecological analysis of the Qu'Appelle Valley, Saskatchewan, Canada. Freshwater Biology, 43(3), 319-337.

Dollevoet, B., Koeckhoven, S., Jeffrey, S. R., & Unterschultz, J. (2008). Lower Souris Watershed Ecological Goods and Services Pilot Proposal: Farm Level Economic Analysis. Deparment of Rural Economy, University of Alberta. Project Report.

Ducks Unlimited Canada. (2011). A Business Case for Wetland Conservation The Black River Sub watershed (pp. 1–32). Available at:

https://rescuelakesimcoe.org/wp-content/uploads/2018/11/duc_blackriver_case.pdf.

Dumanski, S., Pomeroy, J. W., & Westbrook, C. J. (2015). Hydrological regime changes in a Canadian Prairie basin. Hydrological Processes, 29(18), 3893-3904.

Duran-Encalada, J. A., Paucar-Caceres, A., Bandala, E. R., & Wright, G. H. (2017). The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region. European Journal of Operational Research, 256(2), 567-581.

Fang, X., Pomeroy, J. W., Westbrook, C. J., Guo, X., Minke, A. G., & Brown, T. (2010). Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. Hydrology & Earth System Sciences Discussions, 7(1).

Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. System dynamics review, 10(2‐3), 245-256.

García, L. E., Matthews, J. H., Rodriguez, D. J., Wijnen, M., Di Francesco, K. N., & Ray, P. (2014). Beyond downscaling: a bottom-up approach to climate adaptation for water resources management.

Geng, R., & Sharpley, A. N. (2019). A novel spatial optimization model for achieve the trad-offs placement of best management practices for agricultural non-point source pollution control at multi-spatial scales. Journal of Cleaner Production, 234, 1023-1032.

Girard, C., Pulido-Velazquez, M., Rinaudo, J. D., Pagé, C., & Caballero, Y. (2015). Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale. Global Environmental Change, 34, 132-146.

Giri, S., Nejadhashemi, A. P., & Woznicki, S. A. (2012). Evaluation of targeting methods for implementation of best management practices in the Saginaw River Watershed. Journal of environmental management, 103, 24-40.

Government of Alberta (GA). Nutrient Beneficial Management Practices - Introduction., pp 1-16. Available at:

https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/epw11955/$FILE/section1_introduction.pdf.

Government of Canada (GC). Beneficial management practices that impact water quality. Available at:

https://www.agr.gc.ca/eng/agriculture-and-the-environment/agricultural-practices/agriculture-and-water/watershed-protection/watershed-evaluation-of-beneficial-management-practices/beneficial-management-practices-that-impact-water-quality/?id=1553690986434.

Government of Canada (GC). (2018). Canadian Climate Normals 1981-2010 Station Data.Available at:

http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=2992&autofwd=1.

Government of Saskatchewan (GS). Crop Planning Guide 2016. (2016)., pp 1-16.

Available at:

https://publications.saskatchewan.ca/api/v1/products/77820/formats/87217/download.

Government of Saskatchewan (GS). Crop Planning Guide 2017. (2017)., pp 1-16. Available at:

http://publications.gov.sk.ca/documents/20/97026-Complete%20Version.pdf.

Government of Saskatchewan (GS). Crop Planning Guide 2018. (2018)., pp 1-16. Available at:

https://publications.saskatchewan.ca/api/v1/products/88550/formats/105224/download.

Government of Saskatchewan (GS). Crop Planning Guide 2019. (2019)., pp 1-16. Available at: https://pubsaskdev.blob.core.windows.net/pubsask-prod/109885/109885 Crop_Planning_Guide_2019.pdf.

Groves, D. G., Lempert, R. J., Knopman, D., & Berry, S. H. (2008). Preparing for an uncertain future climate in the inland empire: Identifying robust water-management strategies. Rand Corporation.

Gurnell, A. M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., ... &Demarchi, L. (2016). A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences, 78(1), 1-16.

Hall, R. I., Leavitt, P. R., Quinlan, R., Dixit, A. S., & Smol, J. P. (1999). Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. Limnology and Oceanography, 44(3part2), 739-756.

Hassanzadeh, E. (2019). Trade-Offs between Human and Environment: Challenges for Regional Water Management under Changing Conditions. Water, 11(9), 1773.¨

Hassanzadeh, E., Elshorbagy, A., Nazemi, A., Jardine, T. D., Wheater, H., & Lindenschmidt, K. E. (2017). The ecohydrological vulnerability of a large inland delta to changing regional streamflows and upstream irrigation expansion. Ecohydrology, 10(4), e1824.

Hassanzadeh, E., Elshorbagy, A., Wheater, H., & Gober, P. (2014). Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada. Environmental Modelling & Software, 58, 12-26.

Hassanzadeh, E., Elshorbagy, A., Wheater, H., & Gober, P. (2016). A risk-based framework for water resource management under changing water availability, policy options, and irrigation expansion. Advances in Water Resources, 94, 291-306.

Hassanzadeh, E., Nazemi, A., Adamowski, J., Nguyen, T. H., & Van-Nguyen, V. T. (2019). Quantile-based downscaling of rainfall extremes: notes on methodological functionality, associated uncertainty and application in practice. Advances in Water Resources, 131, 103371.

Hassanzadeh, E., Strickert, G., Morales-Marin, L., Noble, B., Baulch, H., Shupena-Soulodre, E., &Lindenschmidt, K. E. (2019). A framework for engaging stakeholders in water quality modeling and management: Application to the Qu'Appelle River Basin, Canada. Journal of environmental management, 231, 1117-1126.

Hengade, N., Eldho, T. I., & Ghosh, S. (2018). Climate change impact assessment of a river basin using CMIP5 climate models and the VIC hydrological model. Hydrological Sciences Journal, 63(4), 596-614.

Hosseini, N., Johnston, J., & Lindenschmidt, K. E. (2017). Impacts of climate change on the water quality of a regulated prairie river. Water, 9(3), 199.

Hurlbert, M., Diaz, H., Corkal, D. R., & Warren, J. (2009). Climate change and water governance in Saskatchewan, Canada. International Journal of Climate Change Strategies and Management.

Ivkovic, K. M. (2009). A top–down approach to characterise aquifer–river interaction processes. Journal of Hydrology, 365(3-4), 145-155.

Jaramillo, P., & Nazemi, A. (2018). Assessing urban water security under changing climate: Challenges and ways forward. Sustainable cities and society, 41, 907-918.

Jeffrey, S. R., Koeckhoven, S., Trautman, D., Dollevoet, B., Unterschultz, J. R., & Ross, C. (2014). Economics of riparian beneficial management practices for improved water quality: A representative farm analysis in the Canadian Prairie region. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, 39(4), 449-461.

Jeong, D. I., Sushama, L., Diro, G. T., Khaliq, M. N., Beltrami, H., & Caya, D. (2016). Projected changes to high temperature events for Canada based on a regional climate model ensemble. Climate dynamics, 46(9-10), 3163-3180.

Jeppesen, E.; Kronvang, B.; Meerhoff, M.; Søndergaard, M.; Hansen, K.M.; Andersen, H.E.; Lauridsen, T.L.; Liboriussen, L.; Beklioglu, M.; Özen, A.; et al. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. J. Environ. Qual. 2009, 38, 1930–1941.

Jiang, Haiyan, et al. "A system dynamics simulation approach for environmentally friendly operation of a reservoir system." Journal of Hydrology (2020): 124971.

Kaste, Ø., Wright, R. F., Barkved, L. J., Bjerkeng, B., Engen-Skaugen, T., Magnusson, J., & Sælthun, N. R. (2006). Linked models to assess the impacts of climate change on nitrogen in a Norwegian river basin and fjord system. Science of the Total Environment, 365(1-3), 200-222.

Kehoe, M., O'Brien, K. R., Grinham, A., & Burford, M. A. (2015). Primary production of lake phytoplankton, dominated by the cyanobacterium Cylindrospermopsis raciborskii, in response to irradiance and temperature. Inland Waters, 5(2), 93-100.

King, K. W., Williams, M. R., Macrae, M. L., Fausey, N. R., Frankenberger, J., Smith, D. R., ... & Brown, L. C. (2015). Phosphorus transport in agricultural subsurface drainage: A review. Journal of environmental quality, 44(2), 467-485.

Koontz, T. M., & Newig, J. (2014). From planning to implementation: Top-down and bottom-up approaches for collaborative watershed management. Policy Studies Journal, 42(3), 416-442.

Lang, A. J. (2016). Soil erosion from forest haul roads at stream crossings as influenced by road attributes (Doctoral dissertation, Virginia Tech).

Lindenschmidt, K. E., Akomeah, E., Baulch, H., Boyer, L., Davies, J. M., Hassanzadeh, E., ... & Wauchope, M. (2018, September). Interfacing Stakeholder Involvement into a Surface Water-Quality Modelling System for Water Management and Policy Development. In International Conference on Urban Drainage Modelling (pp. 312-316). Springer, Cham.

Liu, H., Benoit, G., Liu, T., Liu, Y., & Guo, H. (2015). An integrated system dynamics model developed for managing lake water quality at the watershed scale. Journal of environmental management, 155, 11-23.

Liu, J., Baulch, H. M., Macrae, M. L., Wilson, H. F., Elliott, J. A., Bergström, L., ... &Vadas, P. A. (2019). Agricultural water quality in cold climates: processes, drivers, management options, and research needs. Journal of environmental quality, 48(4), 792-802.

Ludwig, F., van Slobbe, E., & Cofino, W. (2014). Climate change adaptation and Integrated Water Resource Management in the water sector. Journal of Hydrology, 518, 235-242.

Madani, K., & Shafiee-Jood, M. (2020). Socio-Hydrology: A New Understanding to Unite or a New Science to Divide?. Water, 12(7), 1941.

Mailhot, A., Beauregard, I., Talbot, G., Caya, D., & Biner, S. (2012). Future changes in intense precipitation over Canada assessed from multi-model NARCCAP ensemble simulations. International journal of climatology, 32(8), 1151-1163.

Marchau, V. A., Walker, W. E., Bloemen, P. J., & Popper, S. W. (2019). Decision making under deep uncertainty: From theory to practice (p. 405). Springer Nature.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management?. Earth, 4, 20.

Mirchi, A., & Watkins Jr, D. (2013). A systems approach to holistic total maximum daily load policy: case of Lake Allegan, Michigan. Journal of Water Resources Planning and Management, 139(5), 544-553.

Morales-Marín, L., Wheater, H., & Lindenschmidt, K. E. (2018). Potential changes of annual-averaged nutrient export in the south saskatchewan river basin under climate and land-use change scenarios. Water, 10(10), 1438.

Mukundan, R., Hoang, L., Gelda, R., Yeo, M. H., & Owens, E. (2020). Climate change impact on nutrient loading in a water supply watershed. Journal of Hydrology, 124868.

NASA. Earth observatory. World of change: Global Temperatures. Available at: https://earthobservatory.nasa.gov/world-of-change/global-temperatures

Nazari-Sharabian, Mohammad, Masoud Taheriyoun, Sajjad Ahmad, Moses Karakouzian, and Azadeh Ahmadi. "Water quality modeling of Mahabad Dam watershed–reservoir system under climate change conditions, using SWAT and system dynamics." Water 11, no. 2 (2019): 394.

Nazemi, A., &Wheater, H. S. (2014). Assessing the vulnerability of water supply to changing streamflow conditions. Eos, Transactions American Geophysical Union, 95(32), 288-288.

Nazemi, A., Zaerpour, M., & Hassanzadeh, E. (2020). Uncertainty in Bottom-Up Vulnerability Assessments of Water Supply Systems due to Regional Streamflow Generation under Changing Conditions. Journal of Water Resources Planning and Management, 146(2), 04019071.

Panagopoulos, Y., Makropoulos, C., & Mimikou, M. (2011). Reducing surface water pollution through the assessment of the cost-effectiveness of BMPs at different spatial scales. Journal of environmental management, 92(10), 2823-2835.

Pandey, B. K., Khare, D., Kawasaki, A., & Mishra, P. K. (2019). Climate change impact assessment on blue and green water by coupling of representative CMIP5 climate models with physical based hydrological model. Water Resources Management, 33(1), 141-158.

Pattison-Williams, J. K., Pomeroy, J. W., Badiou, P., & Gabor, S. (2018). Wetlands, flood control and ecosystem services in the Smith Creek Drainage Basin: A case study in Saskatchewan, Canada. Ecological economics, 147, 36-47.

Pielke Sr, R. A., Wilby, R., Niyogi, D., Hossain, F., Dairuku, K., Adegoke, J., ... & Suding, K. (2012). Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective. Extreme events and natural hazards: The complexity perspective, 196, 345-359.

Poff, N. L., Brown, C. M., Grantham, T. E., Matthews, J. H., Palmer, M. A., Spence, C. M., ... &Baeza, A. (2016). Sustainable water management under future uncertainty with eco-engineering decision scaling. Nature Climate Change, 6(1), 25-34.

Pomeroy, J. W., de Boer, D., & Martz, L. W. (2005). Hydrology and water resources of Saskatchewan (p. 25). Saskatoon: Centre for Hydrology, University of Saskatchewan.

Pomeroy, J. W., Shook, K., Fang, X., Dumanski, S., Westbrook, C., & Brown, T. (2014). Improving and testing the prairie hydrological model at Smith Creek Research Basin. Centre for Hydrology, University of Saskatchewan.

Qiu, J., Shen, Z., Hou, X., Xie, H., & Leng, G. (2020). Evaluating the performance of conservation practices under climate change scenarios in the Miyun Reservoir Watershed, China. Ecological Engineering, 143, 105700

Qiu, J., Shen, Z., Leng, G., Xie, H., Hou, X., & Wei, G. (2019). Impacts of climate change on watershed systems and potential adaptation through BMPs in a drinking water source area. Journal of Hydrology, 573, 123-135.

Razavi S, Tolson BA, Burn DH (2012) Review of surrogate modeling in water resources. Water Resour Res 48(7). https://doi.org/10.1029/2011WR011527

Roste, J., Baulch, H., 2017. Lower Qu'Appelle Watershed, SK: Land Use and Water Quality. Unpublished report. pp. 1–33.

Roste, J., Baulch, H., 2018. Lower Qu'Appelle Watershed, SK: Land Use and Water Quality. , pp. 1–61. Available at: http://wuqwatr.ca/wp-content/uploads/documents/QuAppelle-Basin-Land-Use-Water-Quality-UofS-study.pdf

Saskatchewan Agriculture, Food and Rural Revitalization, 2003. Stewardship and Economics of Cattle Wintering Sites. Unpublished report, pp. 1-15.

Schwarz, G.E., Hoos, A.B., Alexander, R.B., Smith, R.A., 2006. The SPARROW Surface Water-quality Model: Theory, Application and User Documentation. Available at: https://pubs.usgs.gov/tm/2006/tm6b3/PDF/tm6b3_part1a.pdf.

Sharpley, A., Jarvie, H. P., Buda, A., May, L., Spears, B., & Kleinman, P. (2013). Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. Journal of environmental quality, 42(5), 1308-1326.

Shukla, S., Graham, W., Goswami, D., Knowles, J., Hodges, A., Nair, V., ... & Wu, C. (2011). Evaluation of cow-calf best management practices with regards to nutrient discharges in the Lake Okeechobee Basin. Final report submitted to Florida Department of Agriculture and Consumer Services, Tallahasee, FL, and South Florida Water Management District, West Palm Beach, FL.

Simonne, E. H., & Hutchinson, C. M. (2005). Controlled-release fertilizers for vegetable production in the era of best management practices: Teaching new tricks to an old dog. HortTechnology, 15(1), 36-46.

Statistics Canada (SC). Table 38-10-0052-01 Use of fertilizer and pesticides. Available at:https://doi.org/10.25318/3810005201-eng.

Sterman, J. (2010). Business dynamics. Irwin/McGraw-Hill c2000...

Stewardship and economics of cattle wintering sites. (n.d.). southsaskriverstewards.ca/wp-content/uploads/2019/09/Stewardship-and-Economics-of-Cattle-Wintering-Sites.pdf.

Swarbrick, V. J., Simpson, G. L., Glibert, P. M., & Leavitt, P. R. (2019). Differential stimulation and suppression of phytoplankton growth by ammonium enrichment in eutrophic hardwater lakes over 16 years. Limnology and Oceanography, 64(S1), S130-S149.

The European Commission. Causes of climate change. Availbel at: https://ec.europa.eu/clima/change/causes_en#:~:text=Humans%20are%20increasingly%20influencing%20the,greenhouse%20effect%20and%20global%20warming.

The International Institute for Sustainable Development (IISD), How Temperature Affects the Quality of Fresh Water. Available at: https://www.iisd.org/ela/blog/commentary/temperature-quality-fresh-water/

Thomsen, J., Kulshreshtha, S., Lobb, D., Flaten, D., & MacDonald, K. B. (2010). Agricultural Beneficial Management Practices for Lake Winnipeg–Cost-benefit analysis using an ecological goods and services approach. The Thomsen Corporation.

Tiessen, K. H. D., Elliott, J. A., Stainton, M., Yarotski, J., Flaten, D. N., & Lobb, D. A. (2011). The effectiveness of small-scale headwater storage dams and reservoirs on stream water quality and quantity in the Canadian Prairies. journal of soil and water conservation, 66(3), 158-171.

Tiessen, K. H. D., Elliott, J. A., Yarotski, J., Lobb, D. A., Flaten, D. N., &Glozier, N. E. (2010). Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. Journal of Environmental Quality, 39(3), 964-980.

United States Department of Agriculture (USDA). (2006). Best Management Practices To Minimize Agricultural Phosphorus Impacts on Water Quality, pp. 1–52. Available at:

https://www.ars.usda.gov/is/np/BestMgmtPractices/Best%20Management%20Practices.pdf.

United States Environmental Protection Agency (USEPA), Climate Impacts on Water Quality https://www.epa.gov/arc-x/climate-impacts-water-quality#:~:text=In%20many%20areas%2C%20increased%20water,due%20to%20extreme%20storm%20events.

United States Environmental Protection Agency (USEPA). (2020). The Sources and Solutions: Agriculture. Available at:https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture.

Van Liew, M. W., Feng, S., & Pathak, T. B. (2012). Climate change impacts on streamflow, water quality, and best management practices for the Shell and Logan Creek Watersheds in Nebraska, USA. International Journal of Agricultural and Biological Engineering, 5(1), 13-34.

Van Tra, T., Thinh, N. X., & Greiving, S. (2018). Combined top-down and bottom-up climate change impact assessment for the hydrological system in the Vu Gia-Thu Bon River Basin. Science of the Total Environment, 630, 718-727.

Verburg, P. H., & Overmars, K. P. (2009). Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape ecology, 24(9), 1167.

Walters, K. M., & Babbar-Sebens, M. (2016). Using climate change scenarios to evaluate future effectiveness of potential wetlands in mitigating high flows in a Midwestern US watershed. Ecological Engineering, 89, 80-102.

Water-quality Model: Theory, Application and User Documentation. Available at: https://pubs.usgs.gov/tm/2006/tm6b3/PDF/tm6b3_part1a.pdf.

Water Security Agency (WSA). (2020). The Qu'Appelle Nutrient Mass Balance Report. Available at:https://www.wsask.ca/About-WSA/Publications/The-QuAppelle-Mass-Balance-Report/.

WSA. Stewardship and economics of cattle wintering sites., pp. 1-16. Available at: https://southsaskriverstewards.ca/wp-content/uploads/2019/09/Stewardship-and-Economics-of-Cattle-Wintering-Sites.pdf.

Wheater, H. S., & Gober, P. (2015). Water security and the science agenda. Water Resources Research, 51(7), 5406-5424.

Whitehead, P.; Wilby, R.; Battarbee, R.; Kernan, M.; Wade, A.J. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 2009, 54, 101–123.

Wilby, R. L. (2006). When and where might climate change be detectable in UK river flows?. Geophysical Research Letters, 33(19).

Wilby, R. L. (2017). Climate change in practice: topics for discussion with group exercises. Cambridge University Press.

Woznicki, S. A., & Nejadhashemi, A. P. (2012). Sensitivity Analysis of Best Management Practices Under Climate Change Scenarios 1. JAWRA Journal of the American Water Resources Association, 48(1), 90-112.

Wuite, J. J., Chanasyk, D. S., & Akbar, M. A. (2007). Environmental and economic evaluation of cow-calf wintering site runoff control as a beneficial management practice to improve surface water quality. Water Quality Research Journal, 42(4), 240-251.

Yang, W., Liu, Y., Ou, C., & Gabor, S. (2016). Examining water quality effects of riparian wetland loss and restoration scenarios in a southern Ontario watershed. Journal of environmental management, 174, 26-34.

Young, R.A.; Onstad, C.; Bosch, D.; Anderson, W. Agnps: A nonpoint-source pollution model for evaluating agricultural watersheds. J. Soil Water Conserv. 1989, 44, 168–173.

