Increasing agricultural watershed resilience to climate change and land use change using a water master plan: A case study for the Missisquoi Bay

Augmenter la résilience des bassins agricoles aux changements climatiques et aux changements d'occupation du territoire agricole à venir: Étude de cas de la Baie Missisquoi

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List of Abbreviations

BDCA : Base de Données de Cultures Assurées

BDCG: Base de Données des Cultures Généralisés

BQMA: Banque de la Qualité du Milieu Aquatique

CEHQ: Centre d'Expertise Hydrique du Québec

CHU: Corn Heat Unit

CLUE-S: Conversion of Land Use and its Effects-Small scale

CRCM: Canadian Reginal Climate Model

DEM: Digital Elevation Model

EC: Environment Canada

GCM: Global Climate Model

GDD: Growing Degree Days

HRU: Hydrological Response Unit

IPCC: Intergovernmental Panel on Climate Change

IRDA: Institut de Recherche et Développement en Agroenvironment

kg : kilogram

L: litre

m: metre

MAPAQ: Ministère de l'Agriculture, des Pêcheries et de l'Alimentation

MDDEFP: Ministère du Développement Durable, de l'Environnement, de la Faune et des Parcs

Mg: Megagram

N: nitrogen

NSE: Nash-Sutcliffe Efficiency coefficient

NO_3^--N: Nitrate-nitrogen

OBVBM: Organisme de Bassin Versant de la Baie Missisquoi

P : Phosphorus

PAEF: Plan Agroenvironmental de Fertilisation

PBIAS: Percent Bias

RCM : Regional Climate Model

PDE: Plan Directeur de l'Eau

RSR: Standard Deviation Ratio

RUSLE: Revised Universal Soil Loss Equation

s: second

SCS-CN: Soil Conservation Society-Curve Number

SRES: Special Reports on Emissions Scenarios

SWAT: Soil and Water Assessment Tool

TP: Total phosphorus

UPA: Union des Producteurs Agricoles

Extended Summary

Context

In the future, it is expected that agricultural watersheds in southern Québec will experience impacts due to changes in both climate and land use, and that landscapes will continue to evolve in the watersheds over time. The layout of the agricultural land is determined in part by the local climate, soil, slope, and socio-economic factors. Should the climate significantly alter in the future, crop land use will most likely adapt to the changes as well. In turn, alterations in crop land will influence the quality of surface water, but the magnitude of these changes is unknown.

Beyond the negative hydrological impacts of a warming climate (e.g. higher precipitation intensities leading to more soil erosion), crop production in Québec will be presented with several opportunities, for example: the possibility of earlier planting dates as well as later harvesting dates; multiple harvests per year; planting higher value crops; and intensifying their production. Producers will likely adapt their practices to the future growing conditions.

The decisions of farmers, based on these changing factors will shape the future of rural landscapes. Agricultural cropping activities and their modifications, however, can be a source of non-point source pollution which may have negative consequences on adjacent water quality. A main unknown to manage water sustainably in the future is whether present watershed management strategies, or proposed strategies in water management plans, are sufficiently robust to cope with the impacts of climate change.

The Pike River was identified by the Québec government as a priority watershed in need of integrated water resources management because it has annual amounts of excessive nutrients, in particular of total phosphorus (TP) which exceed the current water quality criterion almost every month. The water management plan (*Plan Directeur de l'Eau*; PDE) for the Missisquoi Bay drawn up by the OBVBM outlines a long-term plan to enhance the surface water quality in the basin. The PDE of 2011 is currently being updated and will constitute the "*Plan Directeur de l'Eau 2010-2016*"; nevertheless, actions in the 2011 PDE as well as actions suggested by stakeholders in the project were considered in this study to examine if they led to an improvement in future water quality in the applied model scenarios.

In this study, combined scenarios of climate change and land use change were applied to a hydrological model to examine the effects on future surface water quality in the Pike River. Although there is substantial uncertainty in the rate and magnitude of the expected changes, this study presents a first attempt to examine if planned adaptation strategies could safeguard water quality from future changes that may occur in the basin.

Objective

The overall objective of this study is to quantify the changes in surface water quality (sediments, total phosphorus and nitrates) within a sub-basin of the Missisquoi Bay watershed for a suite of future scenarios. The surface water quality was modelled by including strategies of adaptation management at the field level, suggested by stakeholders to improve the quality of the water.

The research set out to identify the relative importance of the different changes (i.e. climate *versus* land use change) so that improved adaptation strategies can consequently be developed taking into account the major impacts simulated. Specific objectives were to:

- Develop future land use scenarios in the Pike River watershed by taking into account factors that influence changes in the next 30 years, including climatic as well as local, regional and national driving factors.
- Apply the future land use scenarios and future climate scenarios (future horizon 2050) in a hydrological model (SWAT) to simulate the resulting quality of surface water (streamflow, sediments, total phosphorus and nitrates) at the basin outlet of the Pike River watershed.
- Adjust the parameters of the hydrological model (SWAT) to take into account a series of adaptation strategies proposed by stakeholders to determine the efficiency of these strategies to maintain or to improve the quality of water in light of climate change and land use change.
- Identify measures (adaptation strategies) which are effective at improving the quality of water under potential future climate and land use change in the basin.

Methodology

1. The Pike River watershed, which drains into the Missisquoi Bay was selected for this study.
2. A suite of three climate change simulations for the time period of 2041-2070 were chosen with the assistance of Ouranos.
3. Future scenarios of land use were developed for the basin based in part on responses from a questionnaire sent to farmers to assess their decisions on making crop choices to determine drivers of land use change; and with input from the stakeholders.
4. The CLUE-S model was applied to spatially distribute the corresponding changes in crop land in the basin, as put forth in the land use change scenarios.
5. The hydrological SWAT model was set-up, calibrated and validated for the basin. The model was then used to evaluate the quality of surface water in the basin for a variety of scenarios:
    a. Three scenarios of only climate change for 2041-2070, assuming static agricultural land use (based on a map of 1999).
    b. Four scenarios of only land use change developed for the future: two land use scenarios developed by the stakeholders; and two “extreme” scenarios, one of all forest and one all corn.
    c. Four scenarios of combinations between two selected climate scenarios and two selected land use scenarios.
6. From all simulations, one combined land use and climate scenario was chosen. Three adaptation scenarios (based on agricultural land management practices) were then developed together with stakeholders to examine whether these adaptations can safeguard or improve surface water quality in the future.

Key findings

Running the climate change simulations (2041-2070) in SWAT caused the future streamflow to be significantly higher from November to February by up to 111% compared to the reference simulation (using climate data from 1971-2000 and a land use layer from 1999). A significant decrease in flow was simulated to take place in April, due to the snowmelt gradually advancing in the year, when it started to occur in February, and peaked during March (instead of in April). As a result, flow was reduced by up to 54% in April and less sediment, TP and NO_3^--N loads were transported from the fields in March and April. Conversely, higher amounts were transported during the period of November to February, according to the changes in streamflow.

The climate change impacts did not consistently cause increases to the concentration of nutrients at the outlet of the watershed, compared to the reference simulation. The months in which median TP concentrations increased the most were in winter (December, January and February). Yet, during the months of March and April, TP median concentrations were lower compared to the reference simulation, and for the rest of the year they remained relatively unchanged. However, the water quality criterion of 0.02 mg/L for TP was almost never achieved, and the system remained above the recommended quality criterion.

Climate change impacts had the contrary effect on NO_3^--N concentrations, where concentrations decreased in December, January and February. In April, the NO_3^--N concentrations were higher than for the reference simulation. Otherwise, for the most part, they remained unchanged during the year. Overall, the water quality criterion of 10 mg/L was rarely exceeded for NO_3^--N.

Changing only the land use configuration in the watershed (using one scenario where the historic trends of past changes are extrapolated to the future; and another scenario where the farmer and stakeholder decisions are considered for crop changes to occur) caused the SWAT simulated flow and sediment loads to increase every month except September, but the changes were not significant when compared to the reference simulation. As well, TP loads increased from December to April at a similar magnitude to those found with the climate change simulations alone. Yet, the changes were not statistically significant. The land use scenarios had 10 times less impact on the transport of NO_3^--N loads as the climate change simultions alone. Overall, the land use scenarios caused little impact on the concentrations of nutrients at the basin outlet; the median values were very similar to those of the reference simulation. Since the changes in land use scenarios revolved primarily around altering the crop quantities and types (and not the forest or urban areas so much), the changes in the basin were considered to be subtle. The water quality was not improved or deteriorated to any significant extent by the moderate land use change scenarios alone. However, the “all corn” and “all forest” land use scenarios showed that water quality had the potential to be greatly impacted by land use changes.