Zandmoghaddam, S., Nazemi, A., Hassanzadeh, E., & Hatami, S. (2019). Representing local dynamics of water resource systems through a data-driven emulation approach. Water Resources Management, 33(10), 3579-3594.

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin, V.V. (2019): Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D.S. (Eds.) Canada’s Changing Climate Report. Government of Canada, Ottawa, Ontario, pp 112-193.

Zomorodian, M., Lai, S. H., Homayounfar, M., Ibrahim, S., Fatemi, S. E., & El-Shafie, A. (2018). The state-of-the-art system dynamics application in integrated water resources modeling. Journal of environmental management, 227, 294-304.

APPENDIX A - SUPPLEMENTARY MATERIAL OF CHAPTER 4

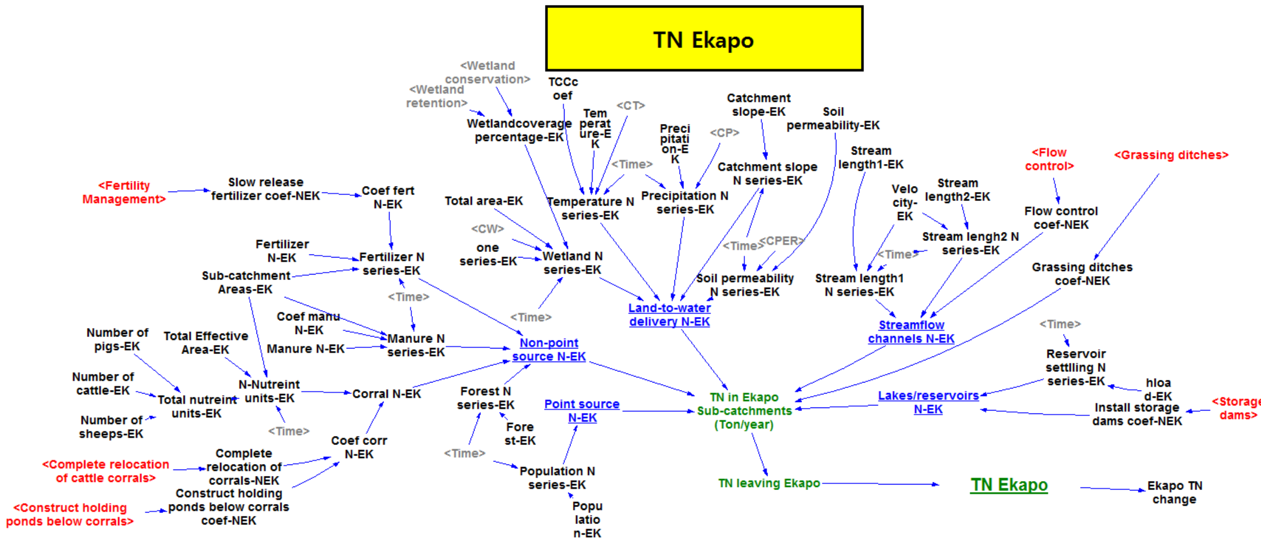

Figure A1 The structure of the water quality module to estimate TN loads in Ekapo.

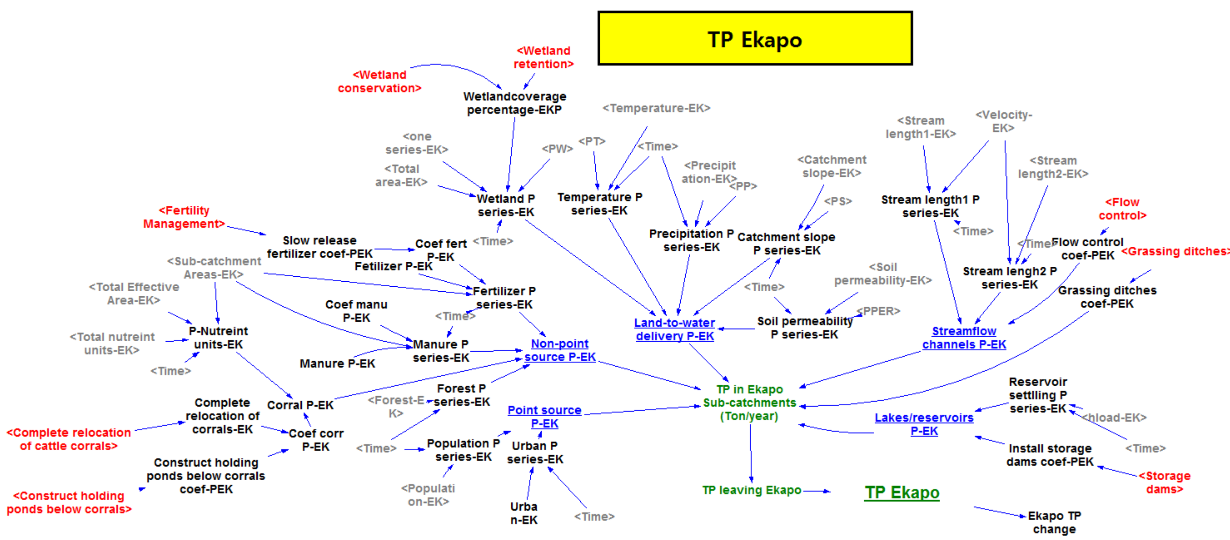

Figure A2 The structure of the water quality module to estimate TP loads in Ekapo.

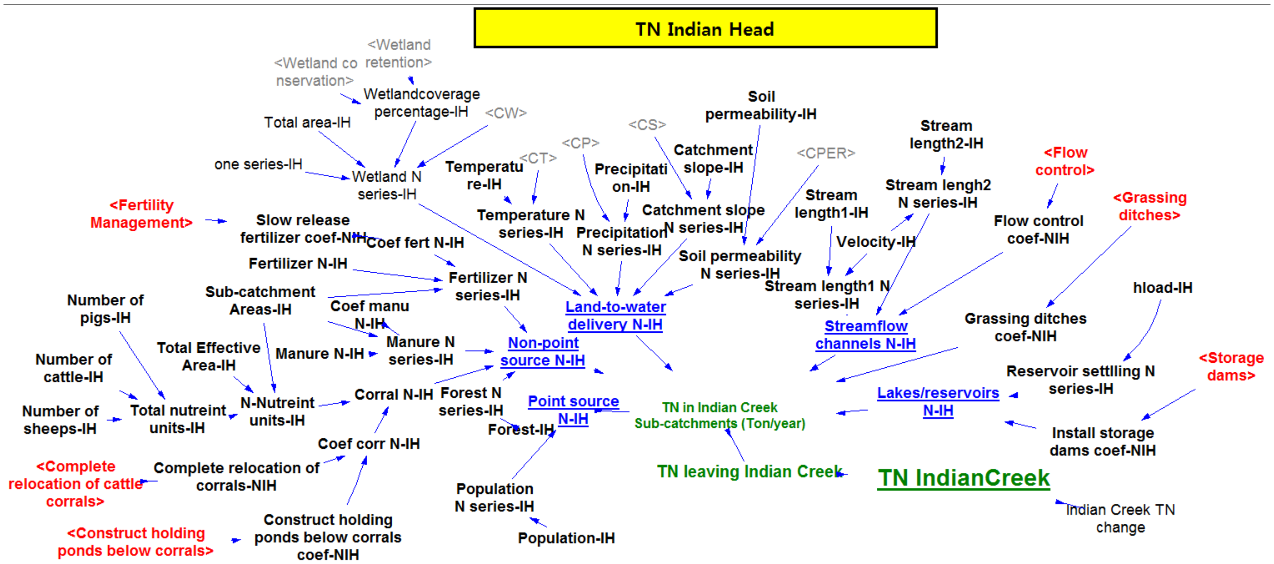

Figure A3 The structure of the water quality module to estimate TN loads in Indian Head.

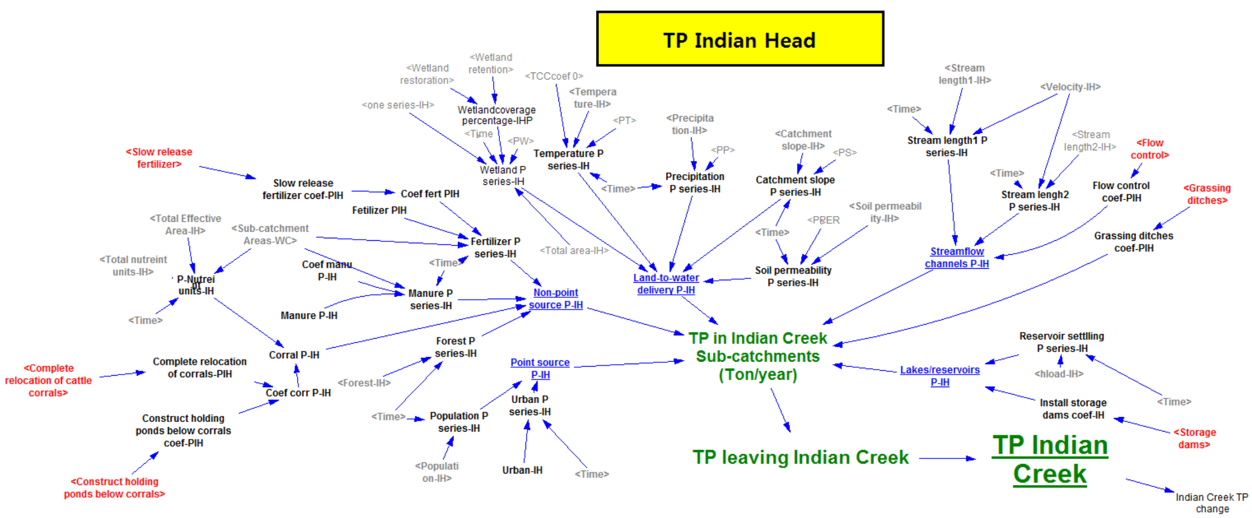

Figure A4 The structure of the water quality module to estimate TP loads in Indian Head

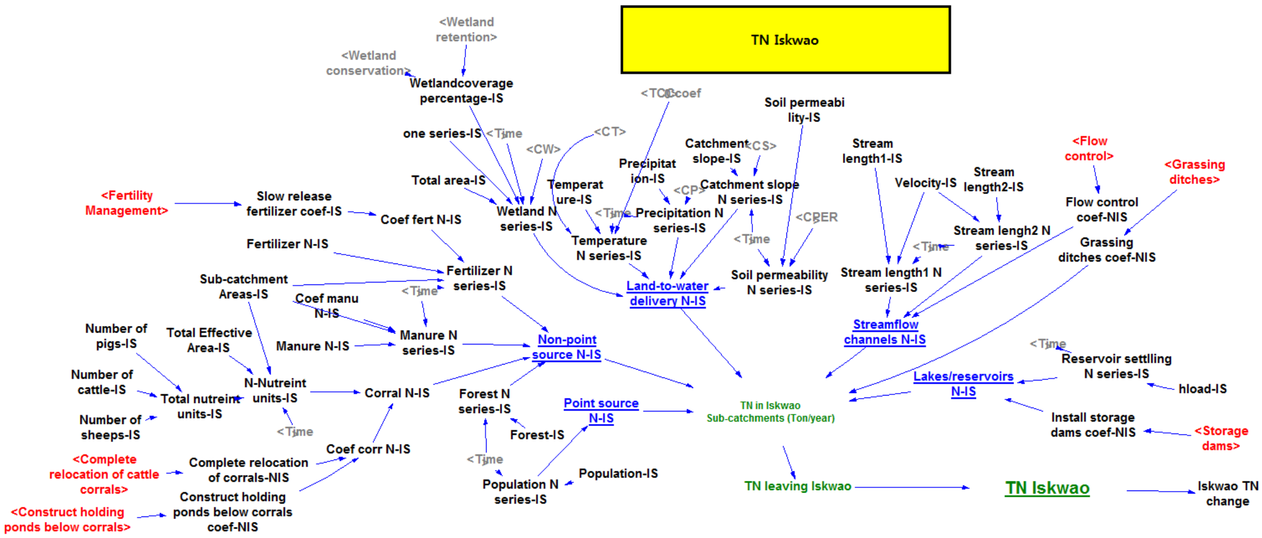

Figure A5 The structure of the water quality module to estimate TN loads in Iskwao

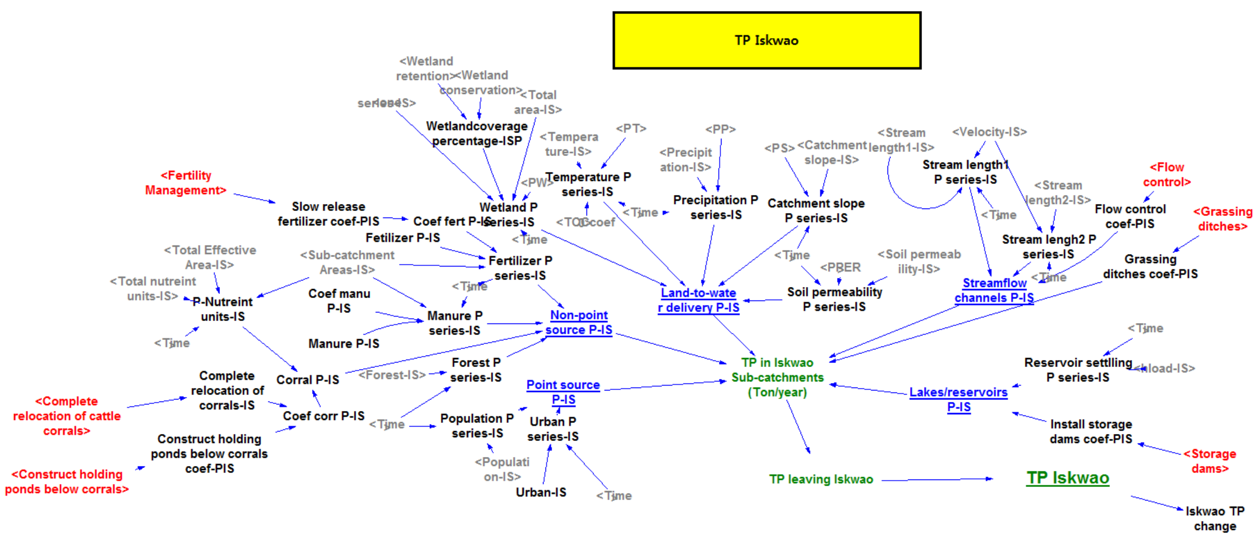

Figure A6 The structure of the water quality module to estimate TP loads in Iskwao.

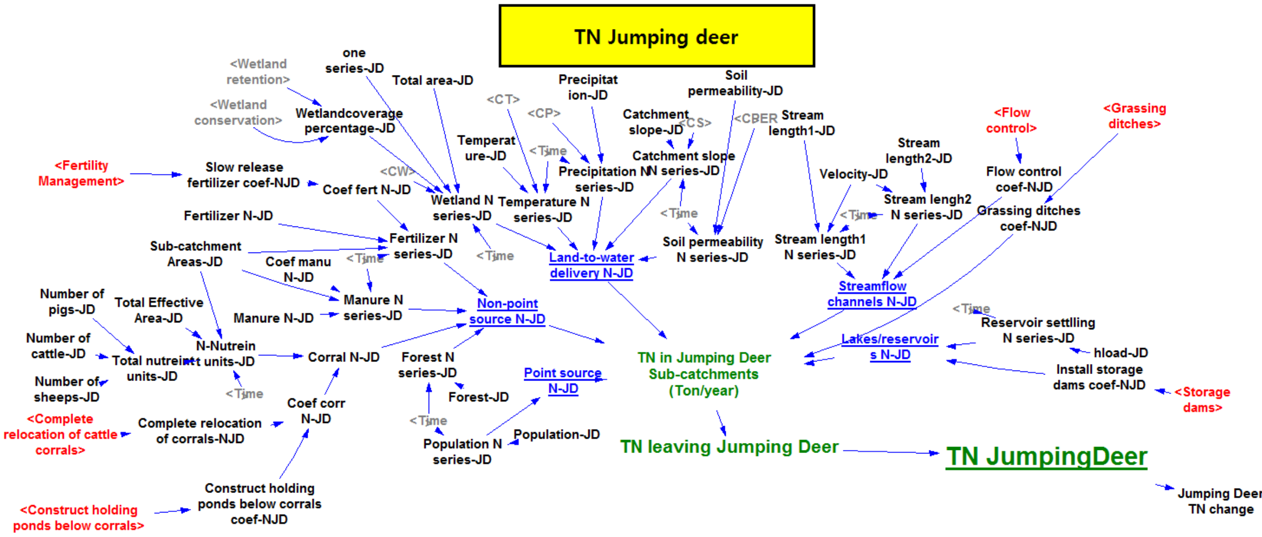

Figure A7 The structure of the water quality module to estimate TN loads in Jumping Deer.

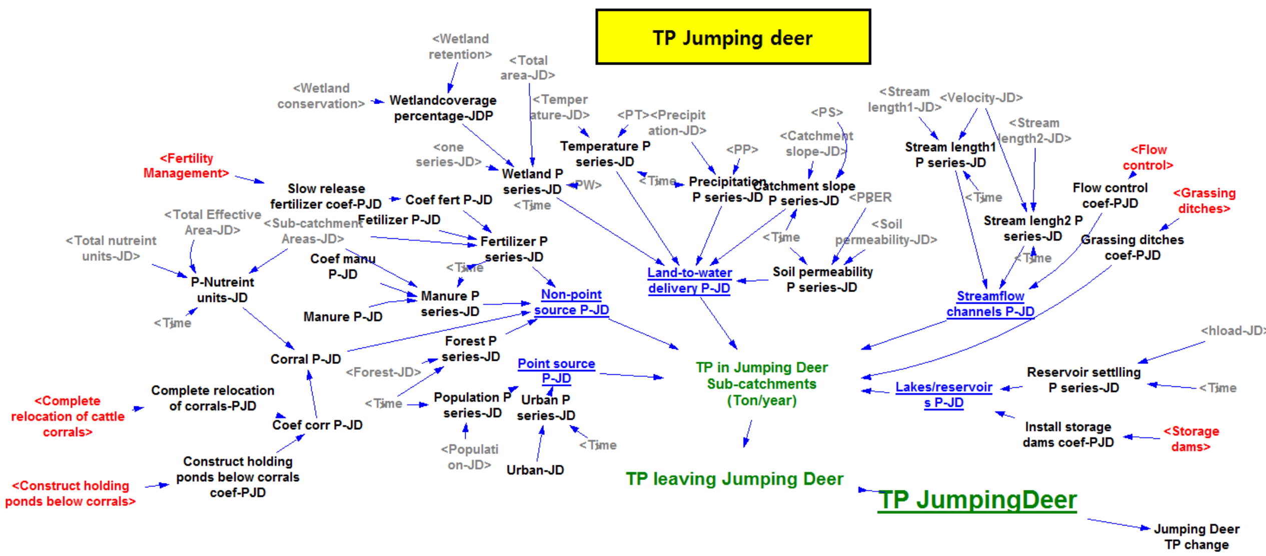

Figure A8 The structure of the water quality module to estimate TP loads in Jumping Deer

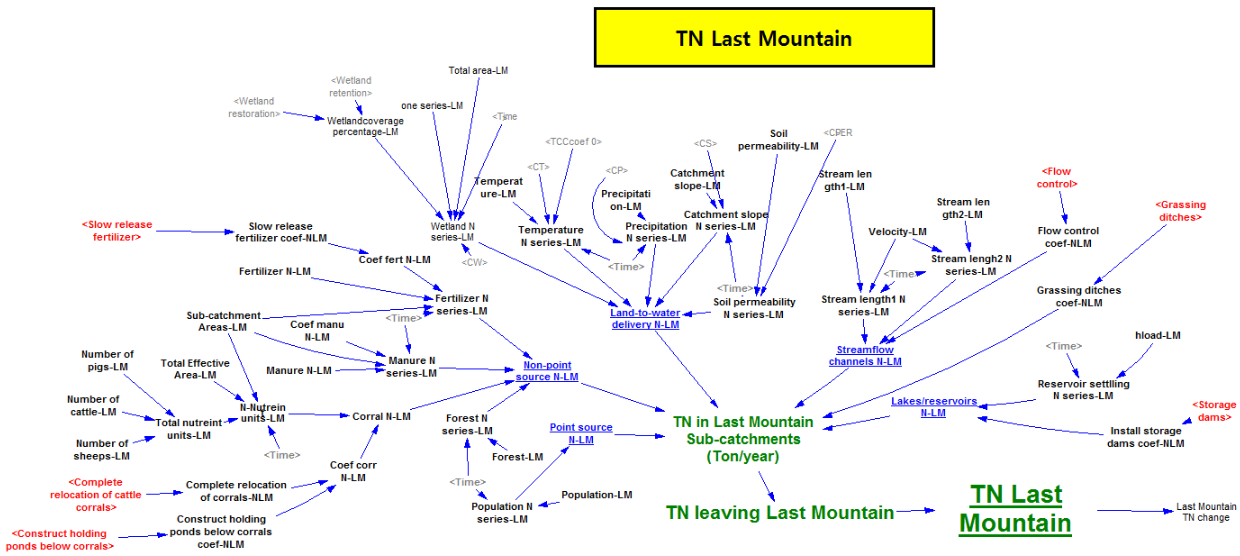

Figure A9 The structure of the water quality module to estimate TN loads in Last Mountain Creek

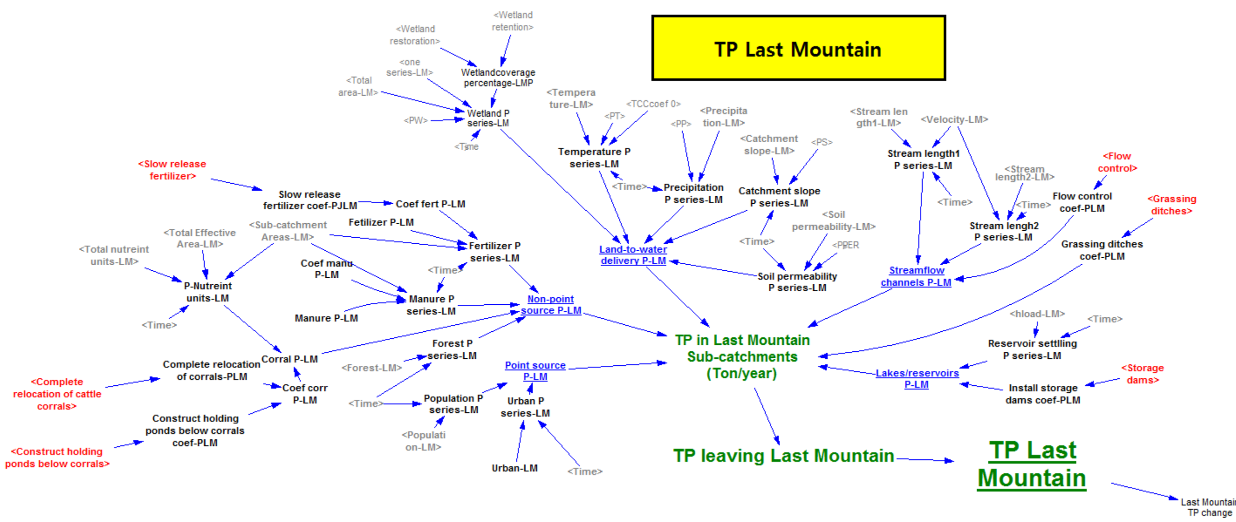

Figure A10 The structure of the water quality module to estimate TP loads in Last Mountain Creek

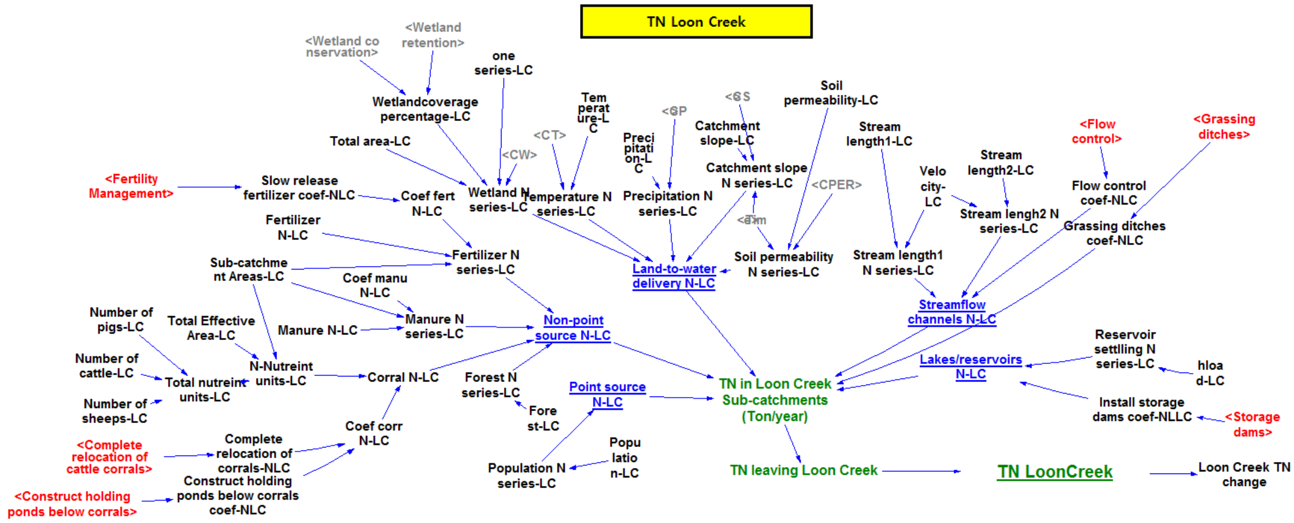

Figure A11 The structure of the water quality module to estimate TN loads in Loon creek

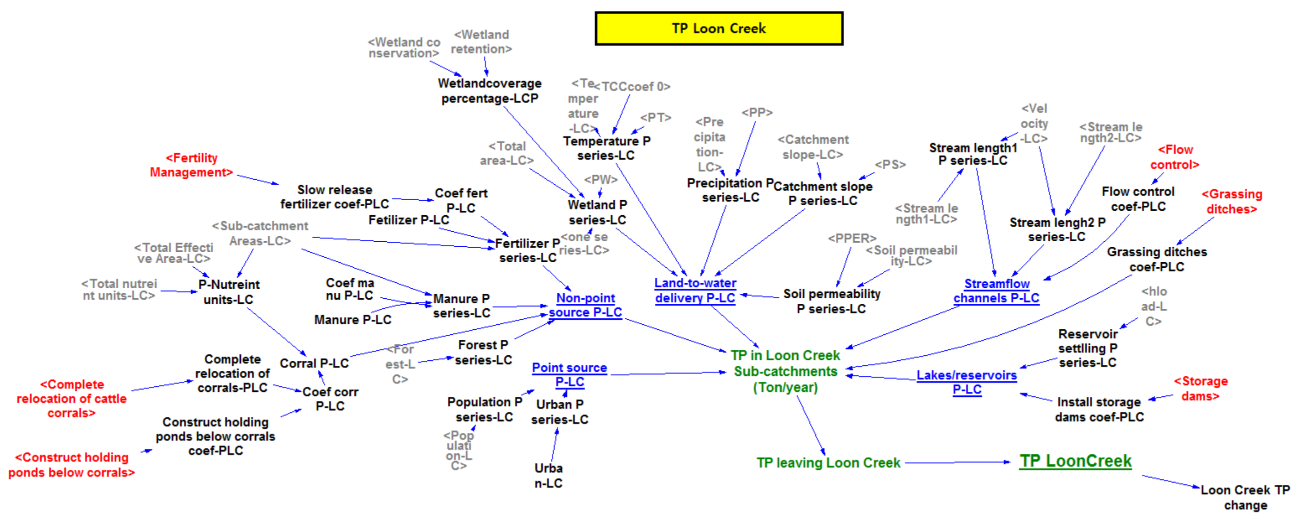

Figure A12 The structure of the water quality module to estimate TN loads in Loon creek

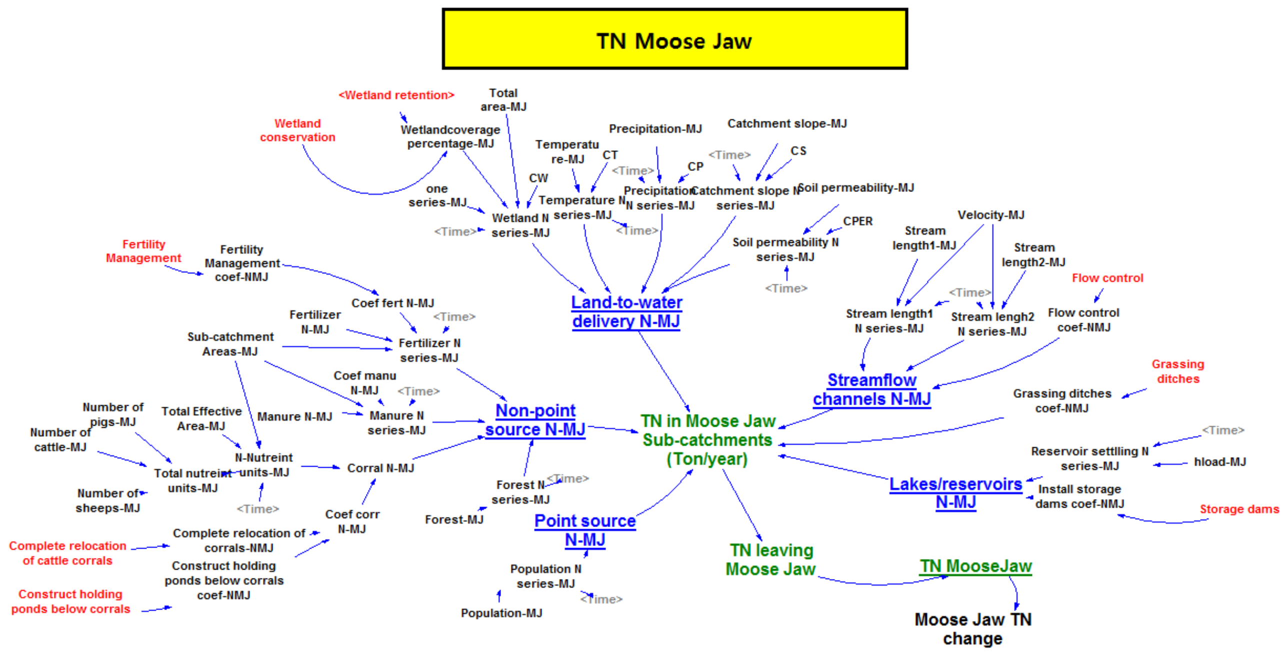

Figure A13 The structure of the water quality module to estimate TN loads in Moose Jaw River.

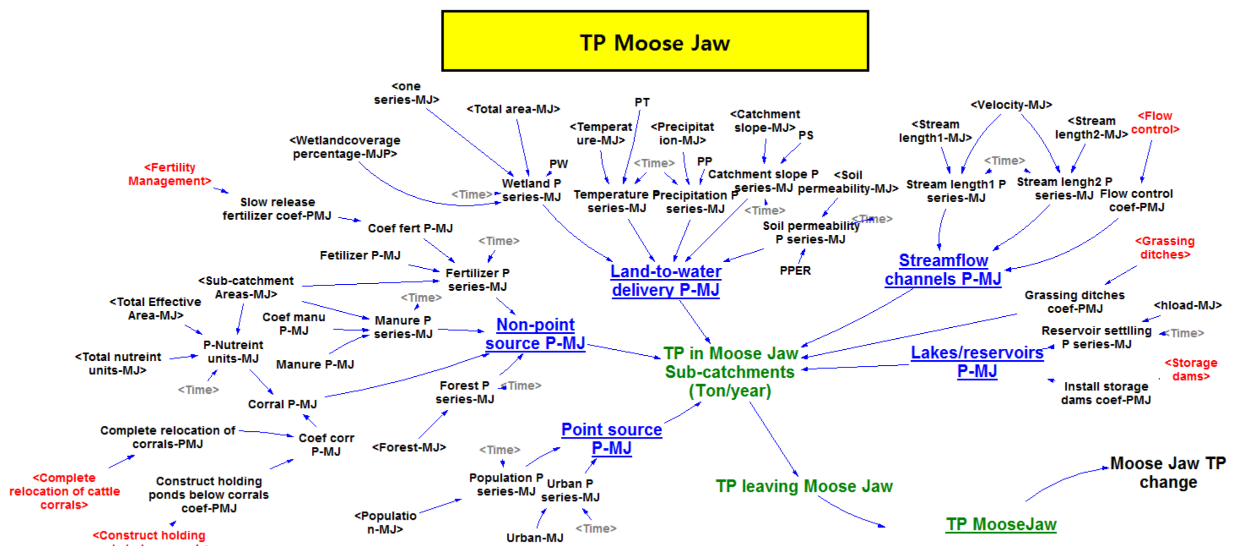

Figure A14 The structure of the water quality module to estimate TP loads in Moose Jaw River.

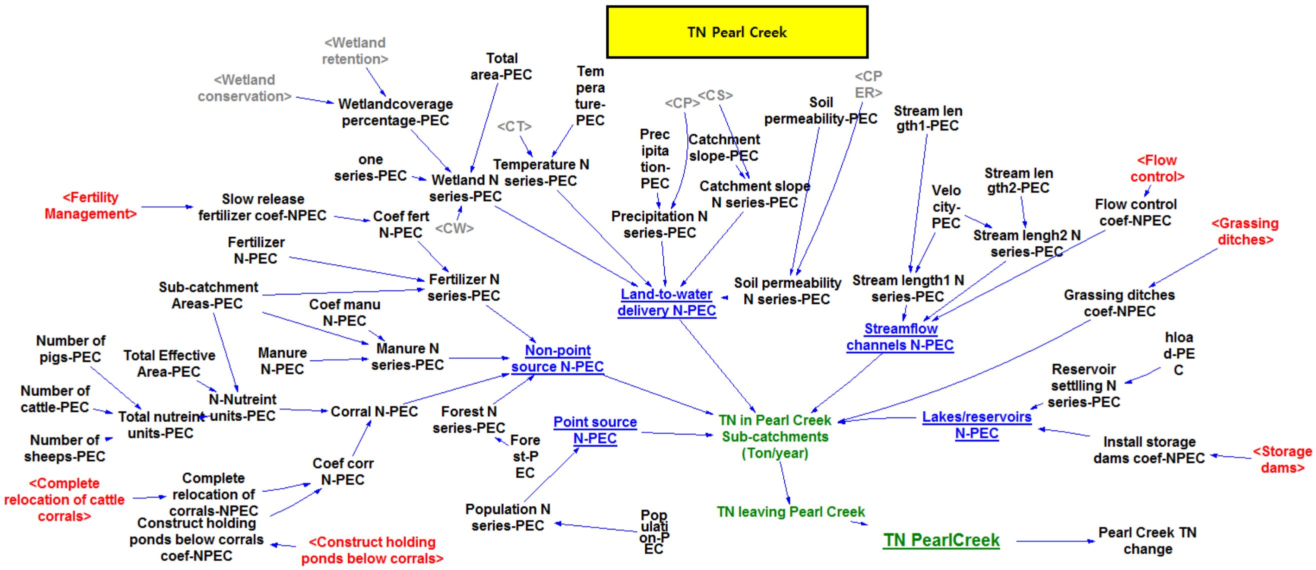

Figure A15 The structure of the water quality module to estimate TP loads in Moose Jaw River.

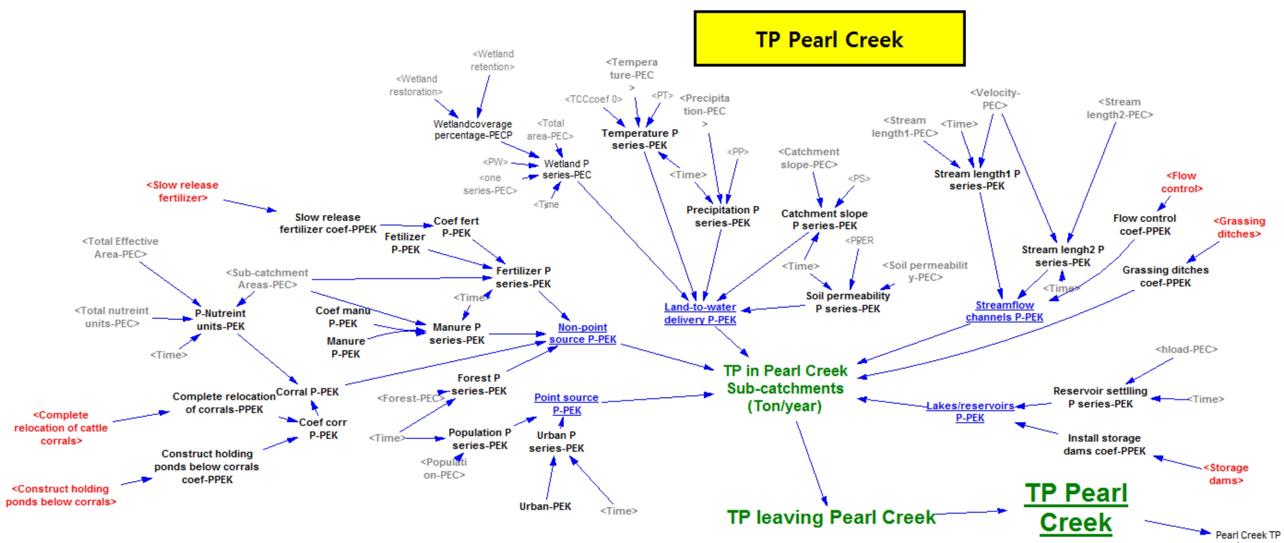

Figure A16 The structure of the water quality module to estimate TP loads in Pearl Creek.

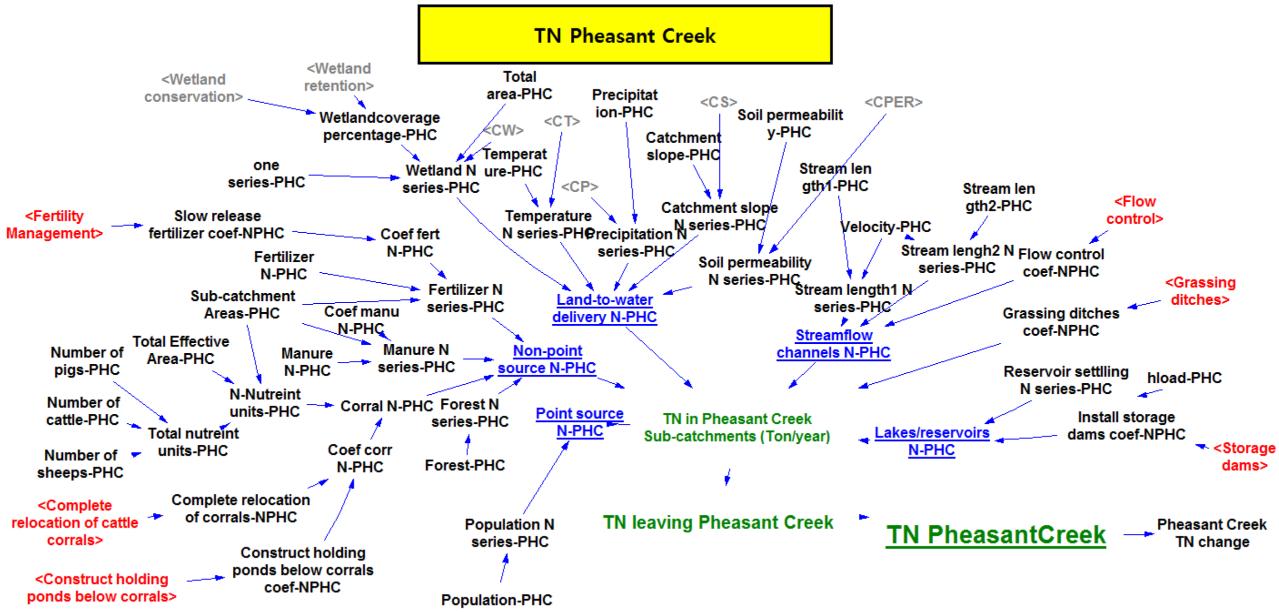

Figure A17 The structure of the water quality module to estimate TN loads in Pheasant Creek.

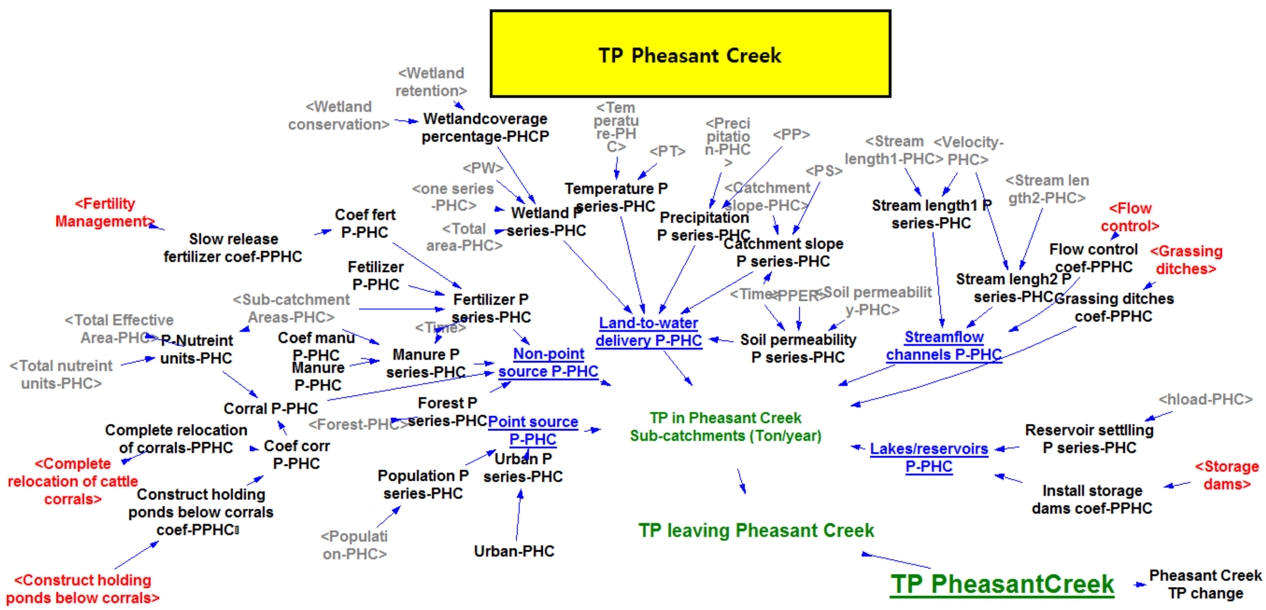

Figure A18 The structure of the water quality module to estimate TP loads in Pheasant Creek.