When a combination of climate change and land use change scenarios was applied, the results were mostly driven by the climate change scenarios (it should be noted, however, that the land use scenarios were originally developed for a less distant future and may thus represent a more conservative trajectory of change). At the monthly time step, the combined climate and land use change simulations had comparable impacts regarding the changes in mean streamflow, sediment and TP loads as their counterpart climate change scenario alone. However, the compounded impacts of both were not the same as adding the mean individual changes to each other: during some months the impacts were less, and during other months greater than the sum. Thus, the magnitude and the direction of the combined change were not predictable as a simple sum of both effects. The scenarios of climate and land use change simulated median TP concentrations to be higher during the months of January and February, but to be lower during April, compared to the reference simulation. The TP water quality criterion of 0.02 mg/L was never met by any of the combined scenarios. Yet, the median NO_3^--N concentrations were lower for the reference simulation during 8 months out of the year, but these concentrations displayed high variability, causing the water quality criterion of 10 mg/L to be exceeded a few times.

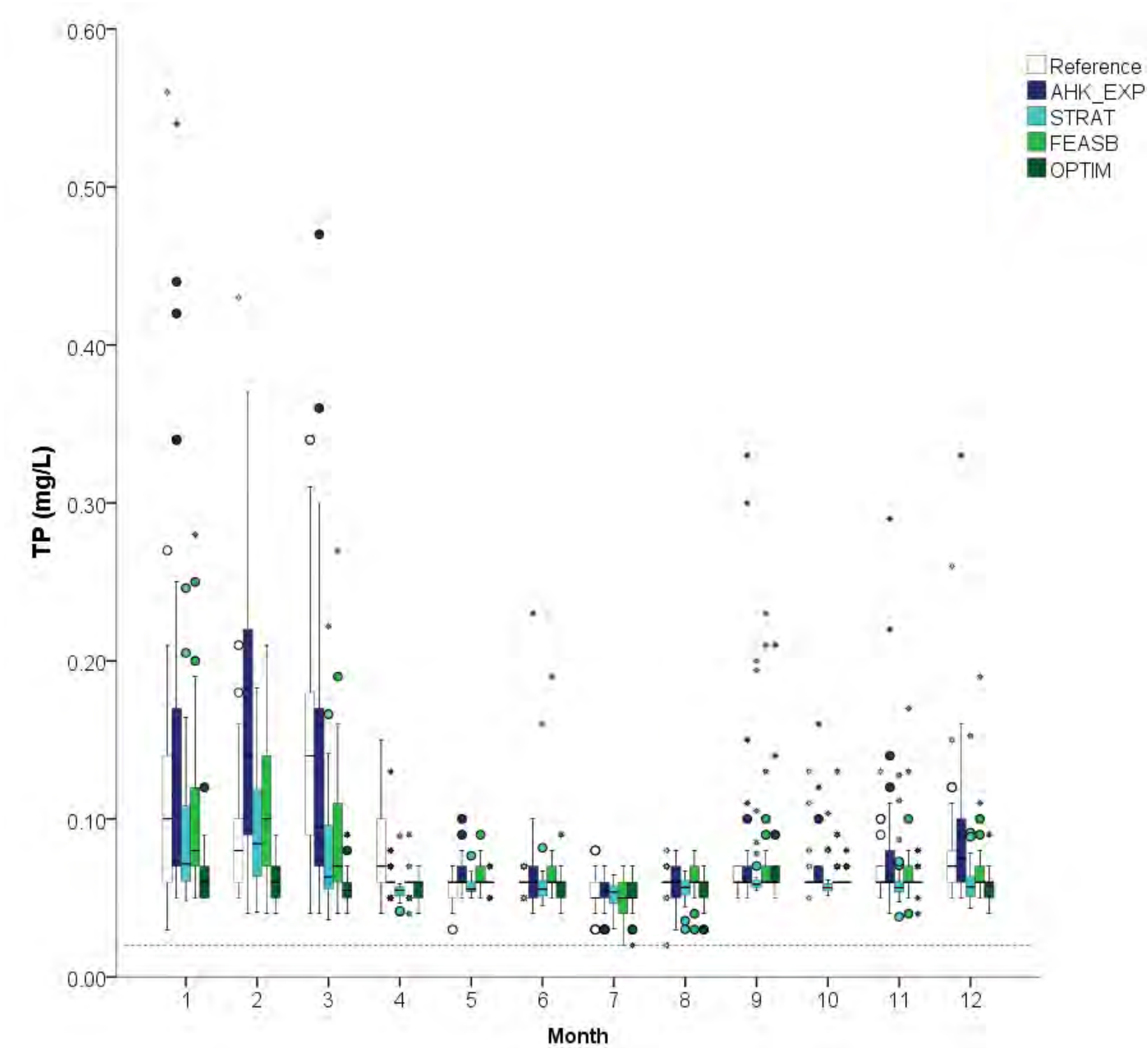


Figure A: Simulated TP (mg/L) at the basin outlet for the reference simulation (white boxes), the climate and land use change AHK_EXP scenario (dark blue boxes) and the AHK_EXP with adaptation scenarios (green boxes). The dotted line is the water criterion of 0.02 mg/L. Boxplots show the central mark as the median; the upper and lower edges of the box are the 75th and 25th percentile, respectively; the whiskers extend to the values that lie inside one and half box lengths from the quartiles. The circles represent values which lie one and a half box lengths away from the quartile (considered outliers), and the smaller, pale markers are values that lie more than three box lengths away from the quartile (considered extremes).

The implementation of adaptation strategies that focus on changing agricultural management practices dampened the effects of the simulated changes (Figure A). One adaptation scenario aimed to reduce the amount of TP at the outlet of the basin by 41% (STRAT); another scenario contained management practices that appeared the most feasible to implement in the short term for the farmers (FEASB); and a third incorporated all of the best management practices known (and that could be modeled), including organic agriculture for the crops (OPTIM). The three adaptation scenarios were able to decrease the median monthly TP concentrations at the outlet of the basin to lower levels than those of the most critical combined climate and land use change scenario (AHK_EXP). Yet, the 0.02 mg/L was not reached by two of the scenarios (STRAT and FEASB), and only rarely by the third (OPTIM) (Figure A). Whereas the water quality criterion of 10.0 mg NO_3^--N/L was respected by the STRAT scenario, but was exceeded 3 times in the FEASB and 7 times in the OPTIM scenario during the complete 30 years of simulation.

Conclusions

1. Our model simulation results suggest that overall, climate change may have a larger impact on sediment and on nutrient transport in the Pike River watershed than changes brought about by alterations in the configuration of agricultural land use. Although the land use changes increased TP loads in winter and spring months by the same magnitude as the increases observed with the climate change simulations alone, the results of the land use driven increases were not significant. Also, the climate simulations caused up to 10 times more NO_3^--N transport than the land use change scenarios.

2. Climate change drives streamflow mainly due to the increases in precipitation and the warmer surface air temperatures which affect certain important hydrological processes, such as snowmelt. Climate change indirectly impacts the transport of TP since TP is driven by surface runoff as well as by snowmelt. Climate change also drives the changes in the transport of NO_3^--N. Generally, the solubility of NO_3^--N is higher than that of TP, making it more labile as a nutrient since it is conveyed by several hydrological pathways (infiltration, seepage, percolation, groundwater flow, surface runoff).

3. Based on our applied scenarios, land use changes also impact water quality, but not to the extent that climate change does. Land use changes imply a different fertilizer regime being implemented in the basin and alterations in the timing of N and P applications to follow crop type changes. Thus, the varied crop types dictate the nutrient input amounts in the basin, whereas the movement of nutrients is governed by the climate. If future land use changes in a watershed are subtle and involve mostly a redistribution of crops, then the impacts of climate change on water quality and hydrology will likely dominate.

4. Specific and tailored changes to land areas, however, can impact water quality to a greater extent, depending on the modifications to the land implemented. For example, targeted alterations such as management practices to reduce erosion in the most vulnerable areas can improve water quality. Or, drastic changes to the vegetation cover in the watershed will alter the water quality and have demonstrated the limits of the impacts modelled. For example, forested or corn areas are two of the more extreme types of land uses that can impact the hydrology; any major changes in these land uses can bring about significant changes to nutrients.