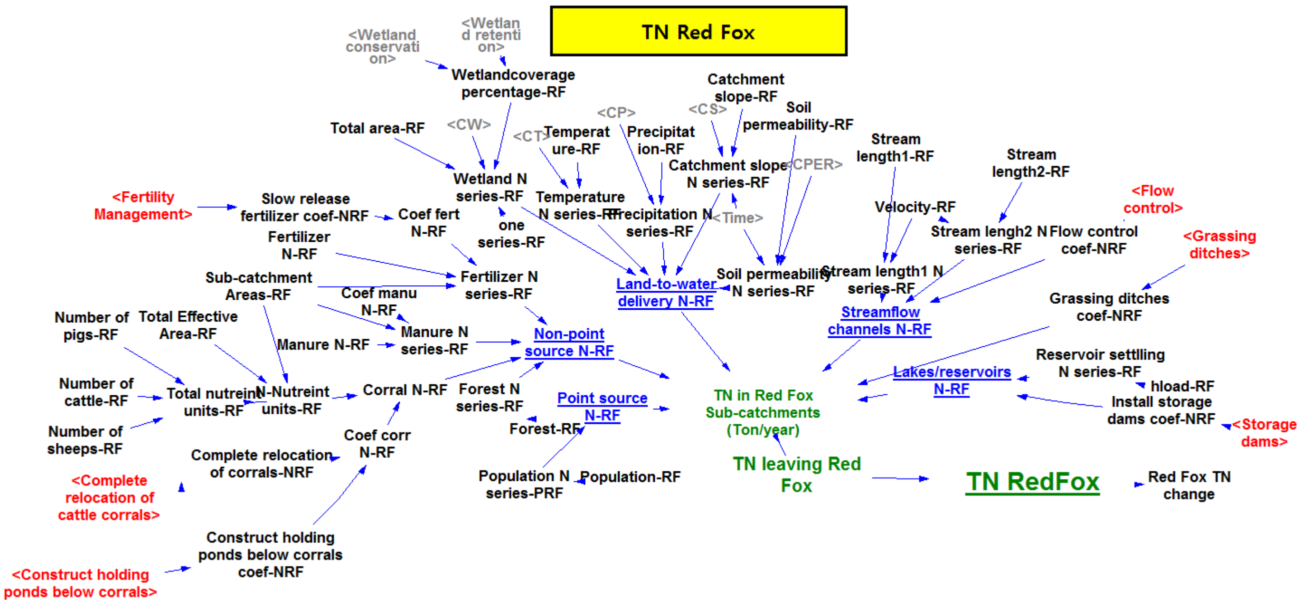

Figure A19 The structure of the water quality module to estimate TN loads in Redfox Creek.

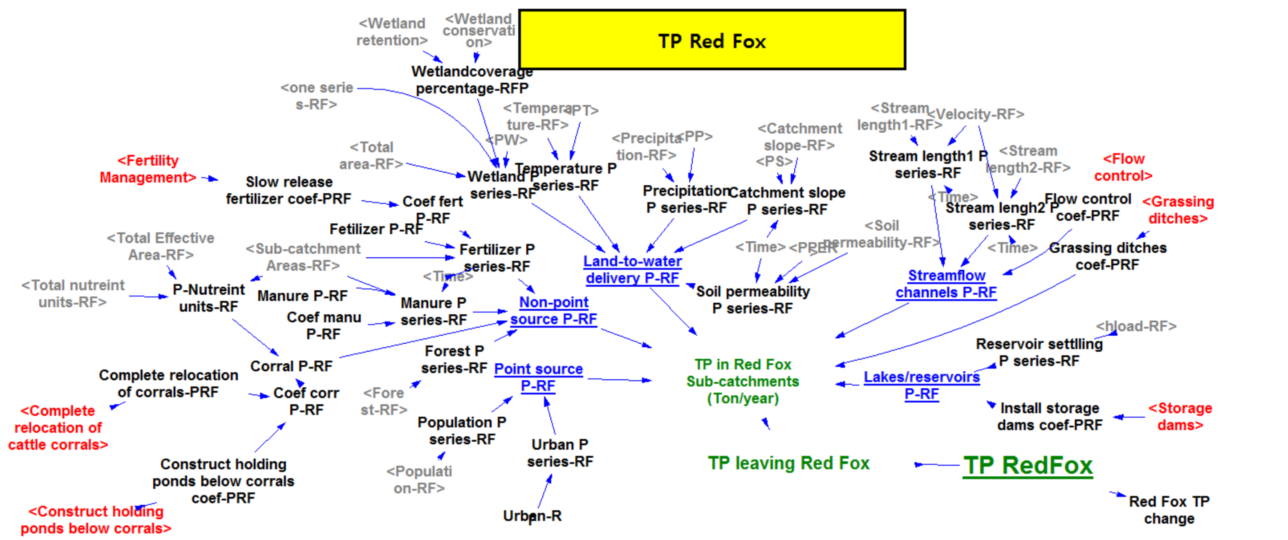

Figure A20 The structure of the water quality module to estimate TP loads in Redfox Creek.

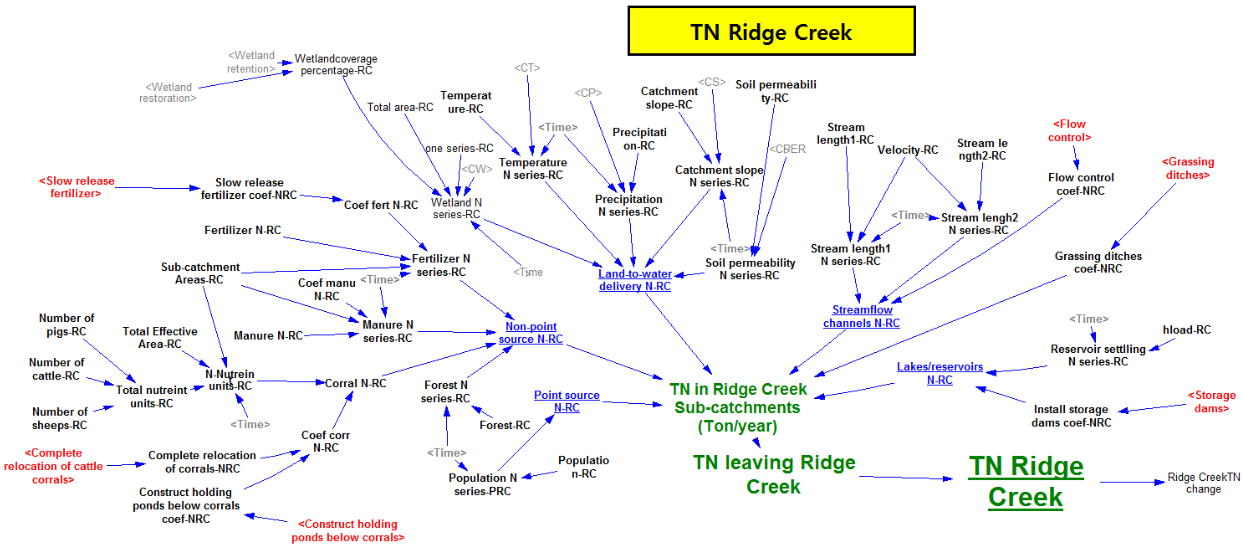

Figure A21 The structure of the water quality module to estimate TN loads in Ridge Creek.

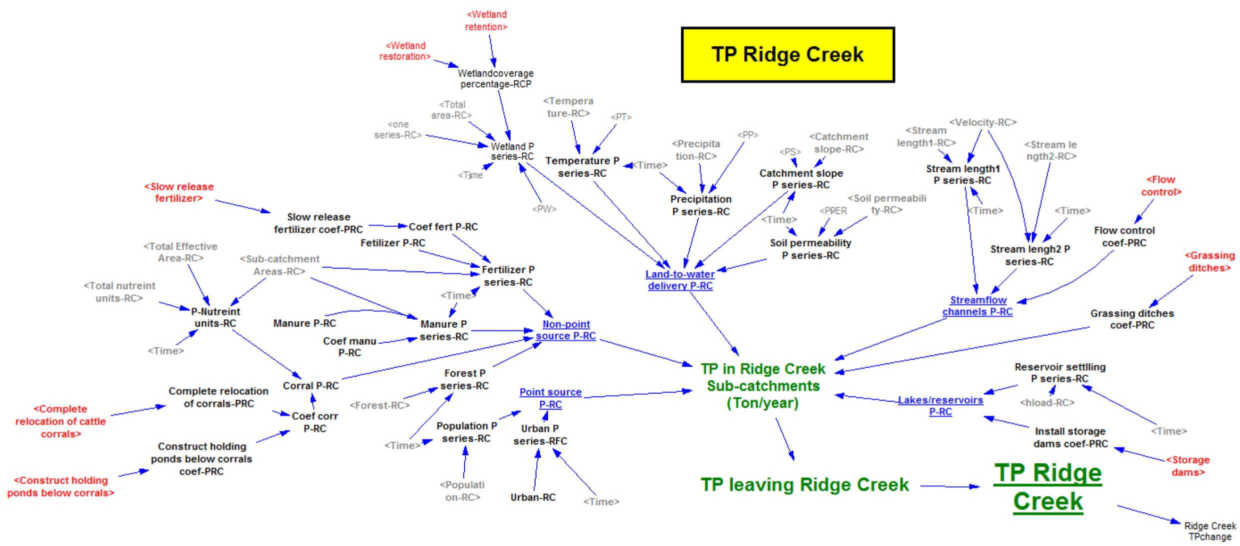

Figure A22 The structure of the water quality module to estimate TP loads in Ridge Creek.

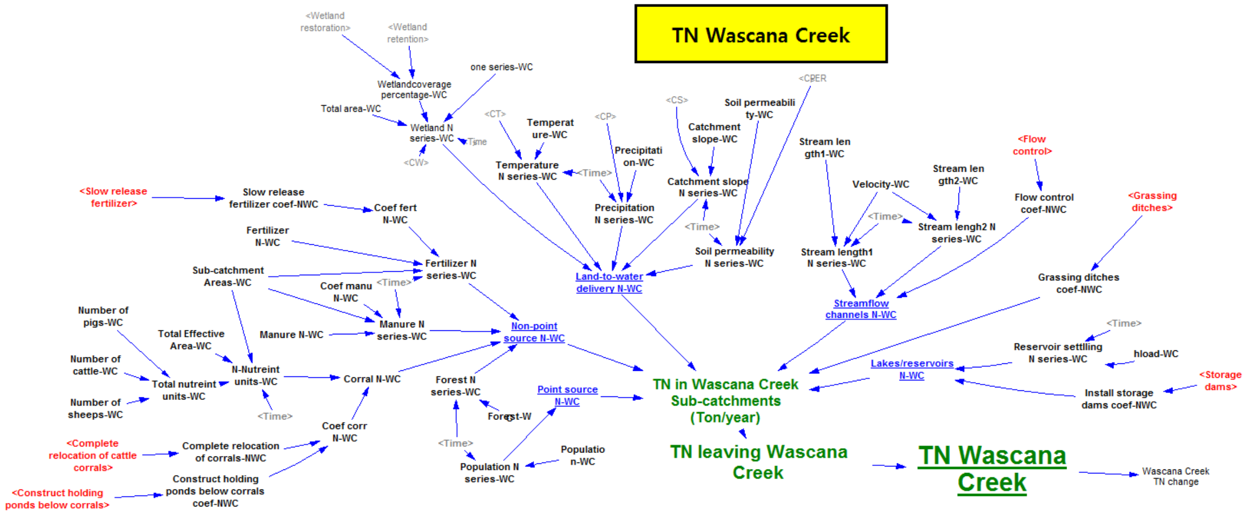

Figure A23 The structure of the water quality module to estimate TN loads in Wascana Creek.

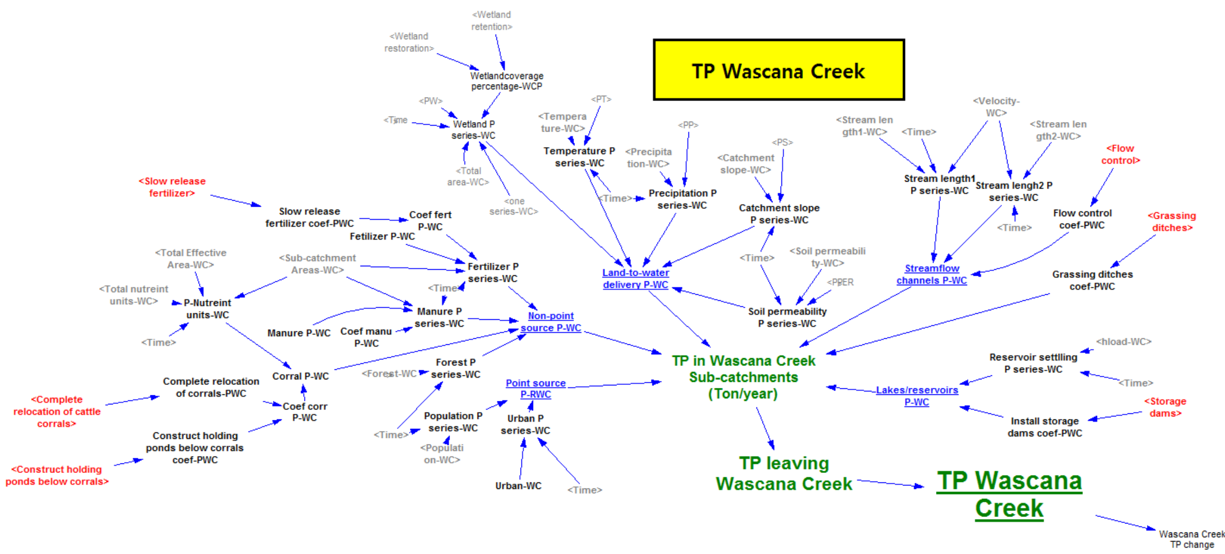

Figure A24 The structure of the water quality module to estimate TP loads in Wascana Creek.

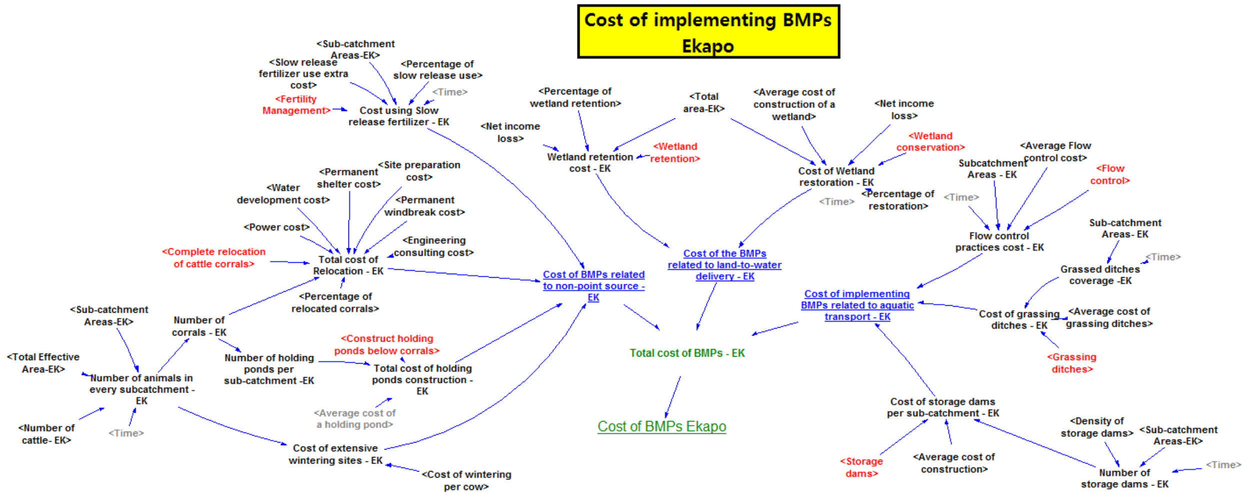

Figure A25 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Ekapo.

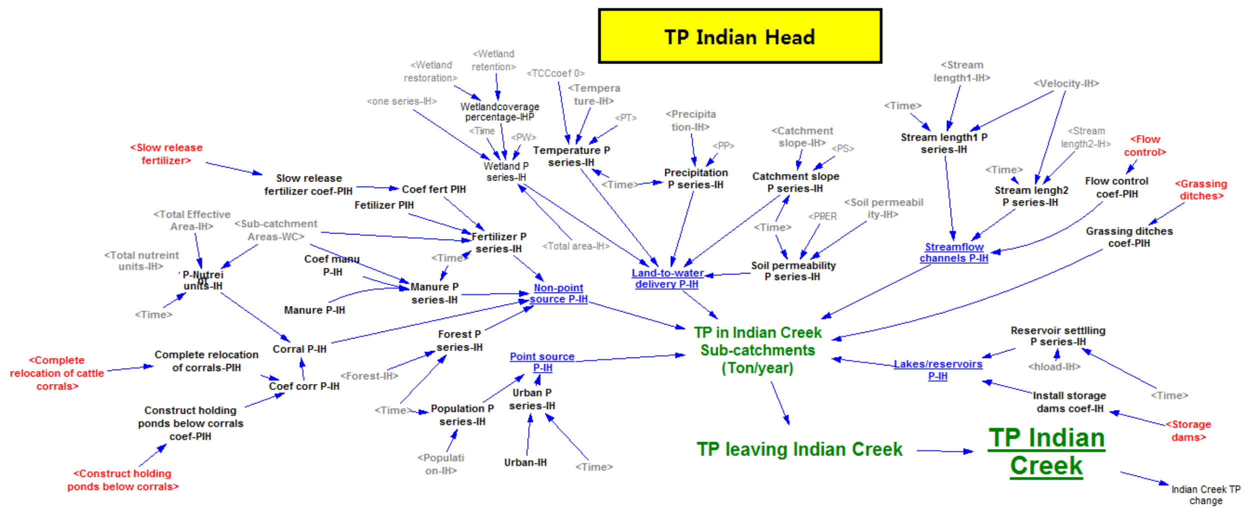

Figure A26 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Indian Head.

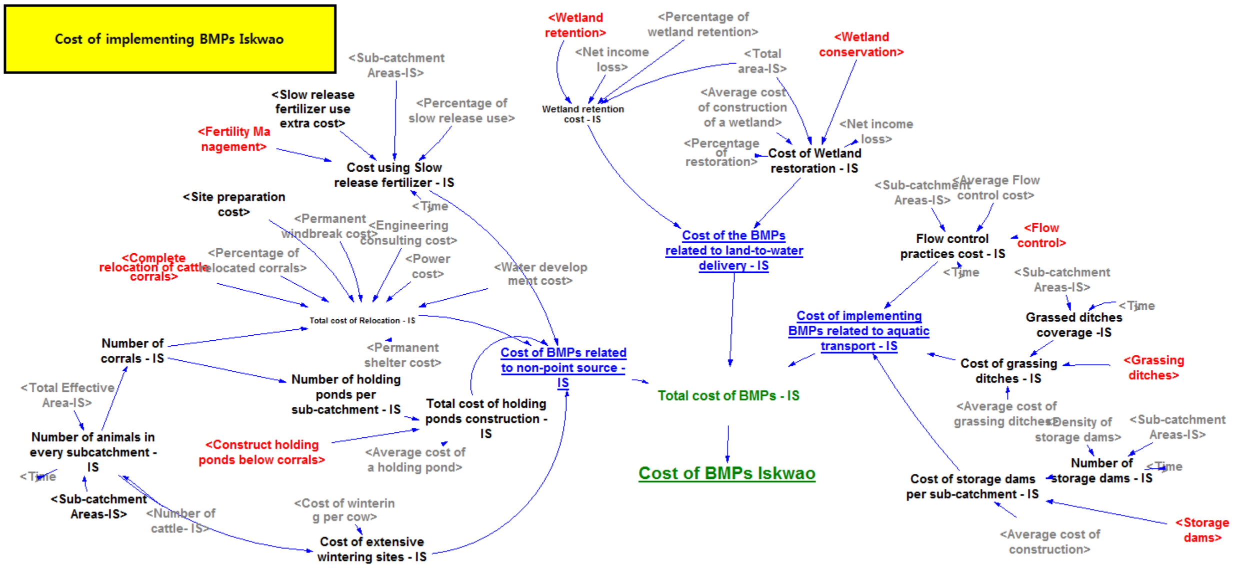

Figure A27 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Iskwao.

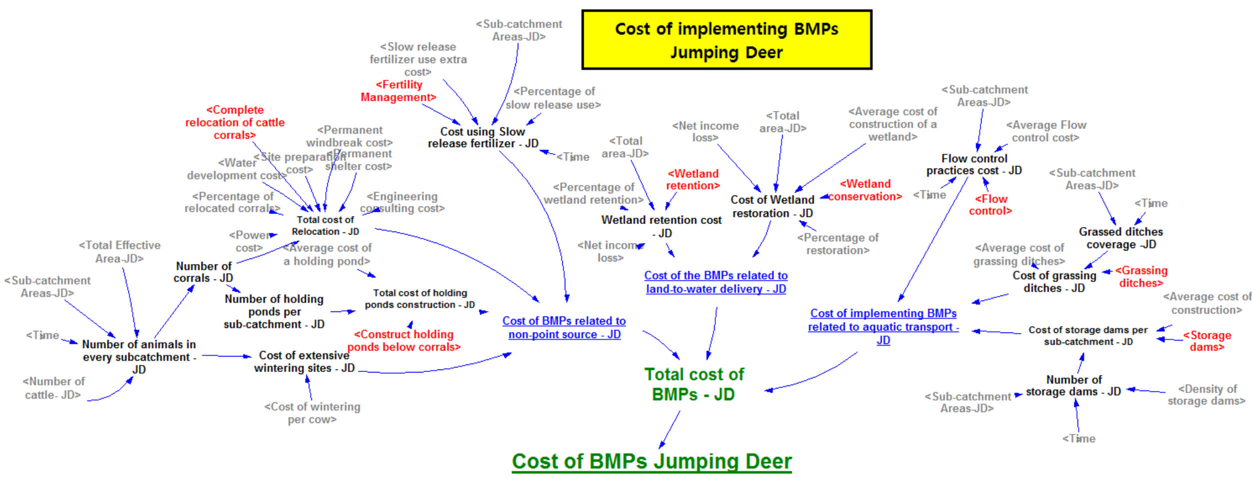

Figure A28 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Jumping Deer.

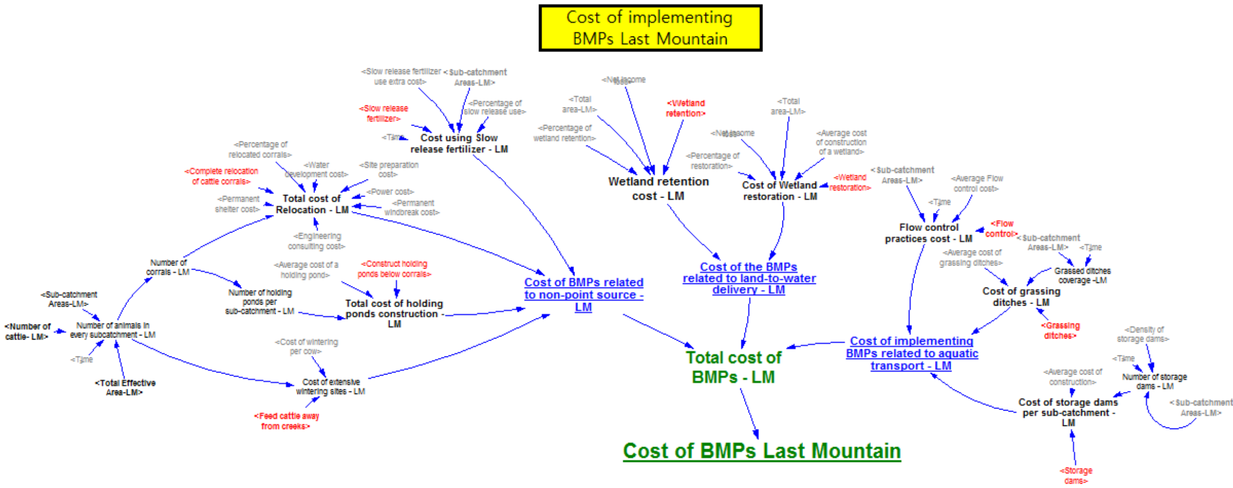

Figure A29 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Last Mountain Creek.

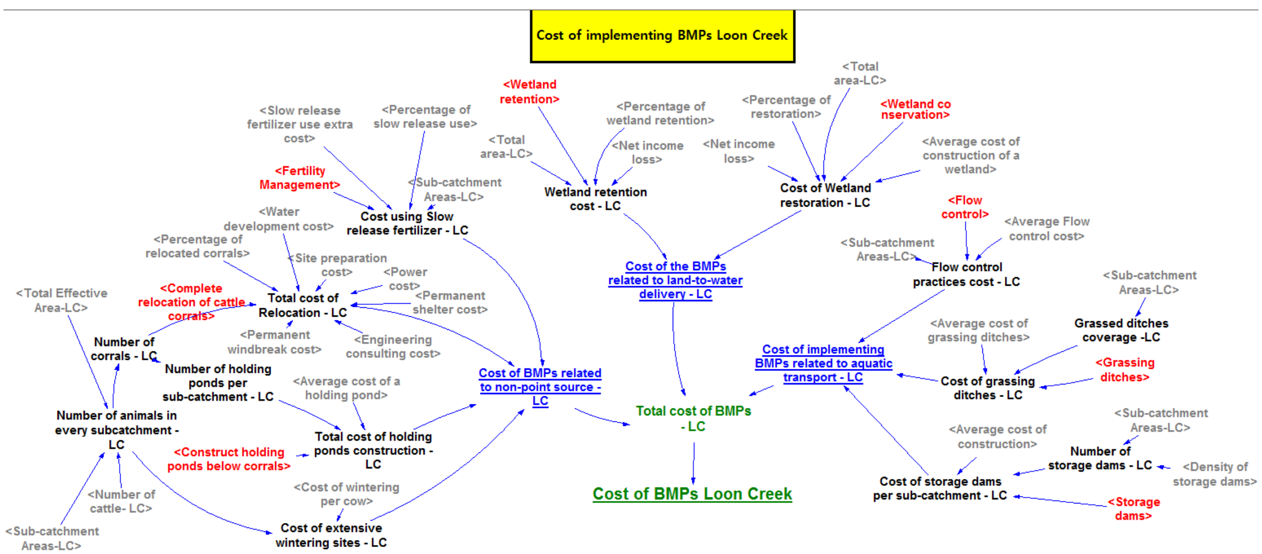

Figure A30 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Loon Creek.

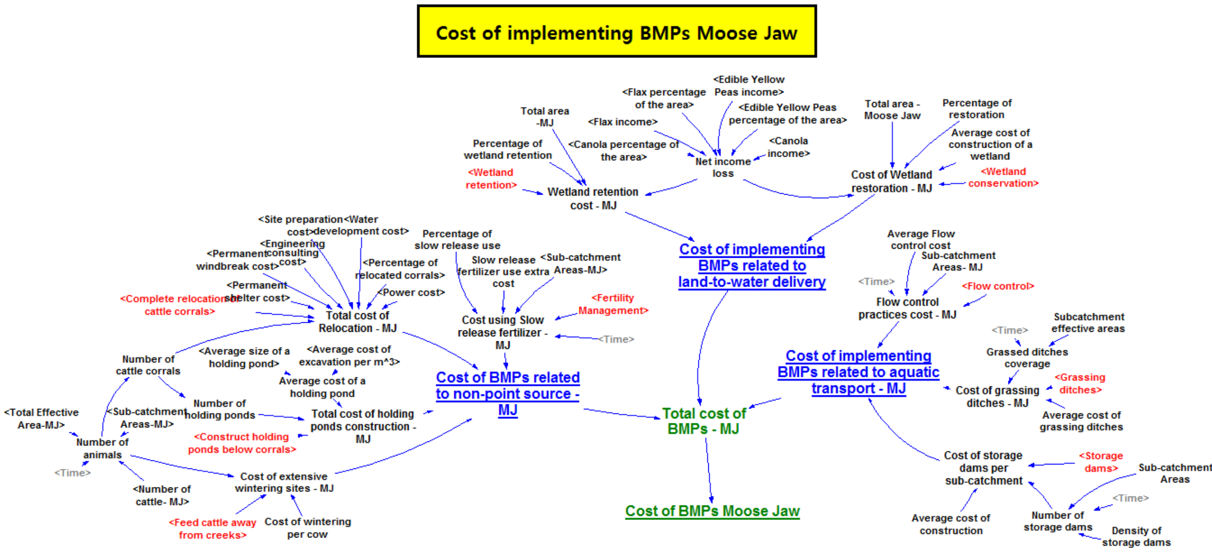

Figure A31 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Moose Jaw River.

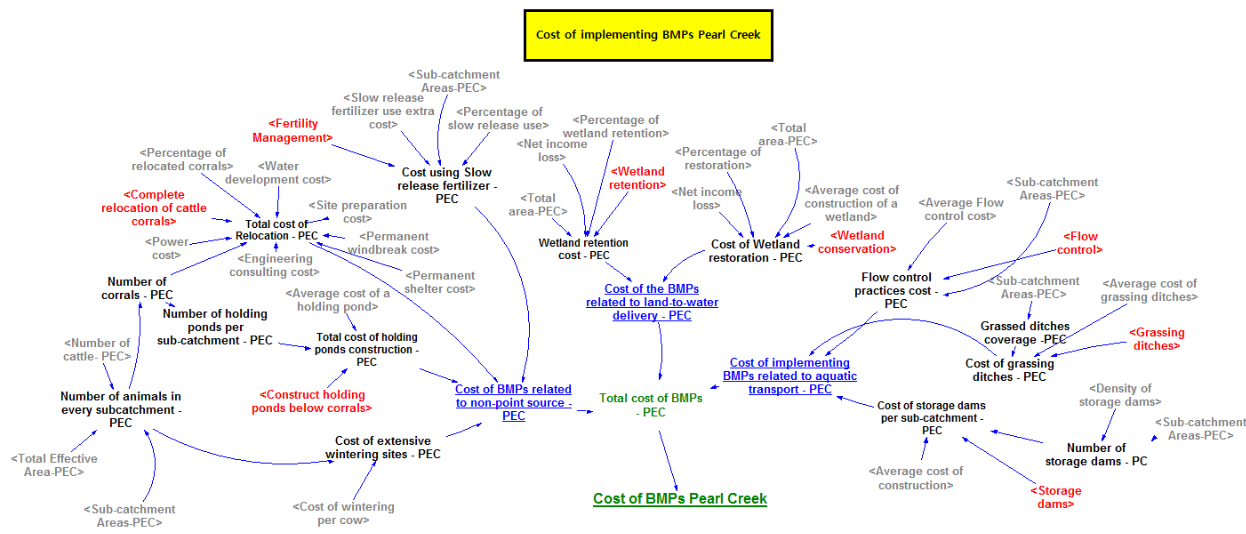

Figure A32 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Pearl Creek.

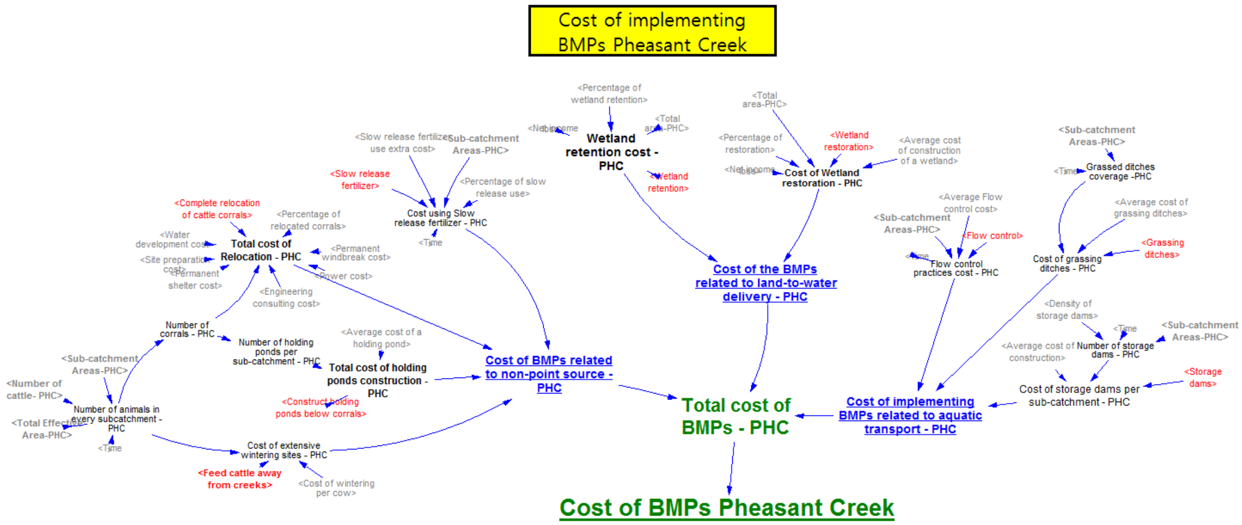

Figure A33 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Pheasant Creek.

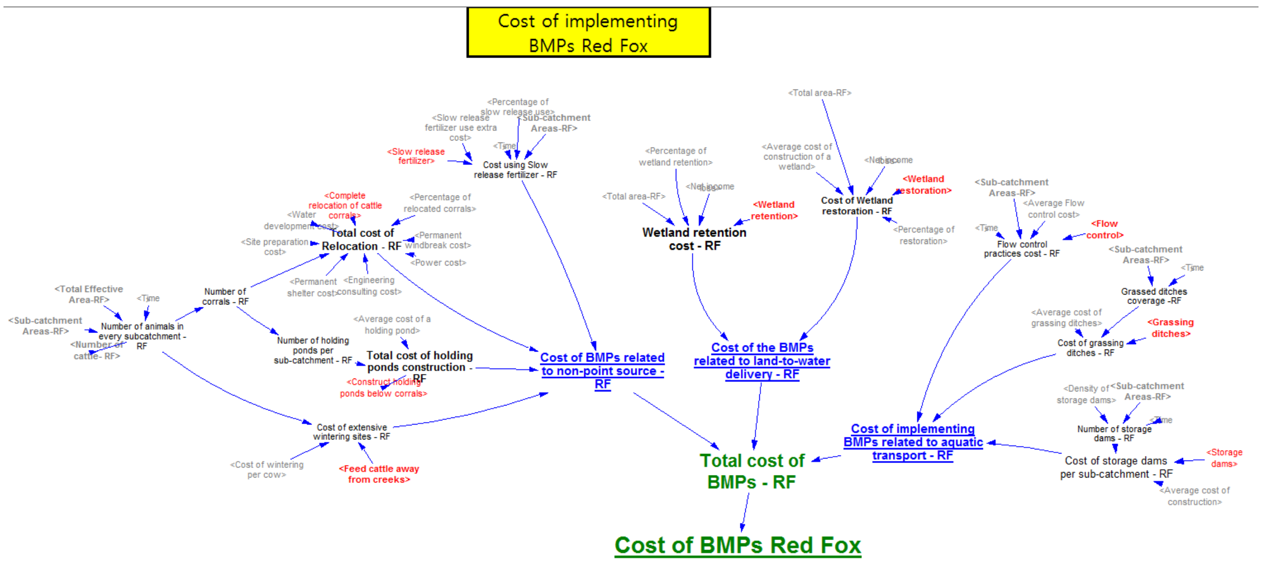

Figure A34 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Redfox Creek.

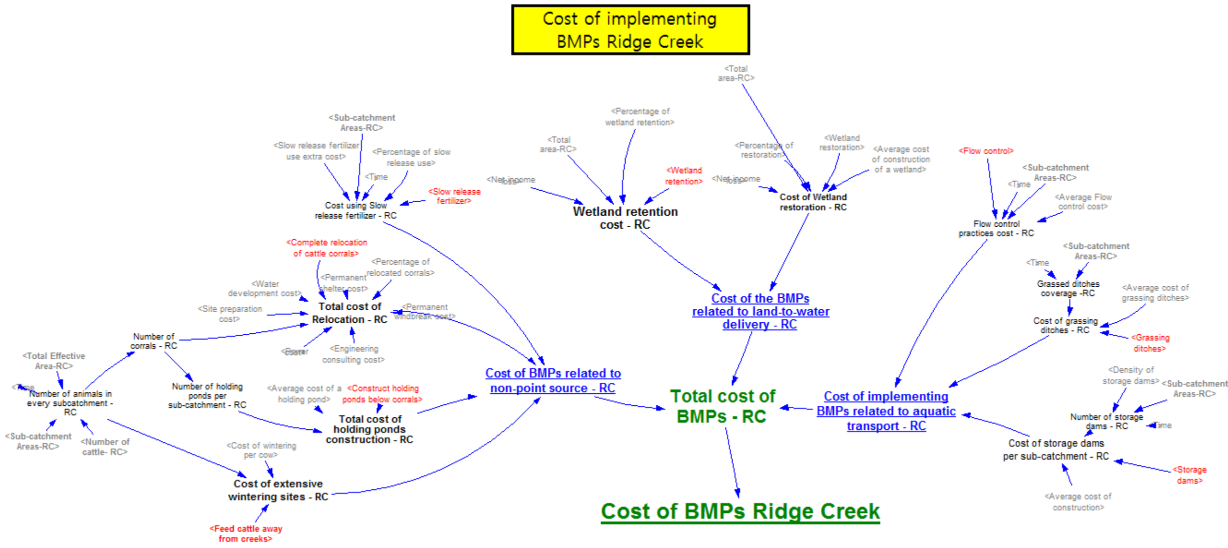

Figure A35 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Ridge Creek.

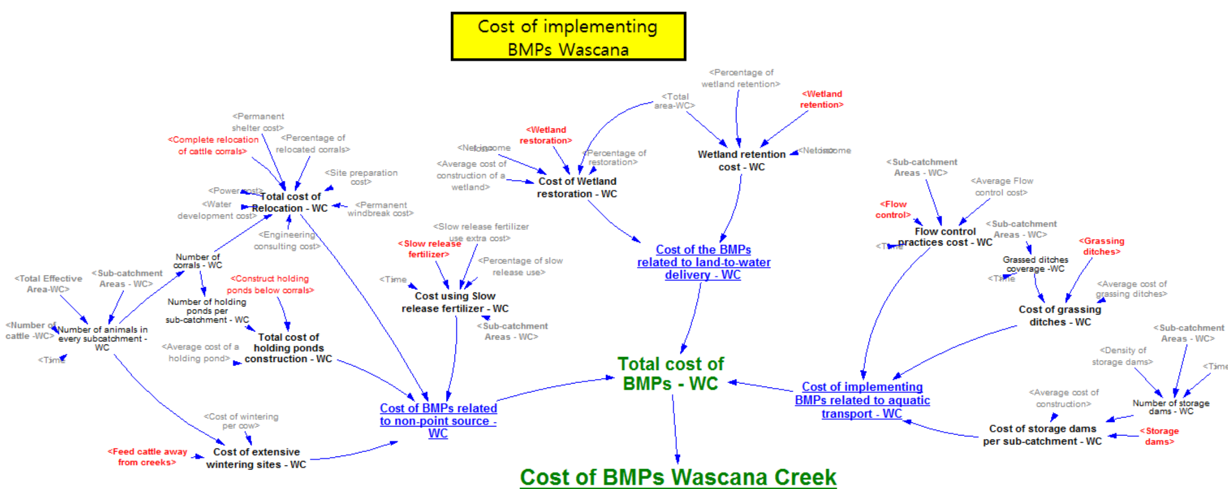

Figure A36 The structure of the economic evaluation module to estimate the costs associated with implementation of BMPs in Wascana Creek.

Table A1 Optimal combinations of BMPs, selected based on their cost of implementation and abatement of TN and TP for the QARB tributaries.