5. The combined interaction between climate change and land use change are unique and non-linear. Although impacts from the climate change simulations were similar for TP and one order of magnitude greater for NO_3^--N than in the land use change scenarios, the combined effects were unpredictable, both in the direction of change and in the magnitude. Therefore, it is recommended to examine both changes simultaneously.
6. According to the four investigated scenarios of combined climate and land use change, the simulated impacts on surface water quality in the Pike River by 2041-2070 led to a degradation of water at the outlet. Additional mean annual sediment loads ranged from 168 ±220 to 301 ±201 Mg; additional mean TP loads ranged from 6 ±4 to 9 ±4 Mg; and additional mean NO_3^--N loads ranged from 59 ±72 to 151 ±74 Mg.
7. If adaptation strategies are implemented to reduce the impact caused by the most severe combination of climate and land use change scenarios, the transport of mean annual sediments can be reduced by 130 ±219 to 2422 ±217 Mg; the mean TP loads by 11 ±4 to 20 ±4 Mg; and mean NO_3^--N loads can be reduced by 36 ±79 to 114 ±73 Mg. The reduction will depend on the types of management strategies. Targeting the 10% most vulnerable lands prone to erosion and P loss by taking them out of agricultural production is an effective option for reducing sediment and nutrient loads. However, implementing wide reaching practices (e.g. buffer strips, cover crops, crop rotations, agroforestry on steep slopes) reduces TP transport almost twice as much and the amount of sediment transported by up to 7 times.
8. All three adaptation scenarios were able to decrease the median TP concentrations at the outlet of the basin and restore concentrations to lower or similar levels than those of the reference simulation. The period of snowmelt was effectively targeted. At a minimum, strategies that reduce overland flow during the month of February should be implemented in the future, with practices such as cover crops, no-till farming, and crop residue management.
9. Despite the implementaion of a suite of agricultural management changes (adaptations) in the basin, the quality of surface water was not improved enough to meet the water quality criterion of 0.02 mg/L for TP. On the other hand, mean monthly NO_3^--N concentrations rarely exceeded 10.0 mg/L for all adaptation scenarios.
10. Finally, it is important to recognize that there is a considerable amount of inherent uncertainty in this modelling study. Main uncertainties are related to both the applied models and the various scenarios that were developed.

Recommendations for adaptation

- The methodology outlined here seems suitable at identifying the impacts of future climate and land use changes in a watershed and can be applied to other basins, provided sufficient data are available to run the models. Collecting data at the field level is therefore imperative to conduct such studies.
- Due to non-linear interactions, the impacts of climate and land use change (including adaptation practices) need to be examined in concert to determine the full extent of impacts that may occur to water quality in a basin.
- Our results (using only 4 scenarios of climate and land use change) suggest that the surface water quality may be negatively affected by 2041-2070 in the Pike River. Implementing best management practices at the field level can help to mitigate the effects of climate and land

use change to retain - and even somewhat improve - the quality of the water at levels currently observed.

- Implementing targeted best management practices on the agricultural land most prone to the transport of TP especially during winter and spring is effective at reducing non-point source pollution, but may not be sufficient to achieve significant enough reductions to consistently meet the water quality criteria throughout the year for TP. Nevertheless, implementing a soil cover to protect the surface of the field from erosion in the winter and spring months should be mandatory to control surface runoff, especially during spring melt.
- A combination of removing the 10% of the crop land most prone to TP transport from production, as well as planting cover crops after cash crops, implementing buffer strips, and using more organic manure instead of inorganic fertilizer can attenuate the impacts of climate and land use change and maintain water quality levels to lower or similar levels as those in the current climate.
- A key driver of change is the increase in precipitation combined with earlier snowmelt and related increases in streamflow. Thus, best management practices at the field level should be targeted to favour infiltration and reduce overland flow at the source in order to protect the soil and curb the effects of sediment and nutrient transport during the snowmelt period. Possible measures include the planting of cover crops, no-till farming, and crop residue management.

Uncertainty and interpretation

Despite all efforts, the results of this study are subject to a considerable amount of uncertainty and any interpretation should be considered with care. Uncertainties are inherent in the various models that were used as well as in the scenarios depicting future conditions. Key limitations and uncertainties are linked to

- the SWAT model and its set-up (uncertainties were taken into consideration by calibrating the model diligently and then analysing changes rather than absolute conditions)
- the climate change scenarios and simulations (uncertainties were taken into consideration by using a suite of simulations with different structures, and covering a wide range of possible outcomes)
- the land use scenarios and CLUE-S simulations (uncertainties were taken into consideration by developing future land uses with farmer input and stakeholder expertise); and
- the adaptation scenarios (uncertainties were taken into consideration by developing several adaptation strategies and by comparing their efficiencies).

Nevertheless, albeit the acknowledged high degree of uncertainties we believe that the general trends of the study results provide meaningful indicators of possible future conditions.

Résumé détaillé

Contexte

Dans le futur, il est prévu que les bassins versants agricoles du Québec subissent des transformations causées par les changements climatiques et ceux d'occupation du sol. On s'attend aussi à ce que les paysages continuent à évoluer avec le temps. L'agencement des terres agricoles est en partie déterminé par le climat local, le sol, la pente et les facteurs socio-économiques. Conséquemment, en réponse à un changement significatif du climat, les cultures et l'agencement des terres cultivées devraient s'ajuster à ce changement. Ces transformations dans le paysage agricole influenceront la qualité de l'eau de surface, mais l'ampleur des changements à venir est inconnue.

Au-delà des impacts hydrologiques négatifs causée par le réchauffement climatique (par exemple, l'intensité des précipitations plus élevées menant à plus d'érosion), la production agricole du Québec pourra jouir de plusieurs opportunités tel que la possibilité de semer plus tôt et de récolter plus tard, de faire plusieurs récoltes dans une année ou encore de planter des variétés de plants de plus haute valeur, ainsi que d'intensifier leur production. Les producteurs adapteront probablement leurs pratiques aux futures conditions de croissance.

Les décisions des agriculteurs, fondées sur ces facteurs de changement façonneront l'avenir des paysages ruraux. Cependant, les activités agricoles reliées et leurs modifications peuvent être une source de pollution diffuse qui peut, à son tour, affecter négativement la qualité de l'eau avoisinante. Le manque d'information sur l'efficacité des stratégies de gestion de l'eau actuelles ou proposées dans les Plans Directeurs de l'Eau (PDEs), face aux changements climatiques, est une lacune principale pour planifier la gestion de l'eau de façon durable pour le futur.

Le bassin versant de la rivière aux Brochets fut identifié par le gouvernement du Québec comme bassin prioritaire pour appliquer le concept de gestion intégrée de l'eau. En effet, les charges annuelles en nutriments y sont excessives, particulièrement celles en phosphore total (PT) qui excèdent presque chaque mois la limite de la concentration acceptable qui est de 0,02 mg/L. Le Plan Directeur de l'Eau (PDE) de la Baie Missisquoi conçu par l'Organisme de Bassin Versant de la Baie Missisquoi (OBVBM) définit un plan sur le long terme pour améliorer la qualité des eaux de surface du bassin. Le PDE de 2011 est actuellement en révision et constituera le *''Plan Directeur de l'eau 2010-2016''*. Cependant, les actions de 2011 ainsi que celles suggérées par les acteurs du bassin furent considérées dans cette étude afin de déterminer si elles aboutiraient à une amélioration de la qualité de l'eau dans les scénarios futurs modélisés.

Dans cette étude, une combinaison de scénarios de changements climatiques et d'occupation du sol a été intégrée dans un modèle hydrologique afin d'examiner les effets de ces changements sur la qualité de l'eau de surface du bassin de la rivière aux Brochets. Malgré les incertitudes relatives à la vitesse et à l'amplitude des changements, cette étude examine comment des stratégies d'adaptation pourraient préserver la qualité de l'eau dans ce bassin.

Objectifs

L'objectif global de cette étude est de quantifier les changements de qualité de l'eau de surface (charge en sédiments, phosphore total et nitrates) dans un sous bassin de la Baie Missisquoi pour une série de scénarios. La qualité de l'eau de surface a été modélisée en incluant des stratégies d'adaptation à l'échelle de la parcelle agricole qui ont été suggérées par les usagers du bassin. Cette étude cherche à identifier l'importance relative des différents changements (changements climatiques *vs* changements d'occupation du sol) de façon à pouvoir améliorer les stratégies d'adaptation en tenant compte des impacts majeurs des changements simulés. Les objectifs spécifiques étaient de:

- Développer des scénarios de changement d'occupation du sol pour le futur pour le bassin de la rivière aux Brochets en tenant compte des facteurs qui influenceront les changements des 30 prochaines années, incluant les facteurs climatiques, ainsi que les facteurs locaux, régionaux et nationaux.
- Appliquer les scénarios des futurs changements d'occupation du sol et du climat (2041-2070) dans un modèle hydrologique (SWAT) afin de simuler la qualité de l'eau de surface résultante (débits, charge en sédiments, en phosphore total et en nitrates) à l'exutoire du bassin de la rivière aux Brochets.
- Ajuster les paramètres du modèle hydrologique SWAT afin de modéliser des stratégies d'adaptation, proposées par les usagers du bassin, pour déterminer leur efficacité à maintenir ou à améliorer la qualité de l'eau dans un contexte de changements d'utilisation du sol et de changements climatiques.
- Identifier les mesures (stratégies d'adaptation) qui sont efficaces pour améliorer la qualité de l'eau face aux changements potentiels d'occupation du sol et de changements climatiques propre au bassin.