QARB tributaries	**Optimal combination of BMPs**	**Changes in TN (%)**	**Changes in TP (%)**	**Total cost of implementation ($M)**
Ekapo	CHP, WRT	-120	-48	2.0
Indian Head	CHP, GRD, CSD, WCN	-101	-58	0.6
Iskwao	WRT	-247	-327	1.3
Jumping Deer	WRT	-165	-61	0.2
Last Mountain Creek	WRT	-166	-125	21.5
Loon Creek	WRT	-602	-223	0.7
Pearl Creek	WRT	-112	-68	1.8
Pheasant Creek	WRT	-104	-48	2.3
Redfox Creek	WCN	-118	-102	0.7
Ridge Creek	CHP, GRD, WCN	-104	-80	0.2
Wascana Creek	CHP, FCP, WCN	-101	-61	7.8

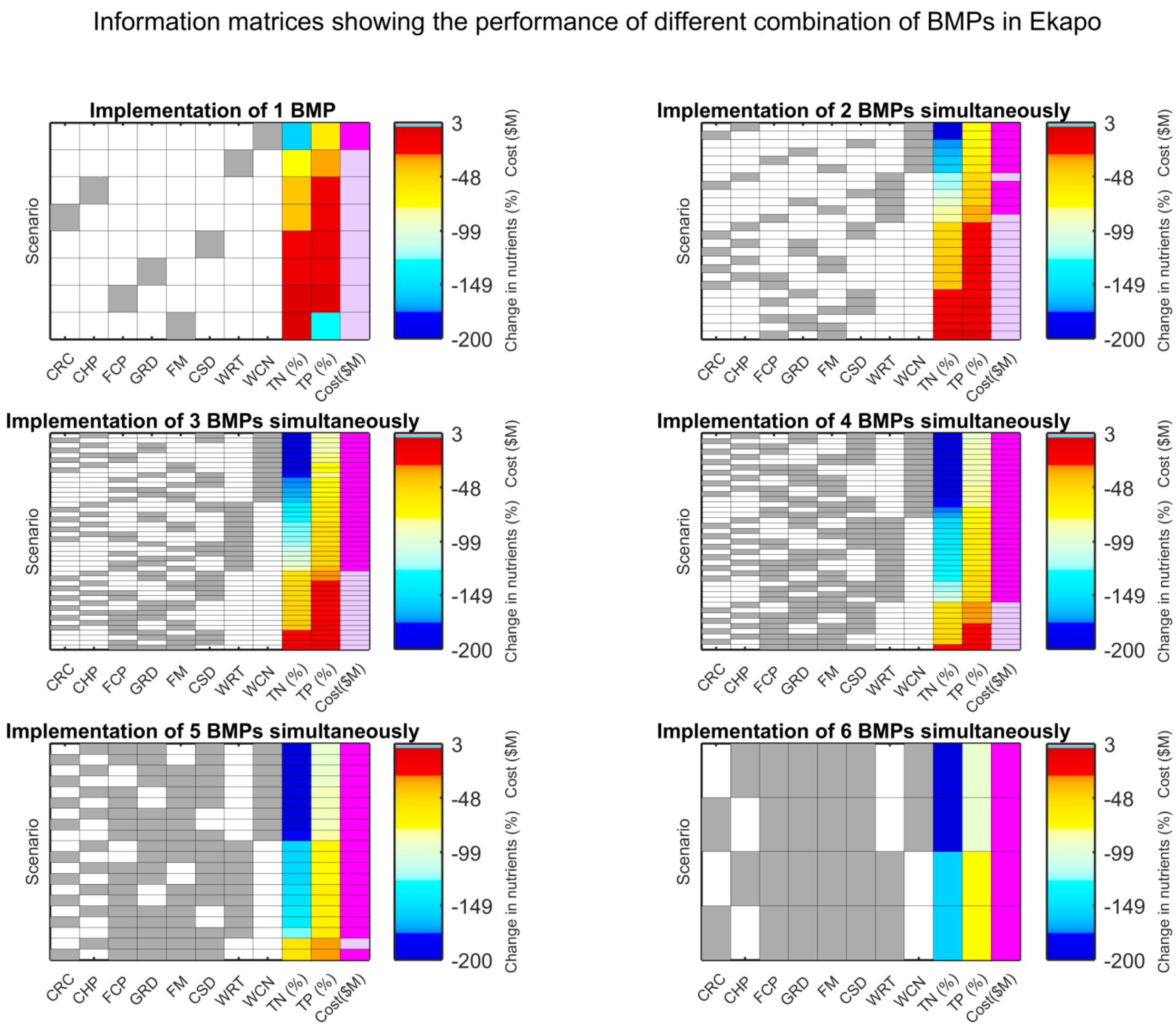

Figure A37 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Ekapo. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

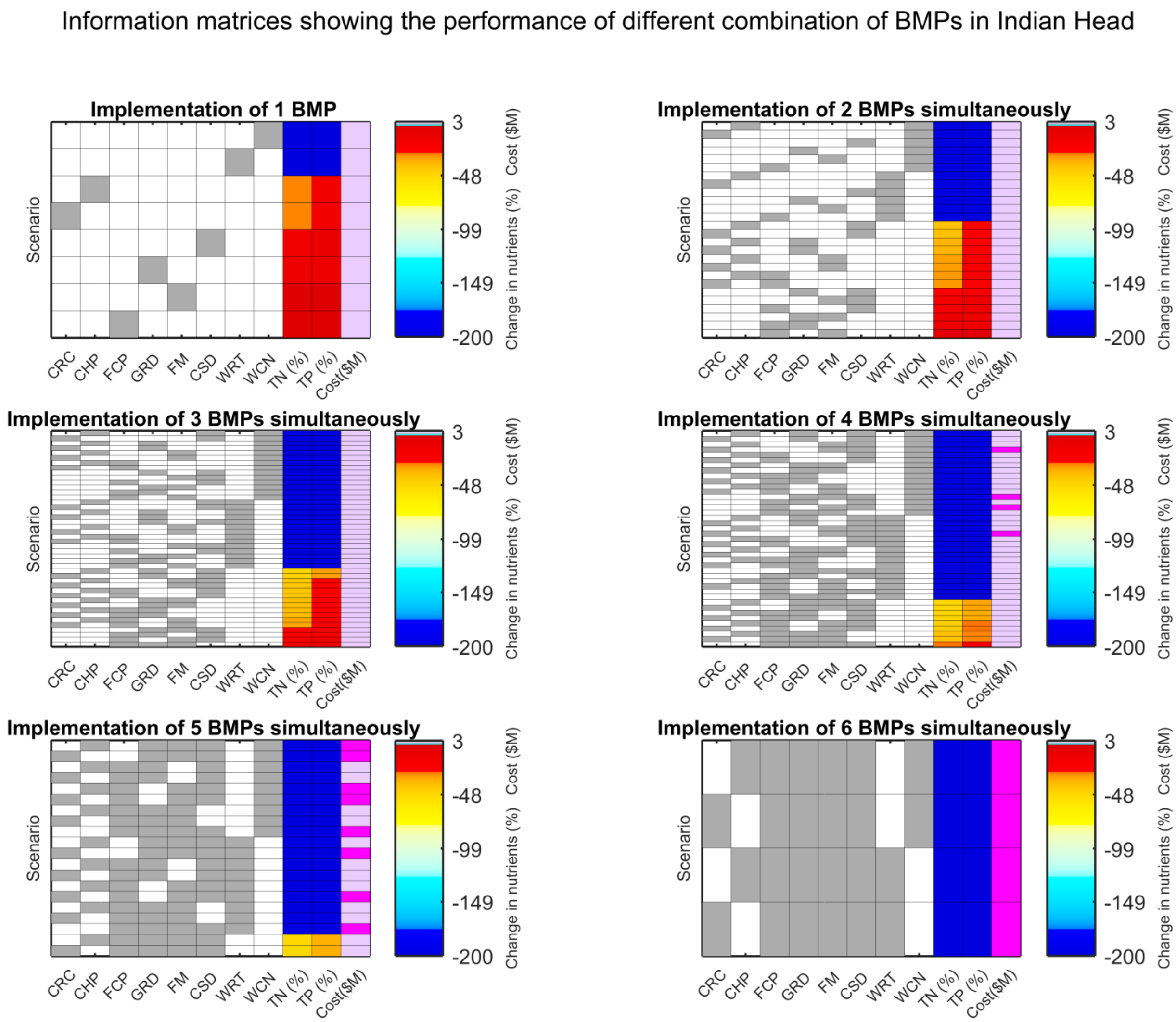

Figure A38 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Indian Head. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

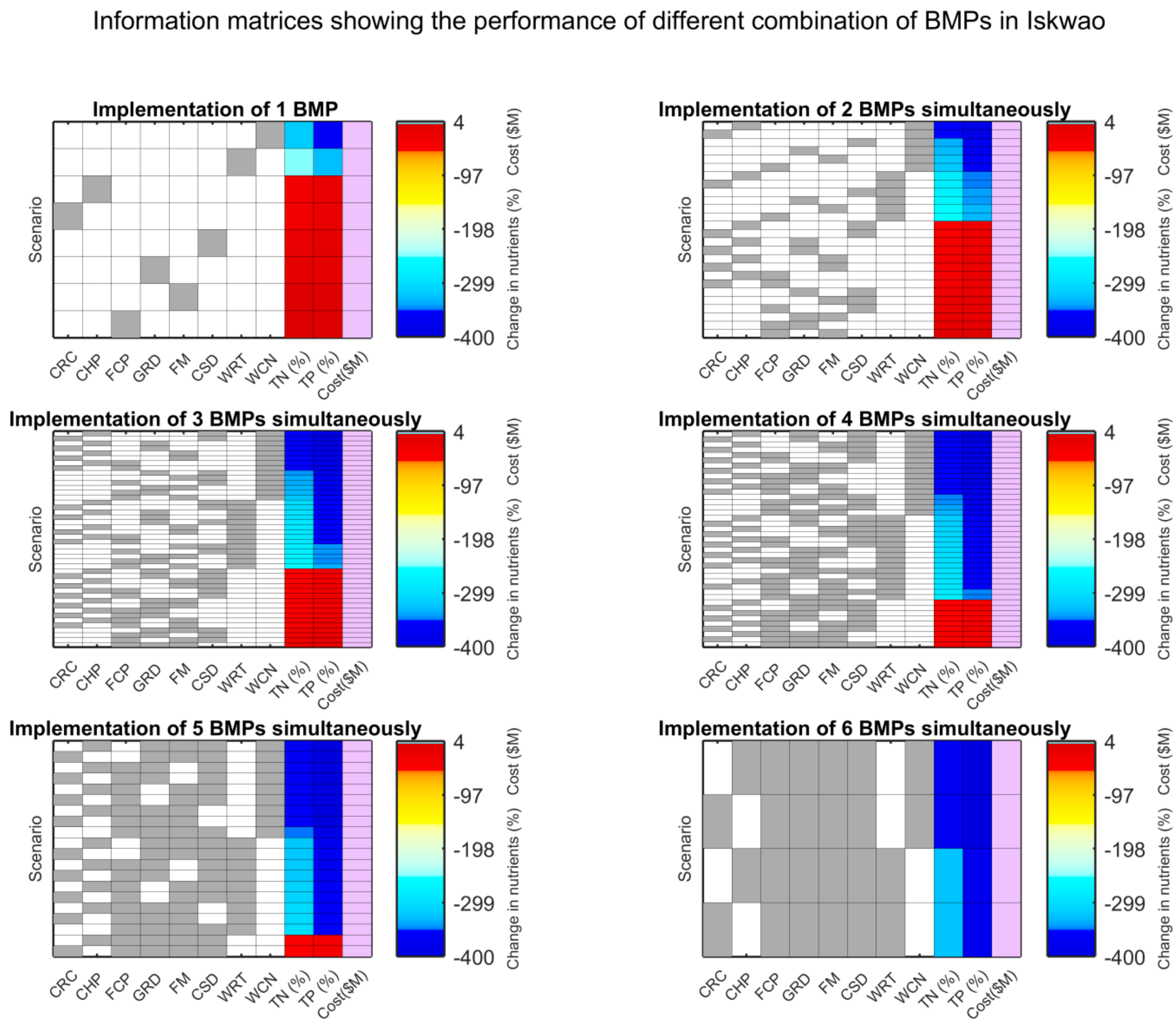

Figure A39 Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Iskwao. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

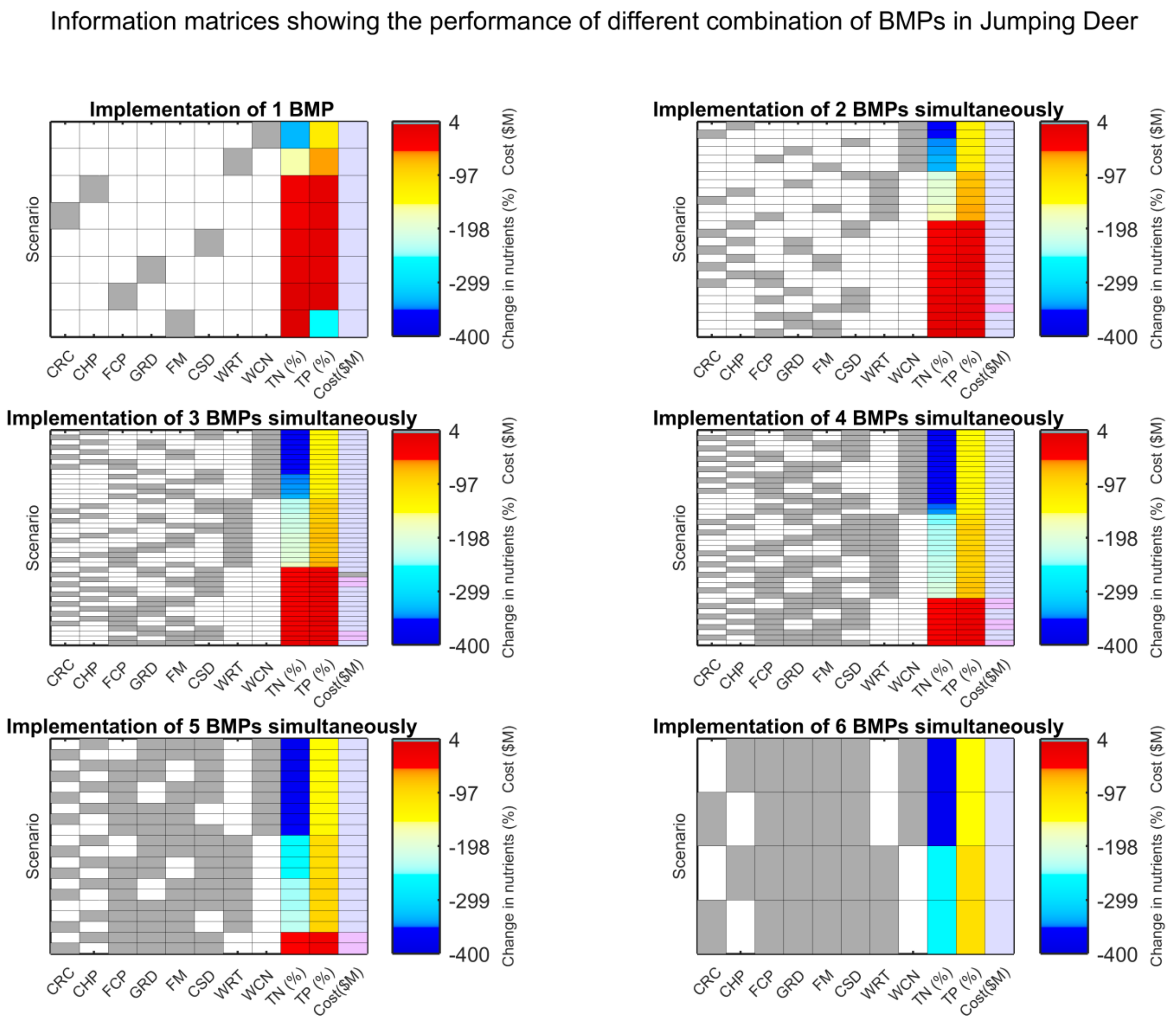

Figure A40 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Jumping Deer. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

Information matrices showing the performance of different combination of BMPs in Last Mountain Creek

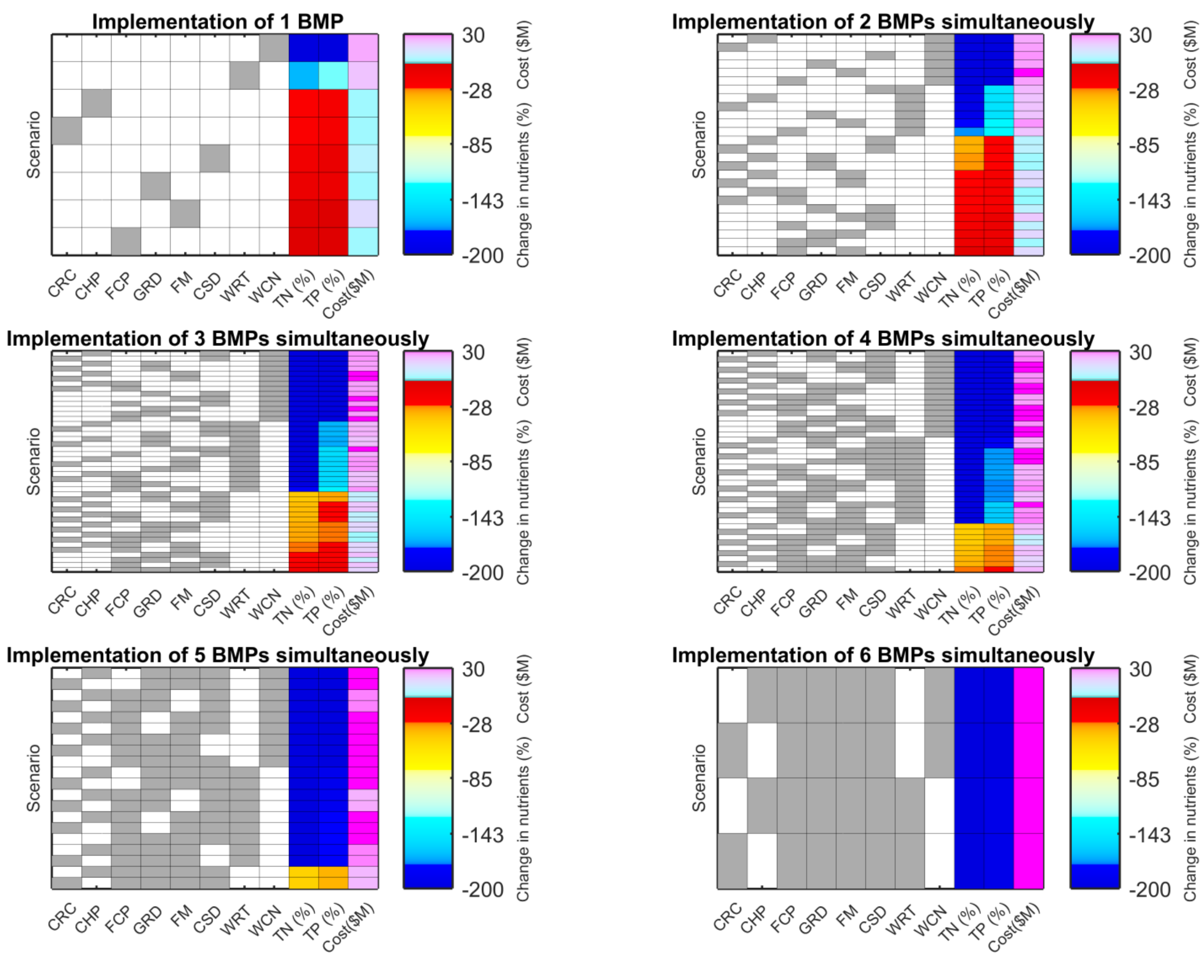

Figure A41 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Jumping Deer. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

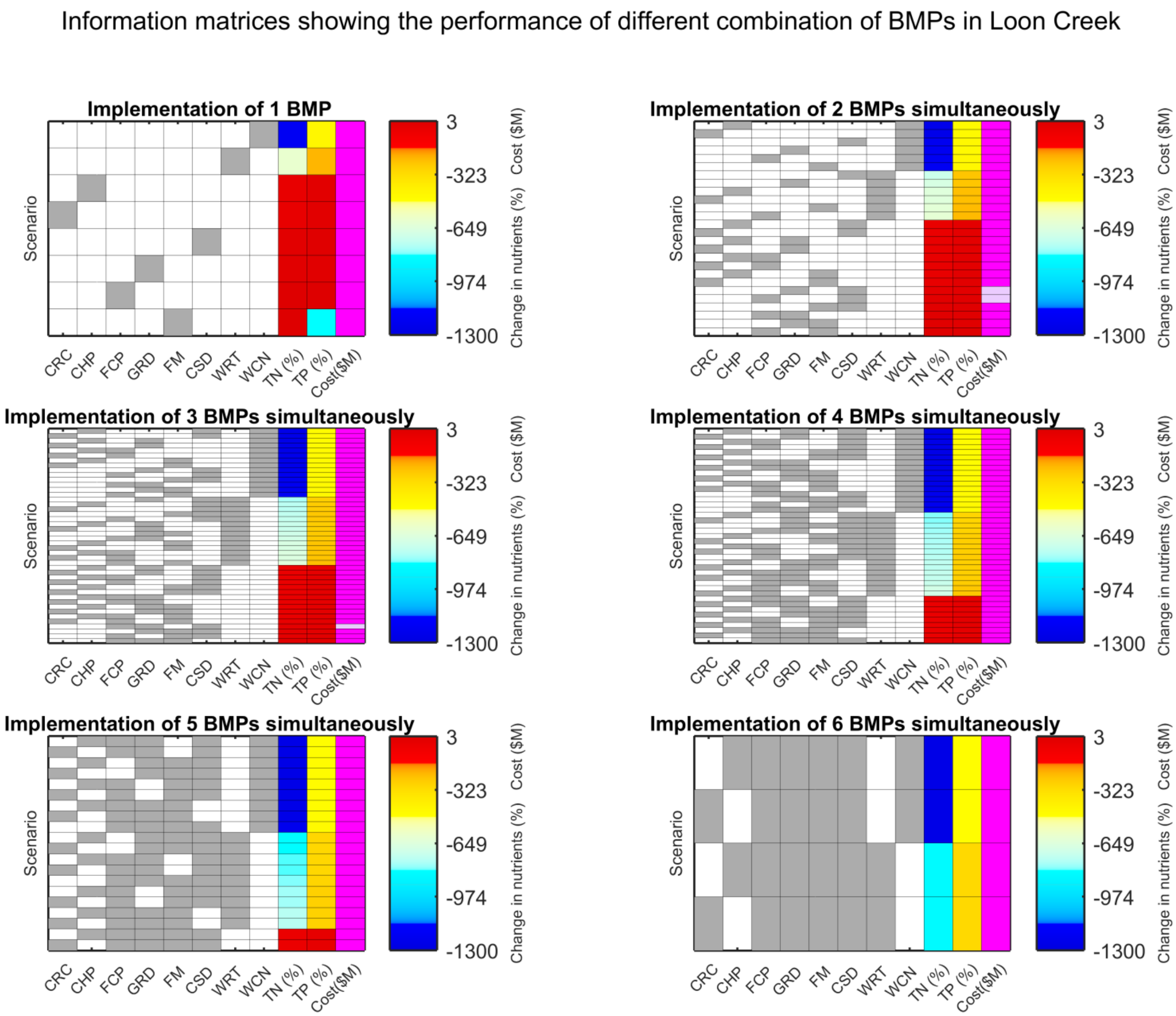

Figure A42 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Loon Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

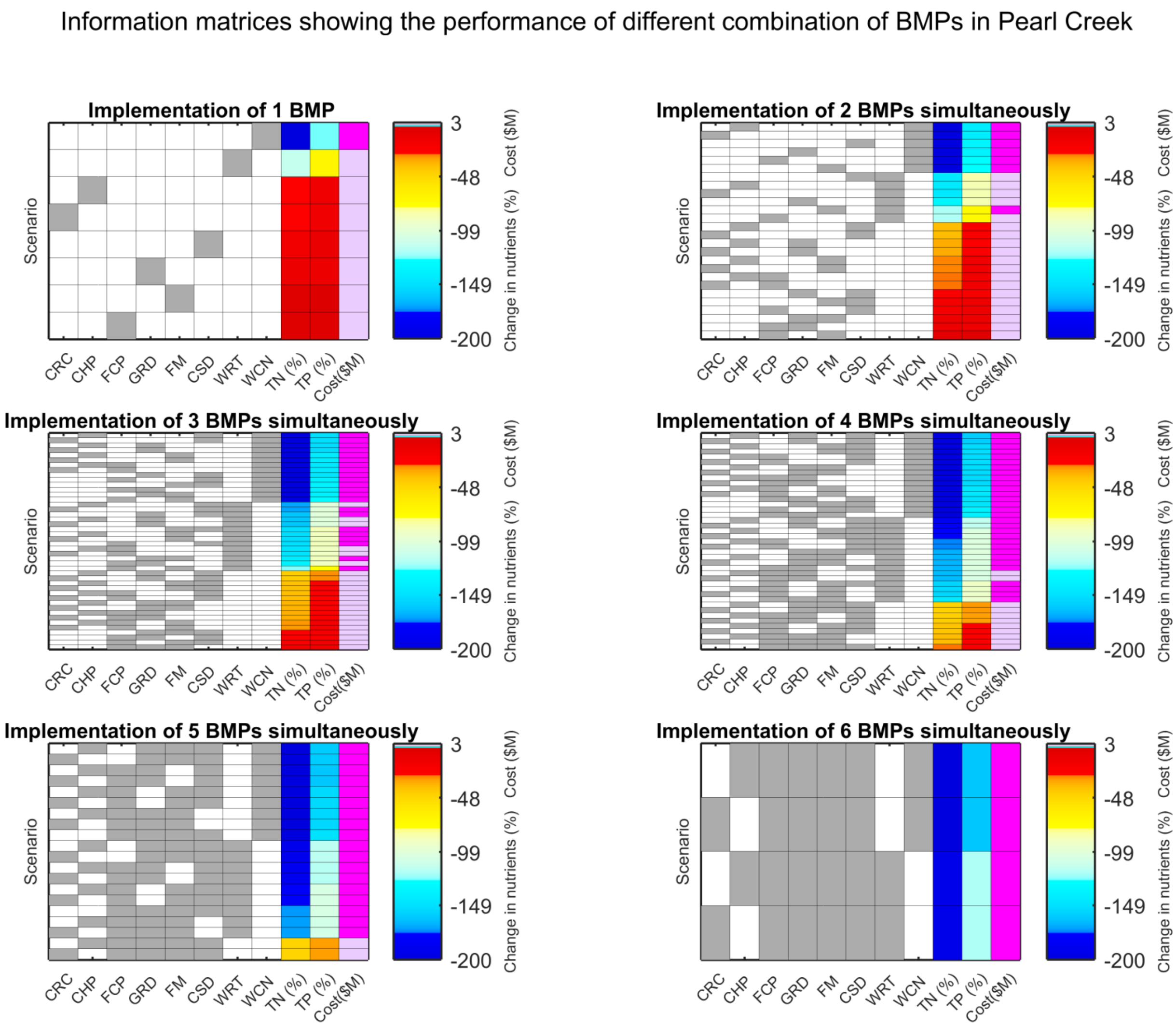

Figure A43 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Pearl Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

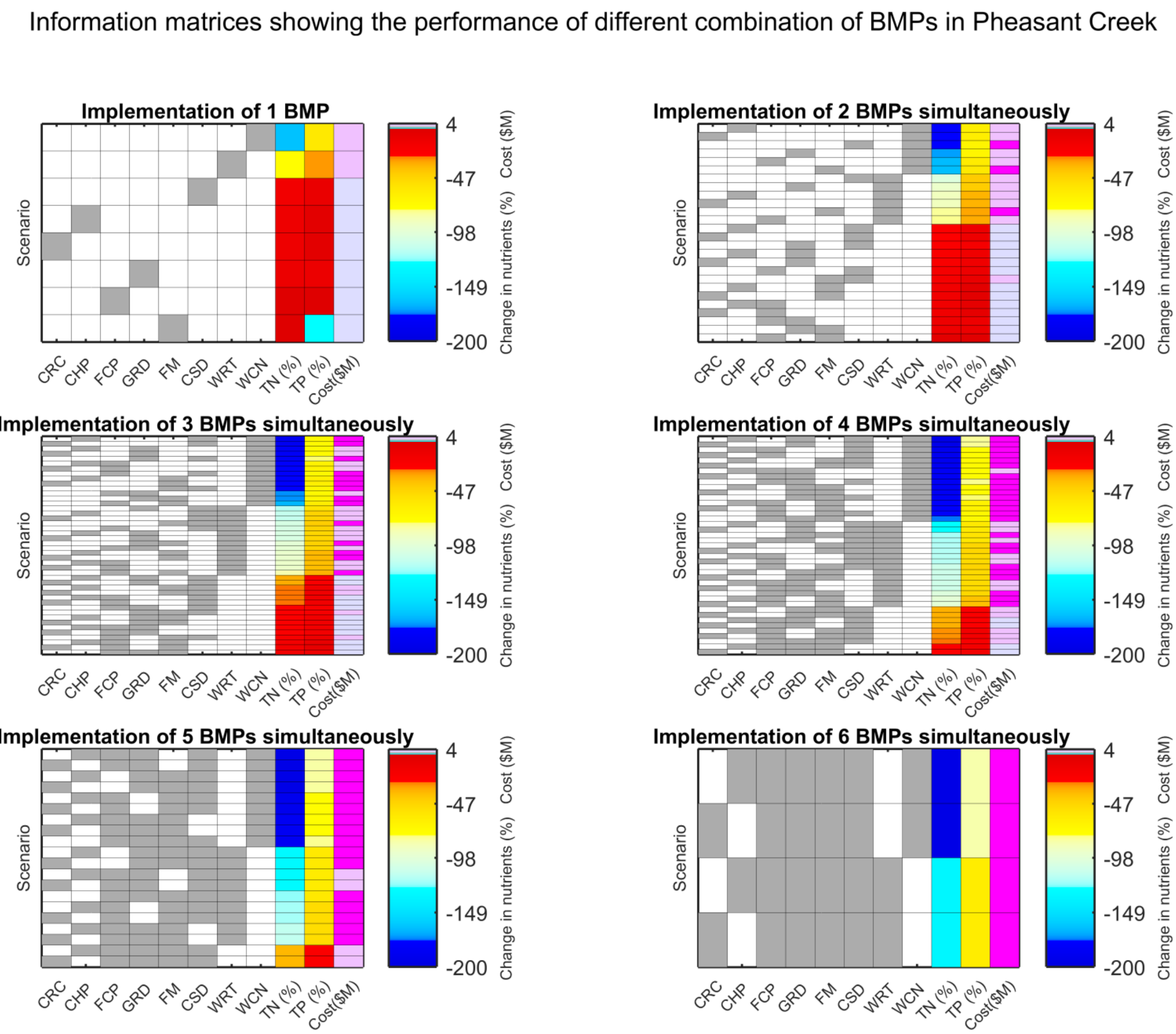

Figure A44 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Pearl Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

Information matrices showing the performance of different combination of BMPs in Redfox Creek

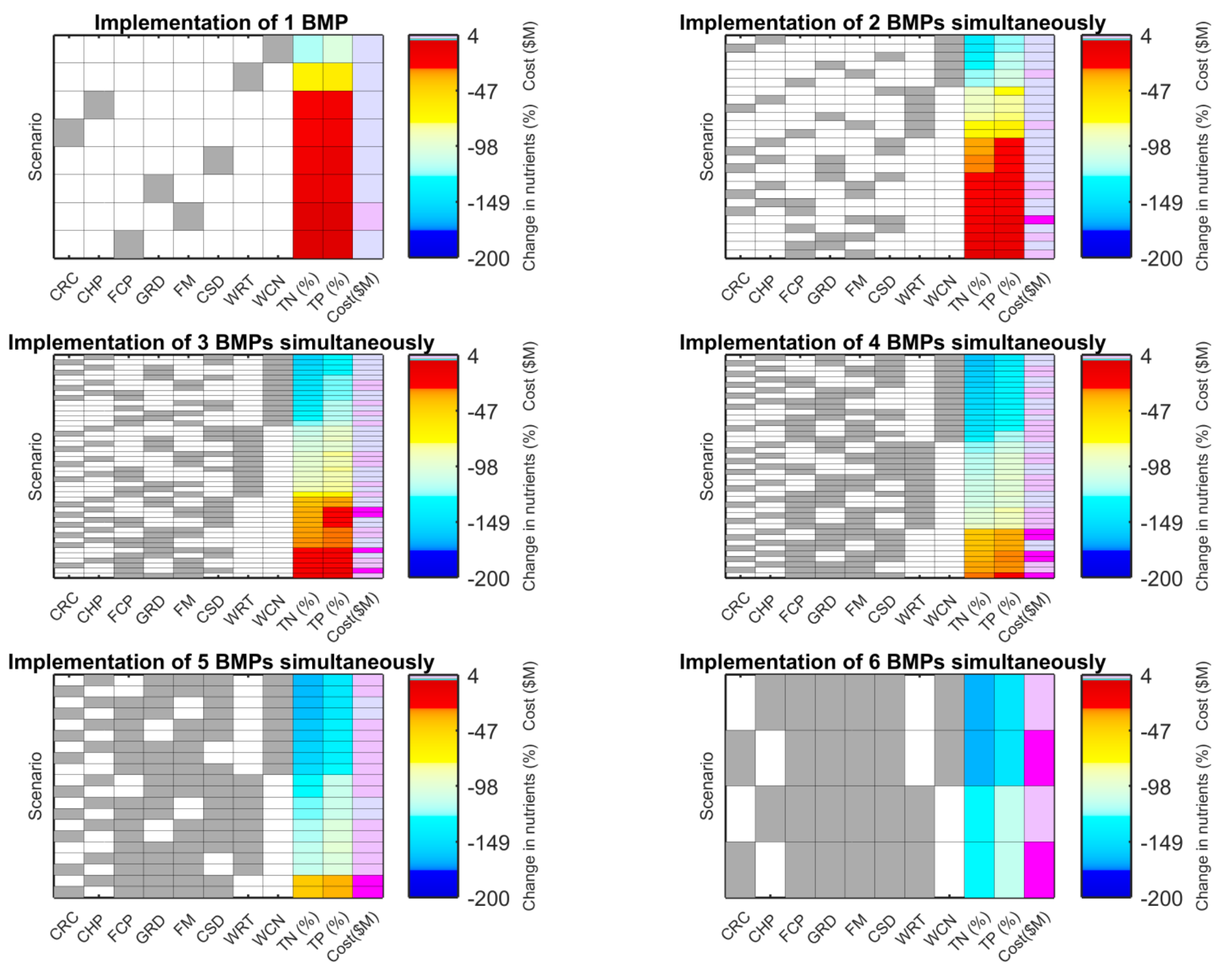

Figure A45 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Redfox Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

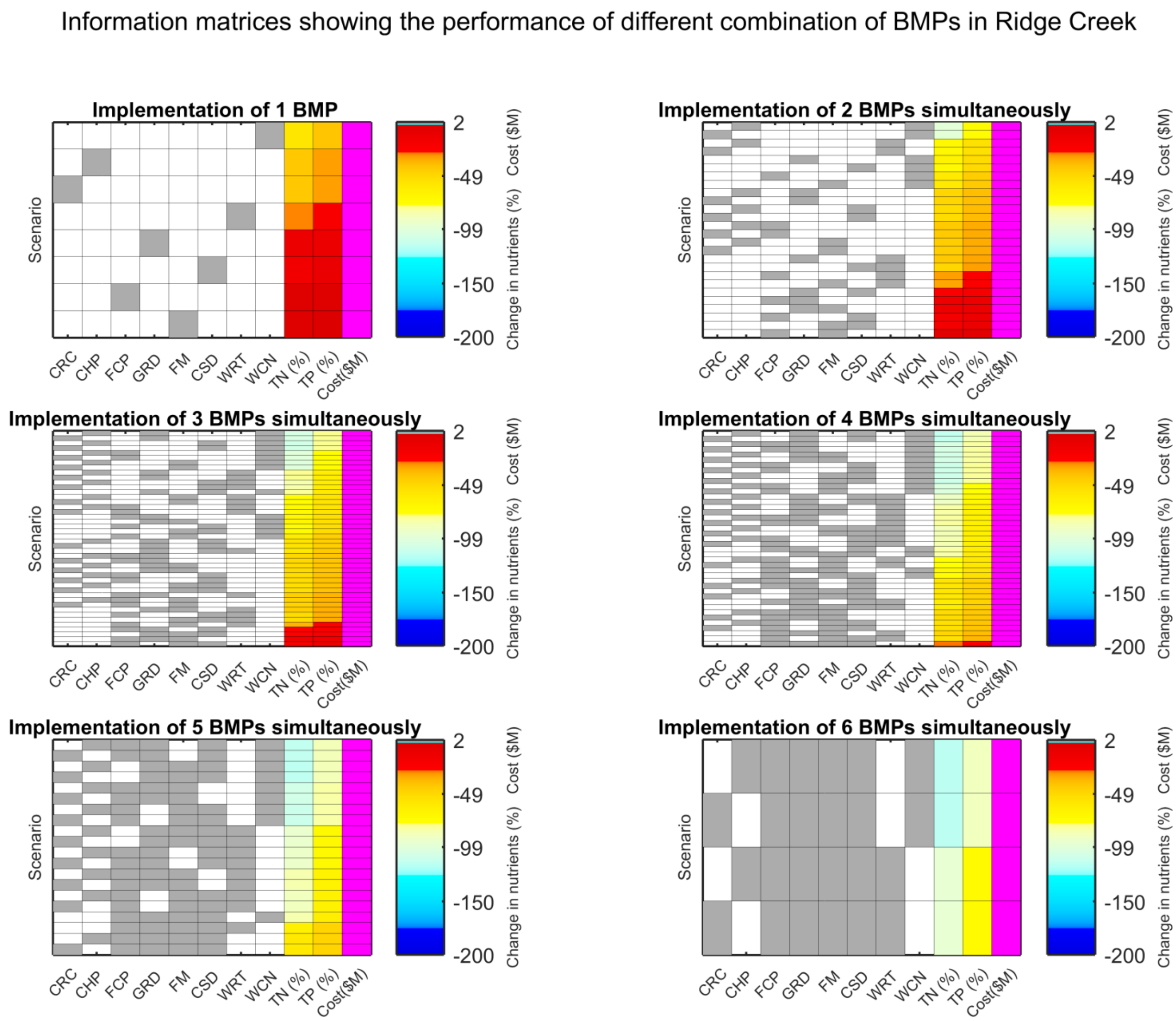

Figure A46 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Redfox Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

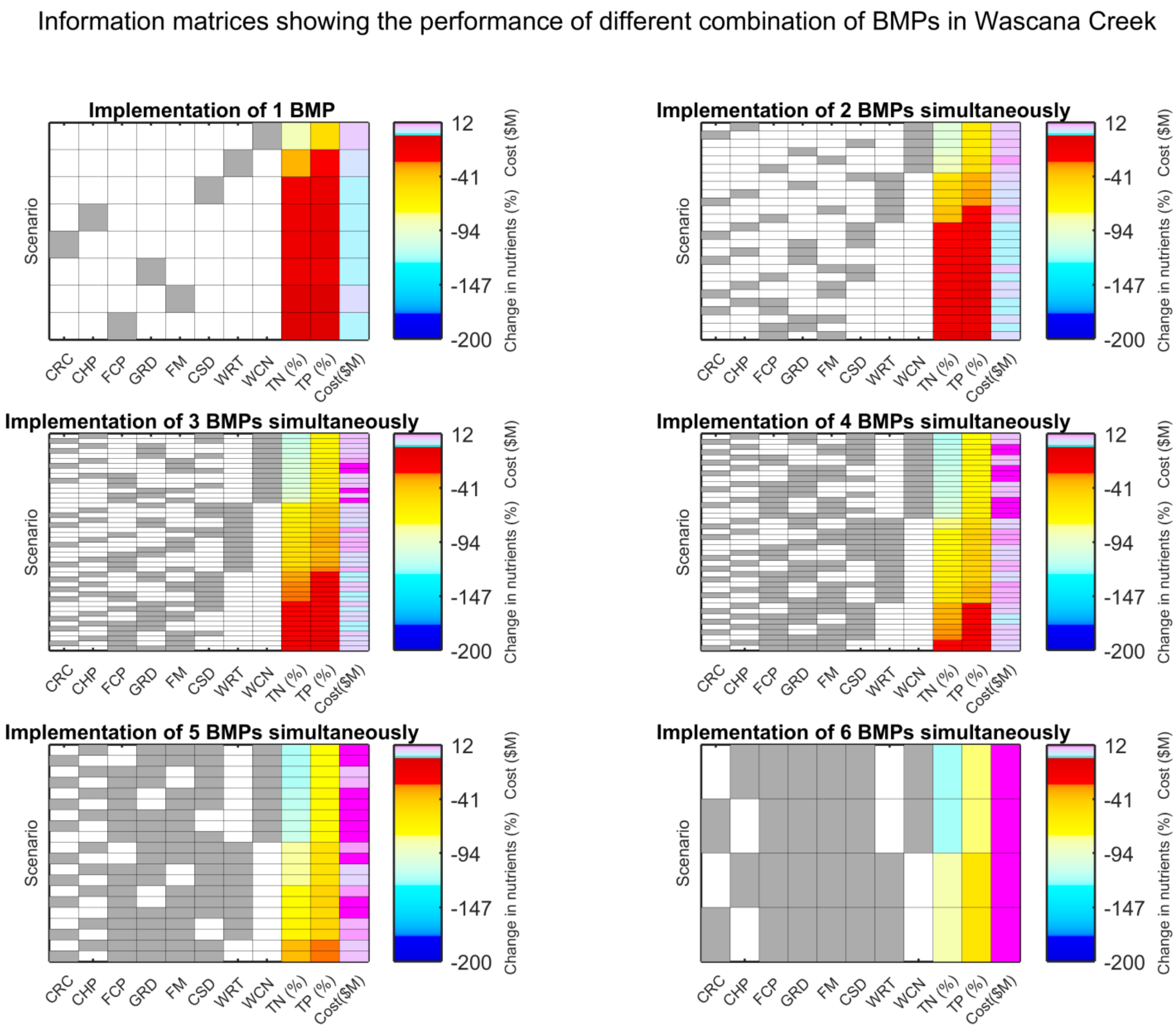

Figure A47 Six Information matrices, corresponding to implementing different combination of BMPs simultaneously in the Redfox Creek. Grey cells in each row in the panels represent the selected BMPs. The percentage of change in TN and TP and total cost ($M) of implementing BMPs are shown in the columns in the right.