Méthodologie

1. Cette étude focalise sur le bassin de la rivière aux Brochets, qui se draine dans la Baie Missisquoi.
2. Trois simulations de changements climatiques pour la période 2041-2070 ont été choisies avec l'aide d'Ouranos.
3. Des scénarios de changements d'occupation du sol futurs ont été développés pour le bassin à partir des réponses à des questionnaires envoyés aux agriculteurs et des informations fournies par les acteurs du bassin. Les questionnaires ont permis d'évaluer les décisions des agriculteurs par rapport aux choix des cultures et, ainsi de déterminer les moteurs des changements d'utilisation du sol.
4. Le modèle CLUE-S a été utilisé pour distribuer spatialement les changements des terres cultivées dans le bassin, selon les scénarios des changements d'utilisation des terres.
5. Le modèle hydrologique SWAT a été développé, calibré et validé pour le bassin. Le modèle a ensuite été utilisé pour évaluer la qualité de l'eau de surface dans le bassin pour un éventail de scénarios:

    a. Trois scénarios de changements climatiques couvrant la période de 2041 à 2070 et en assumant une utilisation du sol statique (carte de 1999).

b. Quatre scénarios de changement d'occupation du sol pour les 30 prochaines années; plus précisément deux scénarios développés par les usagers du bassin, et deux scénarios « extrêmes » : un tout en forêt et un tout en maïs.

c. Quatre scénarios combinés de changements climatiques et occupation du sol montés à partir de deux scénarios de changements climatiques sélectionnés et deux scénarios de changements d'occupation du sol.

6. De toutes les simulations analysées, un seul scénario combiné de changement climatique et d'occupation du sol a été choisi pour la suite de l'étude. Trois scénarios d'adaptation ont ensuite été développés avec les usagers du bassin afin d'examiner si ces adaptations pourraient préserver ou améliorer la qualité de l'eau de surface face aux changements.

Résultats principaux

Pour l'horizon 2050, les débits simulés par SWAT avec les changements climatiques seulement sont significativement plus élevés que pour la simulation de référence (avec les données climatique de 1971-2000 et l'occupation du sol pour 1999), de novembre à février (jusqu'à 111%). Une diminution significative a été simulée en avril avec une baisse allant jusqu'à 54% causée par la fonte de la neige qui se déplace graduellement vers le mois de février et qui atteint son maximum au mois de mars (au lieu du mois d'avril). Conséquemment, suivant les changements de débits, moins de sédiments, PT et NO_3^--N sont transportés des parcelles agricoles vers les cours d'eau en mars et avril, et plus pendant la période allant de novembre à février.

Comparativement à la simulation de référence, les concentrations de nutriment simulées avec les scénarios de changements climatiques n'augmentent pas systématiquement à l'exutoire du bassin. Les mois pour lesquels la médiane des concentrations de PT augmente le plus sont en hiver (décembre, janvier et février). Cependant, les médianes des concentrations de PT en mars et avril sont plus basses comparés à la simulation de référence. Pour le reste de l'année, les concentrations restent relativement inchangées. Il reste que le critère de qualité de l'eau de 0,02 mg/L pour le PT est presque toujours dépassé.

Pour les concentrations de NO_3^--N, un effet inverse a été simulé, les concentrations sous changements climatiques diminuent en décembre, janvier et février par rapport à la simulation de référence alors qu'en avril, les concentrations sont plus hautes. Par ailleurs, pour la plus part des autres mois les concentrations sont restées inchangées. Globalement, avec les scénarios de changements climatiques, le critère de qualité de l'eau pour le NO_3^--N de 10 mg/L fut rarement dépassé.

Par rapport à la simulation de référence, les scénarios de changements d'occupation des terres agricoles insérés dans SWAT (un scénario qui représente les tendances historiques qui continuent à changer au même rythme dans le futur; et un autre représentant les changements des cultures déterminés par les producteurs et les usagers) augmentent le débit et les charges en sédiments pour chaque mois (sauf pour le mois septembre). Ces changements ne sont cependant pas significatifs. Les charges simulées de PT augmentent aussi de décembre à avril sans être encore une fois significatives, et ces augmentations sont d'amplitudes similaires aux augmentations simulées avec les changements climatiques seulement. Les changements d'occupation du sol eurent peu d'impacts sur les charges en NO_3^--N (10 fois moins qu'avec les changements climatiques seulement). Donc, à l'exutoire du bassin les valeurs médianes des concentrations de nutriments étaient similaires à celles de la simulation de référence. Comme la variabilité interannuelle était élevée, la qualité de l'eau ne fut pas améliorée ou détériorée de façon significative avec les scénarios de changements d'occupation du sol.

Lorsque les scénarios combinés de changements climatiques et d'occupation du sol étaient insérés dans SWAT, les scénarios de changements climatiques avaient plus d'impact que les scénarios de changements d'occupation du sol. Toutefois, il est important de rappeler que les scénarios d'occupation du sol étaient développés pour un futur proche, et sont conséquemment plus conservateurs en termes de changements que ceux des simulations de changements climatiques. À l'intervalle de temps mensuel, les scénarios de changements d'occupation du sol combinés à ceux des changements climatiques eurent des impacts sur les débits moyens, et les charges en sédiments et PT similaires aux impacts des simulations avec les changements climatiques seulement. Les impacts combinés étaient, cependant, plus haut ou plus bas pour certains mois, que si les moyennes des deux types de changements (climatiques et occupation du sol) avaient été additionnées. Ainsi, la direction des changements et l'ampleur des changements sont imprévisibles. Les concentrations médianes de PT étaient plus élevées en janvier et février, mais plus basses en avril, que celles de la simulation de référence. Malgré les concentrations plus basses, le PT dépassait toujours le critère de qualité de 0,02 mg/L lorsque les scénarios combinés étaient utilisés. En revanche, pour 8 mois les concentrations médianes de NO_3^--N étaient plus basses que celles de la simulation de référence. Mais ces concentrations démontraient une grande variabilité provoquant à quelques reprises le dépassement du critère de 10 mg/L du NO_3^--N.

Implémenter des stratégies d'adaptation qui ciblent les bonnes pratiques agricoles amenuisera les effets des changements simulés sous changements climatiques et d'occupation du sol. Parmi les stratégies d'adaptation, un scénario vise à réduire le PT de 41% à l'exutoire du bassin (STRAT); un autre contient des aménagements qui semblent les plus faciles et rapides à implanter à court terme pour les producteurs (FEASB); et un troisième incorpore toutes les bonnes pratiques que l'on connait, y compris l'agriculture bio pour les cultures (OPTIM). Les trois scénarios d'adaptation ont permis de diminuer la médiane des concentrations de PT à l'exutoire du bassin versant à des niveaux plus bas que le scénario changements climatiques/changements d'occupation du sol le plus critique (AHK_EXP). Cependant, le critère pour la bonne qualité de l'eau de 0,02 mg PT/L ne fut jamais atteint par deux des scénarios (STRAT et FEASB), et que très rarement par le troisième (OPTIM) (voir Figure A), alors que le critère de 10,0 mg NO_3^--N /L fut respecté par le scénario STRAT, mais dépassé 3 fois par le scénario FEASB et 7 fois par le scénario OPTIM pour les 30 ans de simulation.

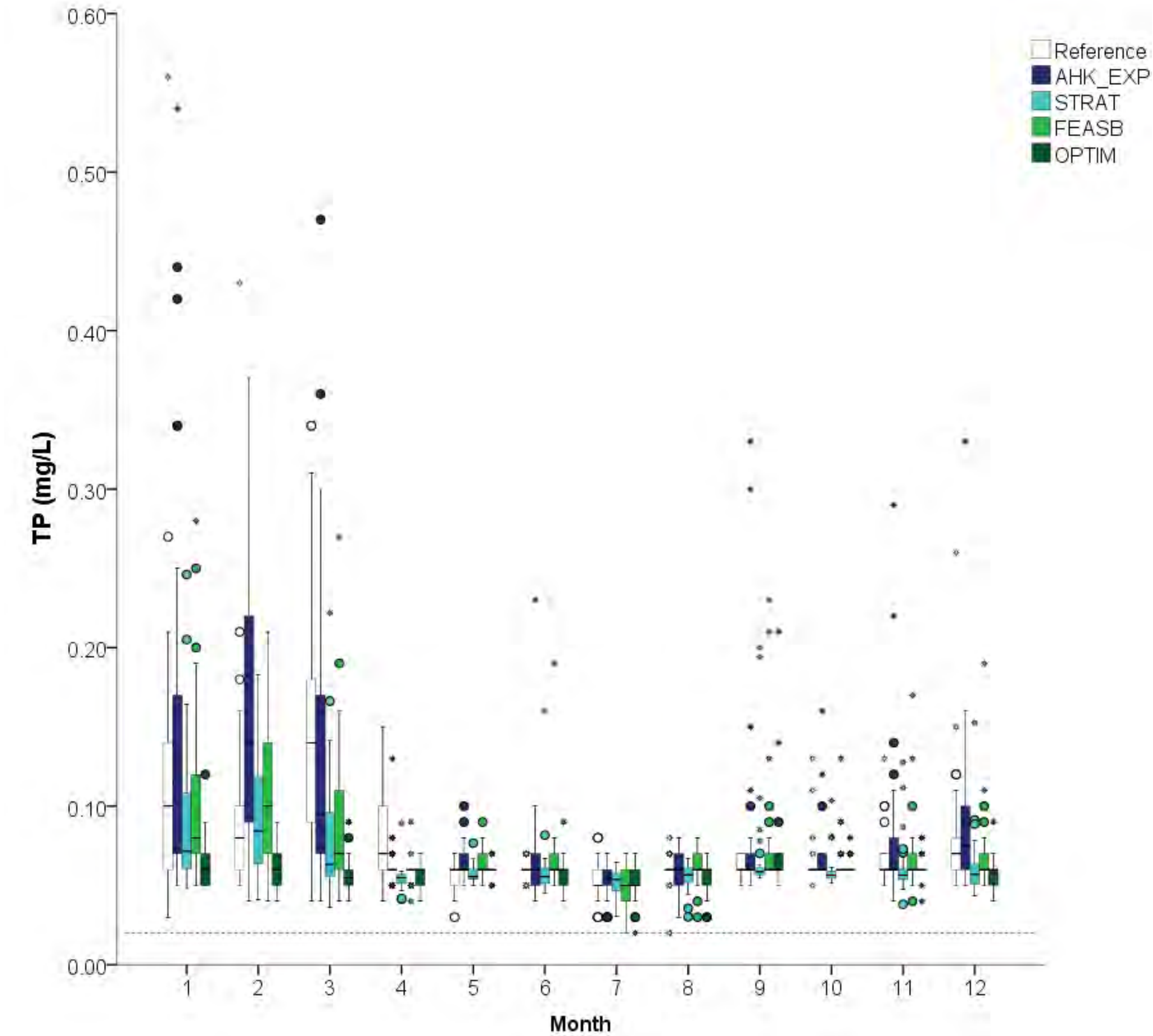


Figure A: Les boîtes à moustaches montrent la dispersion des moyennes mensuelles pour les concentrations en PT (mg/L) simulées à l'exutoire pour la simulation de référence (boîtes blanches), le scénario de changement climatique et d'occupation du sol : AHK-EXP (boîtes bleues foncés) et aux stratégies d'adaptation (boîtes vertes). La marque centrale des boîtes à moustaches montre la médiane, et les marques supérieure et inférieure de la boite les 75ième et 25ième centiles respectivement. Les moustaches représentent les valeurs qui se trouvent à une boîte et demie des quantiles. Les cercles représentent les valeurs situées à plus d'une boîte et demie après les quantiles (et sont considérés comme des valeurs aberrantes), et les plus petites marques claires sont des valeurs se trouvant à plus de trois boîtes des quantiles (et sont considérées comme des valeurs extrêmes).

Conclusions

1. Nos simulations suggèrent que globalement, les changements climatiques auront des impacts plus larges sur le transport des charges en sédiments et en nutriments dans le bassin de la rivière aux Brochets que ceux des impacts d'un changement de configuration de l'occupation du sol agricole. Bien que les changements d'occupation du sol aient augmenté les charges en PT en hiver et au printemps avec la même amplitude que l’ont fait les changements climatiques seulement, les augmentations n’étaient pas statistiquement significatives. De plus, les simulations climatiques ont causé jusqu'à 10 fois plus de transport de NO_3^--N que les changements d'occupation du sol.

2. Les changements climatiques affectent le débit principalement à cause de l'augmentation des précipitations et des températures qui modifient certains processus hydrologiques importants tel que la fonte de la neige. Les changements climatiques ont aussi un impact indirect sur le transport de PT puisque la perte de PT est reliée au ruissellement de surface et à la fonte des neiges. Les changements climatiques entraînent aussi des changements dans le transport de NO_3^--N. La solubilité de NO_3^--N est plus grande que le PT, ce qui le rend plus labile car il est transporté par plusieurs chemins hydrologiques (infiltration, percolation, écoulement souterrain, ruissellement de surface).

3. En fonction des nos scénarios, les changements d'occupation du sol peuvent aussi affecter la qualité de l'eau, mais dans une moindre mesure. Les changements d'occupation du sol impliquent l'utilisation de régimes de fertilisation différents, ainsi que des altérations dans le calendrier de fertilisation en N et P afin de s'adapter aux changements de cultures. La variété de culture influence les quantités de fertilisants appliquées dans le bassin alors que les mouvements des nutriments sont dictés par le climat. Si les futurs changements d'occupation du sol dans un bassin sont subtils et se traduisent surtout par une redistribution des cultures, alors les impacts sur la qualité de l'eau seront probablement dictés par les changements climatiques.

4. Des changements spécifiques à l’utilisation des terres peuvent cependant affecter la qualité de l'eau de façon plus importante dépendamment des changements apportés. Par exemple, des interventions ciblées telles que l'implémentation des pratiques de gestion pour réduire l'érosion sur les parcelles les plus susceptibles à l'érosion peuvent améliorer la qualité de l'eau. De même des changements drastiques apportés à la végétation altèrent la qualité de l'eau; ces simulations extrêmes ont déterminé les limites des impacts modélisés. Par exemple, la forêt ou le maïs sont deux types de végétation dont l'influence sur le débit et la qualité de l'eau sont aux extrêmes opposés et tout changement majeur sur la superficie en forêt ou en maïs engendre des impacts tout aussi majeurs quant à la disponibilité de nutriments dans le bassin.

5. L'interaction combinée entre les changements d'occupation du sol et les changements climatiques est unique et non linéaire. Bien que l'impact des changements climatiques, par rapport à celui des changements d'occupation du sol, était similaire pour le PT et, d'un ordre d'amplitude plus grand pour le NO_3^--N, l'effet combiné des deux types de changement était imprévisible. En effet, la direction et l'amplitude des changements simulées étaient parfois opposées et/ou différentes par rapport à ce que l'on aurait pu attendre en additionnant les deux impacts. Il est donc recommandé d'examiner les deux types de changements (climatiques et occupation du sol) simultanément.

6. Selon les scénarios combinés de changements climatiques et d'occupation du sol examinés, les changements simulés pour le bassin de la rivière aux Brochets (2041-2070) ont contribué à une dégradation de la qualité de l'eau. Pour les sédiments, celle-ci est de l'ordre de 168 ±220 à 301 ±201 Mg/an; pour le PT, elle est de 6 ±4 à 9± 4 Mg/an; et pour le NO_3^--N, elle est de 59 ±72 à 151 ±74 Mg/an.
7. Si les stratégies d'adaptation sont implémentées dans le bût de réduire les impacts les plus sévères du scénario combiné changements climatiques/changement d'occupation du sol, le transport annuel moyen des charges peut être réduit de 130 ±219 à 2422 ±217 Mg/an pour les sédiments; de 11 ±4 à 20 ±4 Mg/an pour le PT; et de 36 ±79 à 114 ±73 Mg pour le NO_3^--N. La réduction dépendra de la stratégie d'adaptation adoptée. Soustraire à la production agricole 10% du territoire le plus vulnérable à l'érosion et à la perte de phosphore est une option efficace pour réduire les charges de sédiments et de nutriments. Mais, implémenter des pratiques à grande échelle (bandes riveraines, cultures de couverture, rotations des cultures, et l'agroforesterie sur les pentes les plus raides) permet de réduire le transport en PT presque deux fois plus, et la quantité des sédiments jusqu'à sept fois plus.
8. Les scénarios d'adaptation ont permis de diminuer la médiane des concentrations de PT à l'exutoire du bassin et aussi de restaurer les concentrations à un niveau plus bas ou similaire que celui de la simulation de référence. Les scénarios d'adaptations ont permis avec succès de réduire le transport en PT pendant la période de la fonte des neiges. Au minimum, toute pratique agricole qui réduit le ruissellement de surface pendant le mois de février devrait être ciblée, avec par exemple les pratiques telles que les cultures de couverture, le travail réduit, et la gestion des résidus.
9. Malgré les stratégies d'adaptation implémentées dans le bassin, les concentrations de PT dans la rivière n'ont pas toujours atteint le critère de qualité de l'eau de 0,02 mg/L. En revanche, les concentrations annuelles moyennes de NO_3^--N ont rarement dépassé les 10.0 mg/L.
10. Finalement, il est important de reconnaître qu'il y a une quantité considérable d'incertitudes inhérentes dans cette étude. Les incertitudes principales sont liées à la fois aux modèles appliqués et les différents scénarios qui ont été élaborés.