APPENDIX - B SUPPLEMENTARY MATERIAL FOR CHAPTER 5

Table B1. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 1.

	Zone 1					
	RCP 4.5			RCP 8.5		
Time episode	TN change (%)	TP change (%)	Cost of implementation ($M)	TN change (%)	TP change (%)	Cost of implementation ($M)
2025-2054	-104	-24	19	-103	-9	21
2026-2055	-103	-23	19	-102	-6	21
2027-2056	-103	-22	19	-100	-2	21
2028-2057	-102	-21	19	-110	-13	21
2029-2058	-102	-19	19	-109	-11	21
2030-2059	-101	-18	19	-110	-13	21
2031-2060	-100	-16	19	-106	-5	21
2032-2061	-99	-15	19	-105	-2	21

Table B1. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 1 (cont'd).

2033-2062	-98	-13	19	-106	-3	22
2034-2063	-117	-26	22	-105	0	22
2035-2064	-116	-25	22	-104	4	22
2036-2065	-115	-23	22	-103	7	22
2037-2066	-115	-22	22	-101	11	22
2038-2067	-114	-20	22	-100	15	22
2039-2068	-113	-19	22	-98	19	22
2040-2069	-113	-18	22	-97	23	22
2041-2070	-112	-17	22	-95	28	22
2042-2071	-112	-17	22	-95	28	22
2043-2072	-111	-14	22	-92	37	22

Table B1. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 1 (cont'd).

2044-2073	-111	-13	22	-90	42	22
2045-2074	-110	-12	22	-89	47	22
2046-2075	-110	-11	22	-87	52	22
2047-2076	-109	-10	22	-85	58	22
2048-2077	-109	-9	22	-83	64	22
2049-2078	-108	-7	22	-81	70	22
2050-2079	-108	-6	22	-79	76	22
2051-2080	-107	-5	22	-78	82	22
2052-2081	-107	-4	22	-76	89	22
2053-2082	-107	-3	22	-73	97	22
2054-2083	-106	-1	22	-72	103	22

Table B1. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 1 (cont'd).

2055-2084	-106	0	22	-70	109	22
2056-2085	-105	0	22	-68	116	22
2057-2086	-105	2	22	-66	123	22
2058-2087	-105	2	22	-64	131	22
2059-2088	-104	2	22	-62	138	22
2060-2089	-104	3	22	-60	146	22
2061-2090	-104	4	22	-58	153	22
2062-2091	-104	5	22	-56	163	22
2063-2092	-103	6	22	-54	173	22
2064-2093	-103	6	22	-52	181	22
2065-2094	-103	7	22	-50	189	22
20662095	-102	7	22	-48	197	22

Table B2. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 2.

	Zone 2					
	RCP 4.5			RCP 8.5		
Time episode	TN change (%)	TP change (%)	Cost of implementation (%)	TN change (%)	TP change (%)	Cost of implementation
2025-2054	-236	-90	34	-255	-102	37
2026-2055	-235	-88	34	-254	-98	37
2027-2056	-235	-87	34	-252	-93	37
2028-2057	-234	-85	34	-251	-88	37
2029-2058	-233	-82	34	-250	-84	37
2030-2059	-233	-80	34	-249	-80	37
2031-2060	-232	-77	34	-248	-76	37
2032-2061	-231	-74	34	-247	-71	37

Table B2. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 2 (cont'd).

2033-2062	-230	-71	34	-246	-66	37
2034-2063	-230	-69	34	-244	-61	37
2035-2064	-229	-66	34	-243	-56	37
2036-2065	-228	-63	34	-242	-51	37
2037-2066	-238	-80	35	-240	-44	37
2038-2067	-237	-78	35	-239	-38	37
2039-2068	-237	-76	35	-238	-32	37
2040-2069	-236	-74	35	-236	-24	37
2041-2070	-236	-71	35	-235	-17	37
2042-2071	-235	-68	35	-233	-10	37
2043-2072	-234	-66	35	-232	-2	37

Table B2. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 2 (cont'd).

2044-2073	-234	-64	35	-230	6	37
2045-2074	-233	-63	35	-233	-1	38
2046-2075	-233	-61	35	-231	7	38
2047-2076	-232	-59	35	-228	25	38
2048-2077	-232	-57	35	-226	34	38
2049-2078	-231	-55	35	-224	44	38
2050-2079	-231	-53	35	-223	53	38
2051-2080	-230	-51	35	-221	63	38
2052-2081	-230	-49	35	-219	73	38
2053-2082	-229	-47	35	-217	86	38
2054-2083	-229	-44	35	-215	96	38

Table B2. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 2 (cont'd).

2055-2084	-228	-43	35	-214	106	38
2056-2085	-228	-42	35	-212	117	38
2057-2086	-227	-40	35	-210	129	38
2058-2087	-227	-39	35	-208	141	38
2059-2088	-227	-38	35	-206	153	38
2060-2089	-227	-37	35	-40	338	38
2061-2090	-226	-35	35	-203	178	38
2062-2091	-226	-34	35	-201	194	38
2063-2092	-226	-33	35	-199	209	38
2064-2093	-225	-32	35	-197	223	38
2065-2094	-225	-31	35	-195	236	38
20662095	-225	-29	35	-193	248	38

Table B3. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 3.

	Zone 3					
	RCP 4.5			**RCP 8.5**		
Time episode	TN change (%)	TP change (%)	Cost of implementation (%)	TN change (%)	TP change (%)	Cost of implementation
2025-2054	-171	-44	61	-175	-40	62
2026-2055	-170	-42	61	-173	-36	62
2027-2056	-170	-40	61	-172	-32	62
2028-2057	-169	-39	61	-171	-27	62

Table B3. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 3 (cont'd).

2029-2058	-168	-36	61	-169	-24	62
2030-2059	-167	-34	61	-168	-19	62
2031-2060	-166	-32	61	-168	-17	62
2032-2061	-166	-29	61	-167	-15	62
2033-2062	-165	-26	61	-164	-6	62
2034-2063	-164	-25	61	-162	-1	62
2035-2064	-163	-22	61	-161	4	62
2036-2065	-162	-19	61	-159	9	62
2037-2066	-161	-17	61	-158	16	62
2038-2067	-161	-14	61	-156	21	62
2039-2068	-160	-13	61	-176	1	70
20402069	-159	-11	61	-174	8	70

Table B3. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 3 (cont'd).

2041-2070	-171	-27	62	-173	14	70
2042-2071	-170	-25	62	-171	20	70
2043-2072	-169	-23	62	-170	26	70
2044-2073	-169	-21	62	-168	33	70
2045-2074	-168	-20	62	-167	40	70
2046-2075	-168	-19	62	-165	48	70
2047-2076	-167	-17	62	-163	56	70
2048-2077	-167	-15	62	-161	63	70
2049-2078	-166	-13	62	-160	72	70

Table B3. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 3 (cont'd).

2050-2079	-166	-11	62	-158	80	70
2051-2080	-185	-31	70	-156	88	70
2052-2081	-184	-29	70	-154	97	70
2053-2082	-184	-28	70	-152	108	70
2054-2083	-183	-26	70	-150	117	70
2055-2084	-183	-25	70	-149	126	70
2056-2085	-183	-24	70	-147	135	70
2057-2086	-182	-23	70	-145	145	70
2058-2087	-182	-22	70	-143	156	70
2059-2088	-182	-21	70	-141	165	70
2060-2089	-182	-20	70	-140	176	70

Table B3. Changes in TN, TP, and cost implementation after implementation of optimal combinations of BMPs in Zone 3 (cont'd).

2061-2090	-181	-19	70	-138	187	70
2062-2091	-181	-18	70	-135	201	70
2063-2092	-181	-17	70	-133	213	70
2064-2093	-180	-16	70	-131	226	70
2065-2094	-180	-16	70	-130	236	70
2066-2095	-180	-14	70	-128	247	70

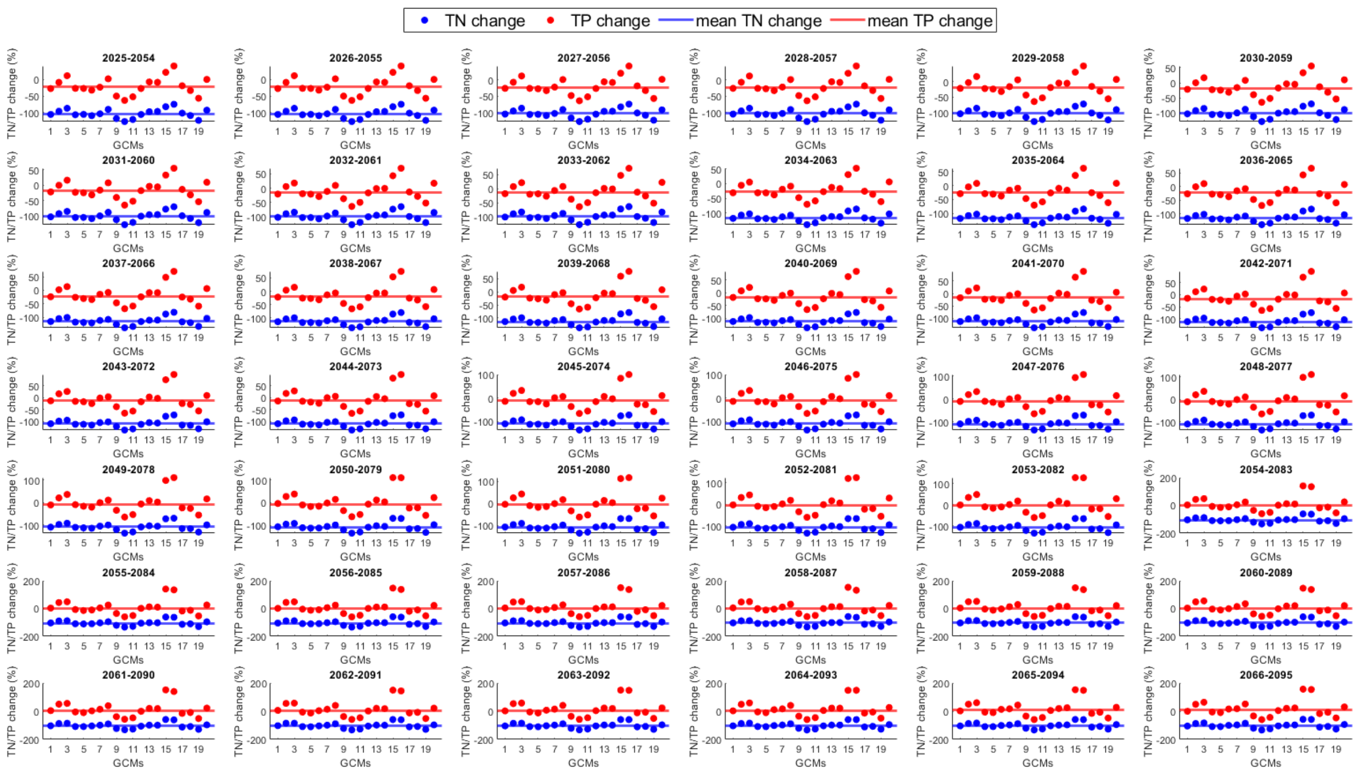

Figure B1 Changes in TN and TP after implementation of optimal BMP combinations in Zone 1 under RCP 4.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 4.5 using projections of individual climate models were shown in blue and red scatters, respectively.

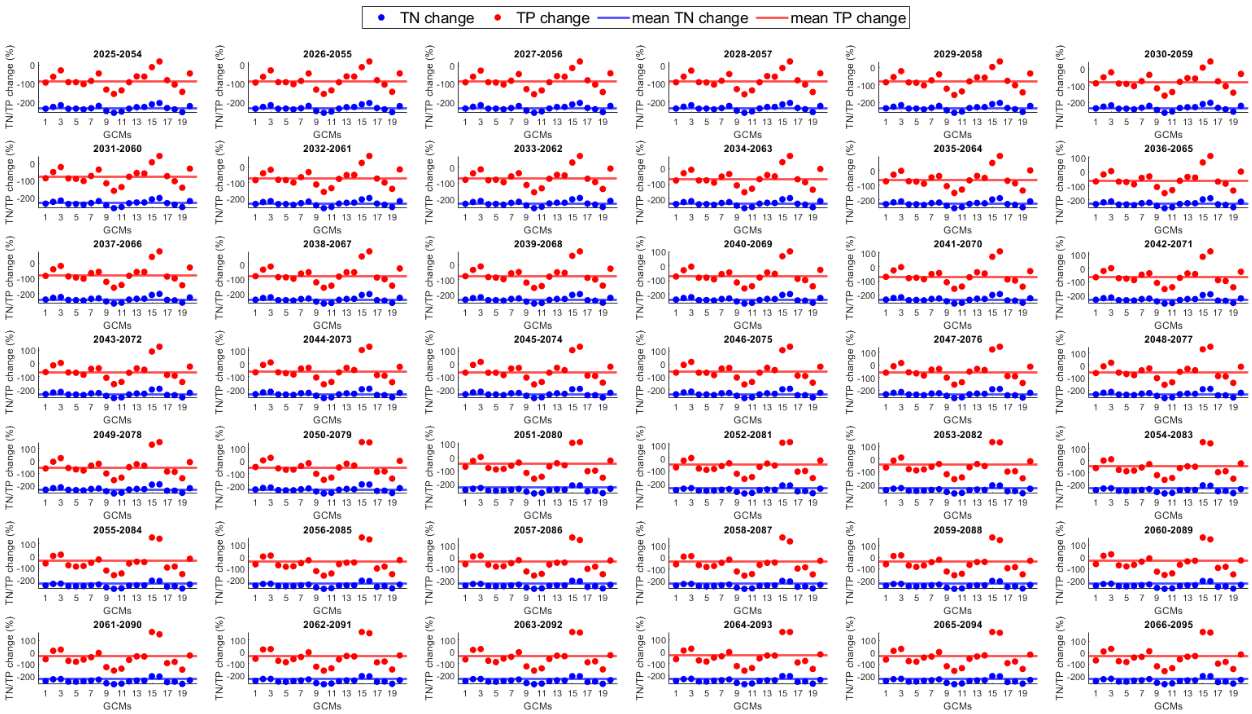

Figure B2 Changes in TN and TP after implementation of optimal BMP combinations in Zone 1 under RCP 4.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 4.5 using projections of individual climate models were shown in blue and red scatters, respectively.

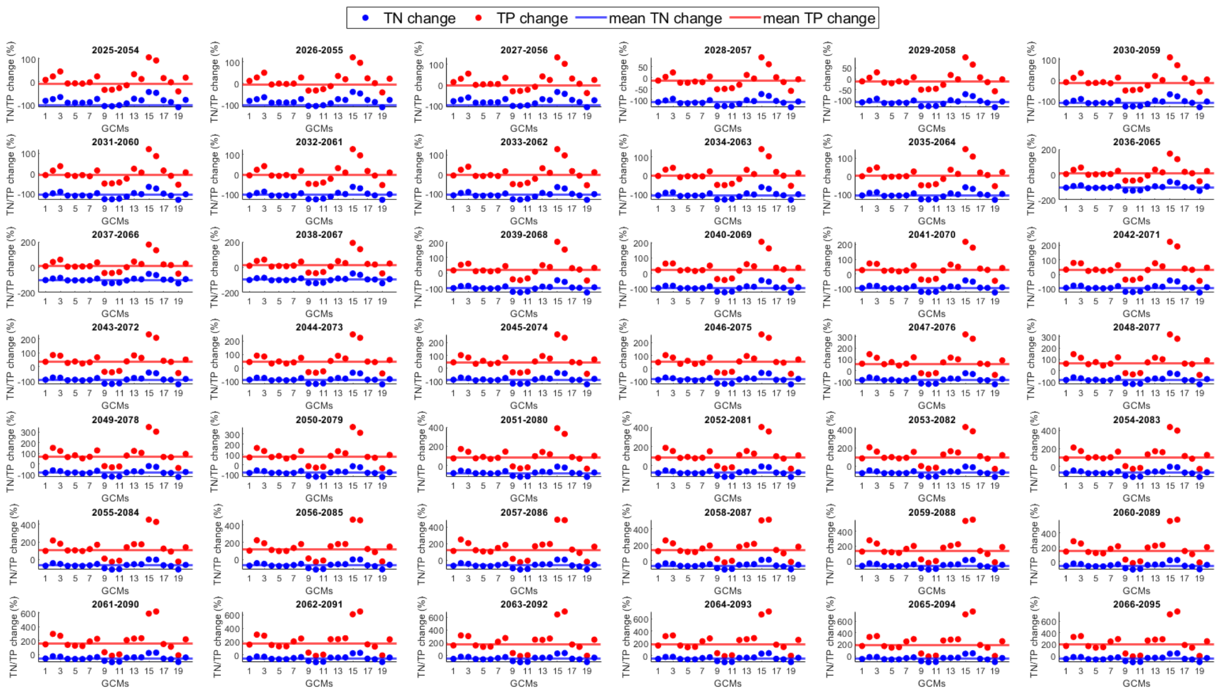

Figure B3 Changes in TN and TP after implementation of optimal BMP combinations in Zone 1 under RCP 8.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 8.5 using projections of individual climate models were shown in blue and red scatters, respectively.

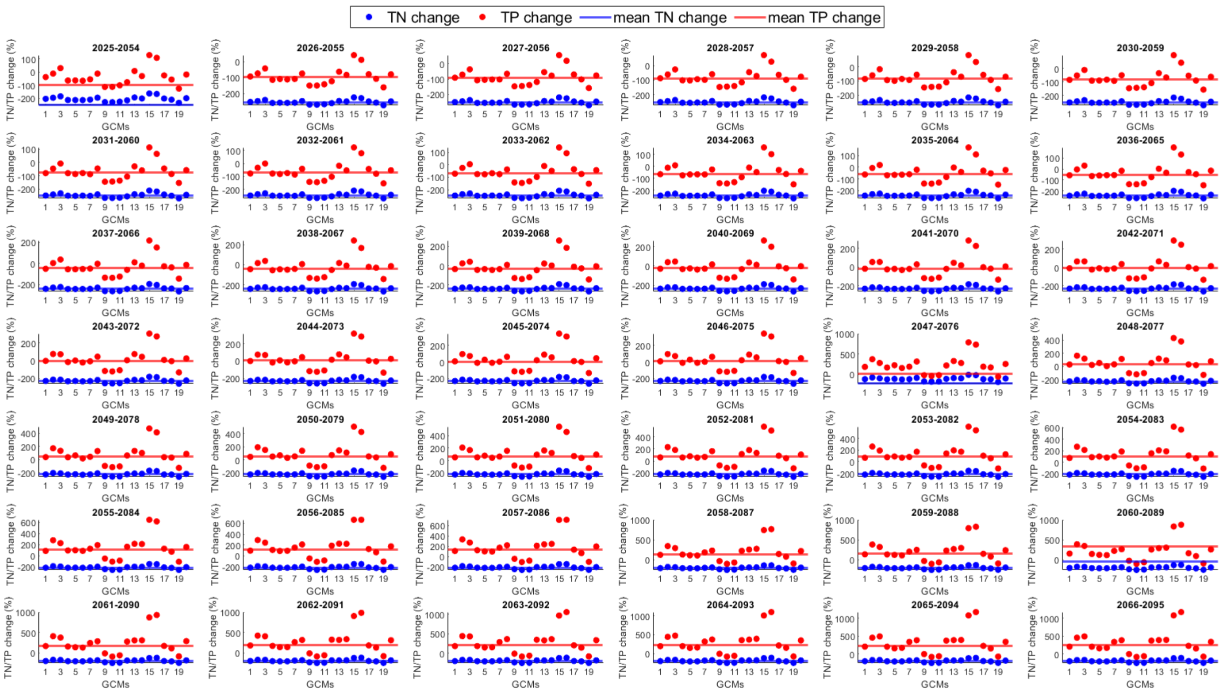

Figure B4 Changes in TN and TP after implementation of optimal BMP combinations in Zone 2 under RCP 8.5 and using the mean of projections of LAAT and LAAP of the GCMs (blue and red lines), respectively. Changes in TN and TP under RCP 8.5 using projections of individual climate models were shown in blue and red scatters, respectively.