Recommandations pour l'adaptation

- La méthodologie présentée dans cette étude semble efficace à identifier les impacts liés aux futurs changements climatiques et d'occupation du sol dans un bassin et peut être appliquée à d'autres bassins s'il existe suffisamment de données pour faire rouler les modèles. La collecte de données à l'échelle du champ est donc primordiale pour effectuer ce genre d'étude.
- À cause des interactions non linéaires, les impacts des changements climatiques et d'occupation du sol (incluant les stratégies d'adaptation) doivent être examinés ensembles afin de déterminer l'ampleur réelle des impacts susceptibles d'arriver dans le bassin.
- Nos résultats (en utilisant 4 scénarios combinés de changements climatiques et changements d'occupation du sol) suggèrent que la qualité de l'eau sera négativement influencée d'ici 2041-2070 pour la rivière aux Brochet. Implémenter des pratiques de gestions bénéfiques à l'échelle de la parcelle agricole peut aider à maintenir la qualité de

l'eau aux niveaux actuellement observés, et même l'améliorer au printemps (en mars et en avril).

- Cibler l'implantation des pratiques de gestion bénéfique (adaptations) sur les terres les plus vulnérables à l'érosion et au transport de PT en hiver et au printemps, est une stratégie efficace pour réduire la pollution diffuse, mais cela ne suffit pas pour arriver à des réductions suffisantes pour atteindre une bonne qualité d'eau toute au long de l'année. Néanmoins, la mise en œuvre d'une couverture du sol pour minimiser l'érosion pendant l''hiver et le printemps devrait être obligatoire pour contrôler le ruissellement de surface, en particulier pendant la période de la fonte de neige printanière.
- Une combinaison de pratique consistant à soustraire de la production agricole 10% des terres exportant les plus grandes charges de PT, à implanter une couverture du sol après les cultures principales, et à utiliser du fumier à la place des fertilisants inorganiques, peut atténuer les impacts des changements climatiques et d'occupation des terres agricoles, et peut maintenir la qualité de l'eau à des niveaux similaires à – et même mieux que - ceux du climat actuel.
- Les moteurs principaux des changements à venir sont l'augmentation des précipitations combinées à une fonte de la neige devancée et leurs impacts sur l'augmentation des débits. Les mesures d'adaptation à l'échelle du champs devraient donc cibler les épisodes de ruissellement de surface à la source pour réduire le transport des sédiments et des nutriments en période de fonte des neiges; comme par exemple, planter un couvert de sol hivernal, pratiquer le semis direct, ou laisser des résidus de culture sur le sol.

Incertitudes et interprétation

Malgré tous les efforts entrepris pour prendre en compte les incertitudes existantes, les résultats de cette étude contient une quantité considérable d'incertitudes et toute interprétation devrait se faire avec précaution. Les incertitudes sont inhérentes aux modèles utilisés ainsi qu'aux scénarios dépeignant les conditions futures. Les limites importantes ainsi que les incertitudes sont reliées aux points suivants:

- Le modèle SWAT et sa configuration pour l'étude (les incertitudes ont été prises en compte en calibrant le modèle rigoureusement et en analysant les changements plutôt que les conditions absolues).
- Les scénarios de changements climatiques (les incertitudes ont été prises en compte en utilisant un éventail de simulations différentes, et couvrant un large éventail de changements possibles).
- Les scénarios de changement d'utilisation du sol (les incertitudes ont été prises en compte en développant l'occupation future du sol avec les agriculteurs et l'expertise des usagers du bassin); et
- Les scénarios d'adaptation (les incertitudes ont été prises en compte en développant plusieurs scénarios et en comparant leur efficacité par rapport à la simulation de référence).

Malgré le degré élevé des incertitudes, nous croyons que les tendances générales dégagées dans l'étude fournissent des indicateurs pertinents sur les conditions futures potentielles à venir.

Increasing agricultural watershed resiliency to climate change and land use change using a water master plan:

A case study for the Missisquoi Bay

1. Introduction

In a future climate, both challenges and opportunities may be presented for agricultural sectors located in temperate regions such as the south of Québec. The latter is not only due to the growing season which is anticipated to increase (Bootsma et al. 2004), but also due to the efficiency of existing infrastructures to support an expanding agricultural sector (e.g. a large number of specialized markets serving a wide variety of agricultural products, numerous processing plants, and modern agricultural technology available). All these factors potentially enable Québec farmers to diversify their crops.

Although there is substantial uncertainty in the rate and magnitude of the expected climate changes, an increase in mean air temperatures and a greater amount of precipitation is likely to take place in Québec in a warming climate (Ouranos, 2010). Producers may potentially adapt to the favourable growing conditions by diversifying their practices; such as planting higher value crops, harvesting several times in a season, or intensifying crop production. Accordingly, agricultural land use is expected to evolve over time in response to various factors (climate, market prices, regulations, etc.). The decisions of farmers, based on these factors will shape the future of rural landscapes. Agricultural cropping activities and their modifications, however, can be a source of non-point source pollution which may have negative consequences on adjacent water quality.

Climate change also may impact surface water quality. Modelling studies of climate change impacts on water quality rarely take into account changes in agricultural land use (Overmars and Verburg, 2005; Houet et al., 2009). In addition, future changes in land use have rarely been examined at the local level, particularly because it requires detailed research regarding individual farms and agricultural watersheds. Therefore, most modelling studies using data at the farm level are based on assumptions rather than on information gathered from farmers concerned (O'Neal et al., 2005; Verburg et al., 2002).

A watershed in the south of Québec was chosen for this study; the Pike River, which empties into the Missisquoi Bay (located at the northern tip of Lake Champlain). The watershed is shared between Québec and Vermont. The Pike River is plagued with annual amounts of excessive nutrients, in particular total phosphorus (TP), which exceed the Québec guidelines on surface water quality set by the MDDEFP (2002) of 0.02 mg/L, as well as the TP limit set for the Missisquoi Bay through the "Agreement between the Gouvernement du Québec and the Government of the State of Vermont Concerning Phosphorus Reduction in the Missisquoi Bay" (2002) of 0.025 mg/L. The TP contributes to non-point source pollution in the bay (Simoneau, 2007). The excess nutrients are an important factor that causes the regular cyanobacteria algal blooms (Blais, 2002) which appear almost every year in the Missisquoi Bay since 2000.

Once the impacts of the future land use and climate change scenarios on the surface water quality are determined, adaptation strategies can consequently be developed to mitigate some of the expected changes. Several researchers (e.g. Scanlon et al., 2007; Schröter et al, 2005) have stressed the need to conduct studies on the adequacy of existing water policies under the influence of anticipated future changes. Scanlon et al. (2007) suggest that current policies require a thorough examination to determine if they are still effective in a future climate.

The water management plan (*Plan Directeur de l'Eau*; PDE) for the Missisquoi Bay (OBVBM, 2011b) was used in this study to examine different adaptation strategies to preserve water quality in the future. The PDE of 2011 is currently being updated and will constitute the "Plan Directeur de l'Eau 2010-2016". Nevertheless, actions outlined in the 2011 PDE are considered in this study when modelling future land use changes and climate change in the basin. Furthermore, strategies to improve the quality of surface water as proposed by stakeholders are examined if they led to an improvement in future water quality in the applied model scenarios.

The Missisquoi Bay was identified by the Québec government as a priority watershed, and as an area in need of integrated water resources management (MDDEP, 2002). This is a well-studied basin for which several sets of water quality data are available, over a relatively long time period, which rendered it highly suitable for this type of research. The aim of the project is to safeguard, and/or improve, surface water quality in the future, given a myriad of changes that may take place in the basin.

2. Objectives

This study is located at the intersection of three inter-related disciplines: 1) climate change; 2) agricultural land use and its change; and 3) quality of surface water. The purpose of the study is to determine if action strategies proposed in the watershed (for example those found in the PDE) are robust enough to protect the quality of surface water also from future changes that may occur in an agricultural basin; in particular changes related to climate and land use.

The overall objective is to quantify the changes in the quality of surface water within a sub-basin of the Missisquoi Bay watershed; the Pike River. The water quality will be determined by modelling suggested strategies of adaptation management at the field level, suggested by stakeholders to improve the quality of the water. These strategies will be examined in a hydrological model, concurrently with future climate scenarios and land use scenarios which are in turn simulated using other appropriate models.

This approach allows for the application of complex modelling tools to examine changes in the future quality of surface water in light of climate change and potential land use change. It is a main goal of this research to identify the relative importance of the different changes (i.e. climate *versus* land use change) so that improved adaptation strategies can consequently be developed taking into account the results.

The specific objectives of this study are as follows:

1. Develop future land use scenarios for the future in the Pike River watershed by taking into account factors that influence changes during this time horizon, including climate, and local, regional and national driving factors.
2. Apply the future land use scenarios and future climate scenarios (provided by the Ouranos Consortium) in a hydrological model (SWAT) to simulate the resulting quality of surface water (streamflow, sediments, NO_3^--N, TP) at the basin outlet of the Pike River watershed.
3. Adjust the parameters of the hydrological model (SWAT) to take into account a series of adaptation strategies proposed by stakeholders to determine the efficiency of these strategies to maintain or to improve the quality of water in light of climate change and land use change.
4. Identify measures (adaptation strategies) which are effective at improving the quality of water under potential future climate change and land use change in the basin.

3. **Literature Review**

3.1. Impacts of a warmer climate on agriculture

3.1.1. *Changes in surface temperatures*

Canada is getting less cold (Bonsal et al., 2001); from 1900-1998, annual mean temperatures in southern Canada have increased on average by 0.9^{o}C (Zhang et al., 2000). During the same period, the growing degree days (GDD; base 5.5^{o}C) have increased significantly in Canada mainly due to increases in minimum daily temperatures. The length of the frost free period has also increased significantly, principally due to warmer temperatures in spring (Bonsal et al., 2001). Similar trends have been found in southern Québec (Yagouti et al., 2008) from 1960-2005. Projected increases in surface temperatures for southern Québec for the 2050 time horizons are expected to be greatest in winter of 3.5 - 4.9^{o}C and least in spring and summer by 1.8 - 3.0^{o}C (Ouranos, 2010).

A study by Bootsma et al. (2004) used global climate model outputs (based on a doubling of CO_2 by 2050) to examine the future climate for southern regions of Québec and Ontario. They found average CHU (corn heat units) are expected to increase from the current 3400-3700 range to over 5200 CHU by the 2070-2099 time period. They also found a longer growing season by 30 to 43 days, mainly because planting dates advanced to mid-April and killing frost dates were delayed to late October/early November.

Plants rely on nature’s cues to develop and to undergo physiological changes; e.g., temperature shifts evoke plants to undergo natural transformations. Rosenzweig et al. (2008) were able to attribute several of the observed phenological changes in plants in spring (such as shifts in leaf unfolding and blooming dates) to anthropogenic climate change.

The IPCC (2007) states that in mid- to high-latitudes, a slight benefit to crop yields is expected (medium confidence) with a present-day warming of up to 1-3^{o}C (plant health is expected to decline with additional warming). Boostma et al. (2004) calculated the increased yield potential of grain corn and soybean, given adequate moisture supply, could be 0.6 Mg ha^{-1} and 0.15 Mg ha^{-1}, respectively for each increase in 100 CHU, up to the seasonal average of 3500 CHU (after this, yields decline due to limited soil moisture and limiting soil conditions). The estimates by Bootsma et al. (2004) were based on a linear regression between average yields from hybrid trials and average CHU across Ontario and the Maritime Provinces.

Studies which have examined expected changes in a warmer climate and how these might affect crop yields have shown that a temperature increase is beneficial only if it brings the crop closer to its optimum temperature for growth and development. For example, Québec JJA (June-July-August) temperatures of 18^{o}C to 26^{o}C will be beneficial for soybeans and maize, but not for wheat or potatoes (Brassard and Singh, 2008). In northern regions of the Great Lakes, Southworth et al. (2000) found how temperatures currently limit the grain filling period of maize; warmer temperatures will results in a longer grain filling period and potentially increase yields.

Short season crops and hybrids may do less well in warmer climates than long-season ones. Warmer surface air temperatures lead to accelerated development (earlier flowering) and subsequently lower yields (Southworth et al., 2000); this is especially true for small grain crops (Bootsma et al., 2004). Planting dates can be adjusted, thereby maintaining or increasing yield. For example, delaying future planting dates of maize and soybean can avoid short-season hybrids to flower too early and prevents yield decreases (Southworth et al., 2002a; Southworth et al., 2002b). Adjusting maize, soybean and spring wheat planting and harvesting dates in temperate regions were found to prevent up to 70% of the crop losses due to climate change (Deryng et al., 2011).

3.1.2. Changes in precipitation

Surface temperature is only one climate factor which will affect future crop yields; there are several others and the interactions between them are often complex and poorly understood. For example, rainfall in spring is a key determinant for producers being able to seed their crops on time. By examining 30 years of past maize and climate data in southwestern Québec, Almaraz et al. (2008) found the variables of July temperatures and May precipitation amounts together account for 62% of the maize yield variability due to climate. The amount of precipitation received in spring can determine how quickly the soil is able to drain excess water and be sufficiently dry to handle tractor traffic, and therefore how early the seeds can be planted. In the US Corn Belt, Kucharik (2008) examined data from 1979-2005 and noted for every 10 mm of precipitation received in April, the planting was delayed by one day.

During 1900-1998, the annual precipitation has increased by 12% in southern Canada; amounts have increased from 5% to 30%, depending on the region (everywhere, except southern Alberta and Saskatchewan experienced increases) (Zhang et al., 2000). From 1900-2003, the number of days with precipitation and the number of days with rain increased at all recording stations in southern Canada. On average, there are 43 more days of precipitation of which 29 are with rain (Vincent and Mekis, 2006).

Sushama et al. (2010) examined the occurrence of mean dry days from April-September for the 2050 and 2080 horizons, and found the dry days (threshold of 0.5, 1, 2 and 3 mm of rain) to remain unchanged or to increase very slightly (by 5-10 days) compared to 1971-2000 for southern Québec. The same study found the number of dry spells in southern Québec to either remain unchanged or to decrease by 0-4 days.

Multiple regional climate model precipitation projections show a precipitation increase of 5% to 10% in summer (JJA) for almost all regions in Canada by 2041-2060 compared to 1971-1990 (Plummer et al., 2006). Specifically, for southern Québec by the 2050 time horizon (2041-2070), projections simulate precipitation increases in winter (DJF) from 8.6% to 18.1%, with less snow accumulation, however in JJA, no significant changes are projected compared to 1971-2000 (Ouranos, 2010).

The impact of increased rainfall on crop yields, especially when field studies are conducted, is difficult to predict. A lot of variability and conflicting results have been found (Changnon and Hollinger, 2003).

Extreme precipitation events can be expected to gain importance in the near future, particularly towards the beginning of the twenty first century. It should be noted that in Canada, extreme precipitation events (>90th percentile) have not increased significantly in the twentieth century, neither in frequency nor intensity (Zhang et al., 2001). Yet, several model projections expect extreme precipitation events in Canada, and globally, to increase in the future. In part because the atmospheric water vapour content will increase due to warmer air temperatures, and provide for a greater thermodynamic instability of the atmosphere (Kunkel, 2003). Model simulation results from the global coupled model of the Canadian Centre for Climate Modelling and Analysis show increases in extreme precipitation for almost everywhere on the globe by the end of the 21st century (Kharin and Zwiers, 2000). On average, the return periods for extreme events may be halved by the end of this century, compared with 1975-1995 (Kharin and Zwiers, 2005). This corroborates with findings for southern Québec by Mailhot et al. (2007), who analyzed Canadian Regional Climate Model outcomes and found return periods to be approximately halved in a future climate (2041-2070), compared to the 1961-1990 climate.

3.1.3. Changes in soil erosion

Higher precipitation intensities are correlated to greater soil erosion and increased runoff rates. The rainfall-runoff erosivity is a measure of the total kinetic energy of a storm, times its maximum 30-minute intensity (Wischmeier and Smith, 1978). Long-term soil loss from sheet and rill erosion can be calculated by using the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1991). The RUSLE implies that the higher the erosivity, the greater the soil loss, thus illustrating how rainfall intensity is closely linked to soil erosion. Since rainfall intensity data is not always available, the Modified Universal Soil Loss Equation (MUSLE; Williams, 1995) was developed, which uses the runoff volume and the peak flow to determine rainfall erosivity.

Several studies have investigated the impacts of future precipitation regimes on soil erosion. Although there is much spatial variation across the globe in terms of the amount of soil loss, there appears to be a general consensus that the soil loss will be enhanced through higher precipitation amounts and greater intensities (SWCS, 2003). Soil loss is more sensitive to changes in the amount and intensity of rainfall in a day, as compared to the number of wet days (Pruski and Nearing, 2002). As well, in Québec, the snowmelt period in spring is particularly prone to soil erosion and a consequent transport of nutrients (Beaudet et al., 2008).

In the continental USA, the average soil erosion losses as related to expected changes in rainfall erosivity for 2080-2099 were calculated to range from 16% to 58%, depending on which erosivity - precipitation equation was used (Nearing, 2001). Using future climate data and the WEPP model to simulate soil loss from three locations in the US for three different soil types, four crop types, and three slopes, Pruski and Nearing (2002) found that on average a 1% increase in total daily precipitation can cause a 2.4% increase in soil loss.

A study by O'Neal et al. (2005) using data from eleven regions of the Midwest USA examined the effect of crop land management practices on soil erosion for the year 2050. Their study was based on an economic model used to determine the most profitable crop rotations for representative farms in the area of study, but which were not necessarily the most realistic (such as continuous soybean cropping). The higher temperatures caused maize yields to decrease, subsequently the soybean acreage increased. Although there was quite a bit of variation across the country, the study found soil loss to increase (+10 to +274%) through almost all of the eastern US Corn Belt, mainly due to higher precipitation (10% to 20% increase), changes in runoff (up to 300%), and less interception from crops (wider rows and shifts in planting dates).

3.2. Modelling land use change

Changes in agricultural land use involve altering the location, nature, or quantity (units per area) of agricultural crop or livestock production (Smit and Skinner, 2002). To assist in determining such future changes, land use models can be useful tools to build plausible scenarios based on a range of possible inputs (driving factors) and to consequently visualize the spatial representation of future land patterns to determine impacts of change on the environment.

Farm-level driving factors of land use determine future cropping practices and watershed compositions. Studies that have collected data at the farm level (Overmars and Verburg, 2005; Overmars et al., 2007) found that the data helped explain current land uses and also improved deductive analyses when projecting land use changes in the future.

The farm is often not the spatial scale of choice. Land use models do not tend to examine the farm level land (Houet et al., 2009; Overmars and Verburg, 2005), perhaps due to the required integration of social and physical sciences (Verburg et al., 2004b) which is not undemanding, or because it is difficult to predict the evolution of crop land use at a watershed scale due to the complex relationships between producers and their management of land resources (Lambin et al., 2000), or because the spatial-temporal evolution of land-use is highly site-specific and thus difficult to draw out generalizations that can be input into a larger scale land use model.

3.2.1. Drivers of land use change

Drivers of land use change can be distinguished into two broad categories; direct and underlying drivers (Lambin and Geist, 2006). Direct drivers are immediate actions or activities which cause a change in land cover. These causes are usually - but not always - local in scale (i.e. producer or household level) and involve a physical action limited to a specific set of activities, such as agriculture. Underlying drivers are more diffuse in nature and usually operate at a larger scale, such as the regional or national level. They influence the direct drivers through incentives or other guiding principles, such as economic, technological, or demographic (Lambin and Geist, 2006). Both direct and underlying factors interact with one another and have feedbacks to which each is sensitive. For example, the direct driver of selecting and growing only one type of crop in a local region may lead to overproduction of this crop type which will have economic repercussions at the national/global scale and may decrease the price for the crop the following year, which in turn may cause the producer to select another crop to grow. To ascertain drivers of change at the farm level, several levels need to be considered; national, regional and local (Bürgi et al., 2004).

The literature contains several indices of both types of driving factors that are influential on shaping land uses at the local (farm) scale; for example: the farm characteristics (intensity of farming, and farm size) (Reidsma et al., 2009); the type of producer (based on age, education, innovation and farm characteristics) (Bakker and van Doorn, 2009); the economic return available for the land (Dockerty et al., 2006); social characteristics (Veldkamp and Lambin, 2001); geophysical features, accessibility to markets, demand for food, available technology, and government subsidies (Bürgi et al., 2004; Busch, 2006; Schröter et al., 2005). Drivers of land use change are highly site specific, and therefore need to be verified in each watershed before implementing them in any model.

3.3. Effects of land use change and climate change on water quality

In the developed world in particular, the historic expansion and intensification of agriculture has been a significant factor in transforming landscapes (Lambin et al., 2000), and the non-point source pollution caused by agriculture stems largely from the transport of applied fertilizers to water bodies (Scanlon et al., 2007).

Agricultural land use influences the hydrological regime of a watershed (Quilbé et al., 2008). For example, arable land is more prone to generate surface runoff than hay areas or forest areas (Eckhardt et al., 2003). The area of maize cropland is especially strongly correlated to nitrogen and phosphorus amounts in adjacent or downstream water bodies (Donner, 2003).

The magnitude of the impacts of future changes of agricultural land on the quality of water is largely unknown (IPCC, 2007, Chapt 3). It is particularly unclear how driving factors such as renewable energy incentives will increase maize land for biofuel production (Schilling et al., 2008), and how this will affect the quality of surface water.

Most of the studies which have investigated the impacts of climate change on hydrological responses in a watershed have assumed that land use remains static. On the other hand, studies that examine agricultural land use change rarely look at it from a climate change perspective (Fohrer et al., 2001; Weber et al., 2001).

3.4. Best management strategies as protection measures of water quality

Soil erosion is related to land cover and to the amount of rainfall more than it is to runoff (Nearing et al., 2005). Therefore, adequate soil and residue management practices which increase the amount of interception, such as no-till, cover crops or perennial crops, may curb soil erosion rates during intense precipitation events by providing a physical barrier and reducing the rainfall erosivity.

The future crops and management practices implemented will determine, in large part, the potential for soil erosion to occur. Row crops with wide row spacing (i.e. maize and soybeans) with no residue cover on the soil, present the largest potential for erosion to occur (SWCS, 2003). If these types of crops make up the primary crops in a watershed, coupled with a longer growing season, the amount of soil erosion may increase due to the greater exposure of the soil to the elements. As well, increased amounts of fertilizer may be required to grow the crops for a longer time (Brassard and Singh, 2008), which may amplify the runoff or leaching of nutrients from agricultural fields, especially given the risk of more intense precipitation events.

A main unknown to manage water sustainably in the future is whether present watershed management strategies, or proposed strategies in water management plans, are sufficiently robust to cope with the impacts of climate change (IPCC, 2008; Scanlon et al., 2007).

According to Scanlon et al. (2007), linkages between land use and water resources should be taken into consideration when developing related policies. As well, current management strategies require close examination to determine whether they hold in the future. The development of adaptation strategies requires a better understanding of the interplay between stakeholders and their environment in the context of local constraints and regulations (Schröter et al., 2005).

4. Conceptual Framework and Study Area

In addition to changes in climate, we can expect land use to continue to evolve in a watershed with time. Agricultural land is determined in part by climate parameters, bio-climatic and socio-economic factors. Should these determinants significantly alter in the future, crop land use will most likely change as well. Alterations in crop land will in turn most likely affect the quality of surface water, but the magnitude of these changes is unknown.

Beyond the negative hydrological impacts of a warming climate (e.g. higher precipitation intensities), crop production in Québec will be presented with several opportunities, for example: the possibility of earlier planting dates as well as later harvesting dates; multi harvests per year; planting higher value crops; and cultivating new areas of land. Concomitantly, given the expected higher variability of precipitation and a likely longer growing season, agricultural land has the potential to contribute to high rates of non-point source pollution.

Agricultural land use change is highly site specific and requires a local scale of study to link specific land uses to impacts on water quality. In this study, a mesoscale watershed in Québec is used to develop a range of future climate and land use scenarios for evaluating their combined impacts on water quality. The main steps in this research are to:

1. determine a range of future climate variables for 2041-2070 from Regional Climate Models (RCMs), including the future growing season length, temperature and precipitation;
2. determine main drivers of land use change (informed by producer questionnaires) as well as a baseline of historical land use (based on existing maps and remote sensing imagery);
3. develop land use scenarios for the future and apply a land use model (CLUE-S) which spatially allocates the changes in crop land uses;
4. determine the water quality resulting from these changes in climate and land use through the application of a hydrological water quality model (SWAT); and
5. develop and determine the effect of various adaptation strategies and their capacity to mitigate the simulated changes in water quality due to climate and land use change.

Detailed studies in the Pike River watershed have been conducted by several research groups since the early 1990s. For example, previous research has been undertaken in which the SWAT model was applied with four climate simulations for the time period 2041-2070 to simulate sediments, phosphorus and nitrate loads transported in the watershed (Gombault, 2012). At the field scale, Gollamudi et al. (2007) examined the transport of phosphorus loads using SWAT to recommend best management practices. Also using SWAT, Eastman (2008) investigated P transport via surface and subsurface pathways in the basin, and Jamieson et al. (2003) measured the effects snowmelt and runoff events on P transport. The partitioning of particulate P and the bioavailable P in surface and subsurface flows stemming from fields has been investigated from water sample analysis by Poirier et al. (2012) and also by Michaud and Laverdière (2004) through runoff sample analysis using simulated rainfall experiments. As well, the efficiency of best management practice implementation on reducing the TP loads in the basin was investigated with SWAT (Michaud et al., 2007).

This study applied the SWAT 2005 model with the modified code for Québec (SWAT-QC: Michaud et al. 2008). Modifications of the code by Michaud et al. (2008) included improving the soil moisture flow to the drains; including preferential flow for clay soils; and increasing the amount of surface storage in the curve number method (SCS-CN). The same model was also used in previous research in the watershed (Michaud et al., 2008, Gombault 2012). We applied the same SWAT-QC model version, but updated to SWAT 2009, and we altered the SWAT set-up to suit our study purposes so that there were less sub-basins; this entailed carrying out a new calibration and validation. The initial parameters in the calibration from Gombault (2012) were used in this study. These parameters were then added to or removed, depending on the sensitivity. A list of final calibrated parameters can be found in Appendix 1.

Table 1. Corresponding gauge names to outlet numbers.

Previous study gauge names	This study
Walbridge Creek upstream	Outlet 4
Walbridge Creek downstream	Outlet 6
Pike River downstream	Outlet 8
Pike River upstream	Outlet 14
Pike River water quality station (MDDEFP # 03040015)	Outlet 18
Outlet	Outlet 23

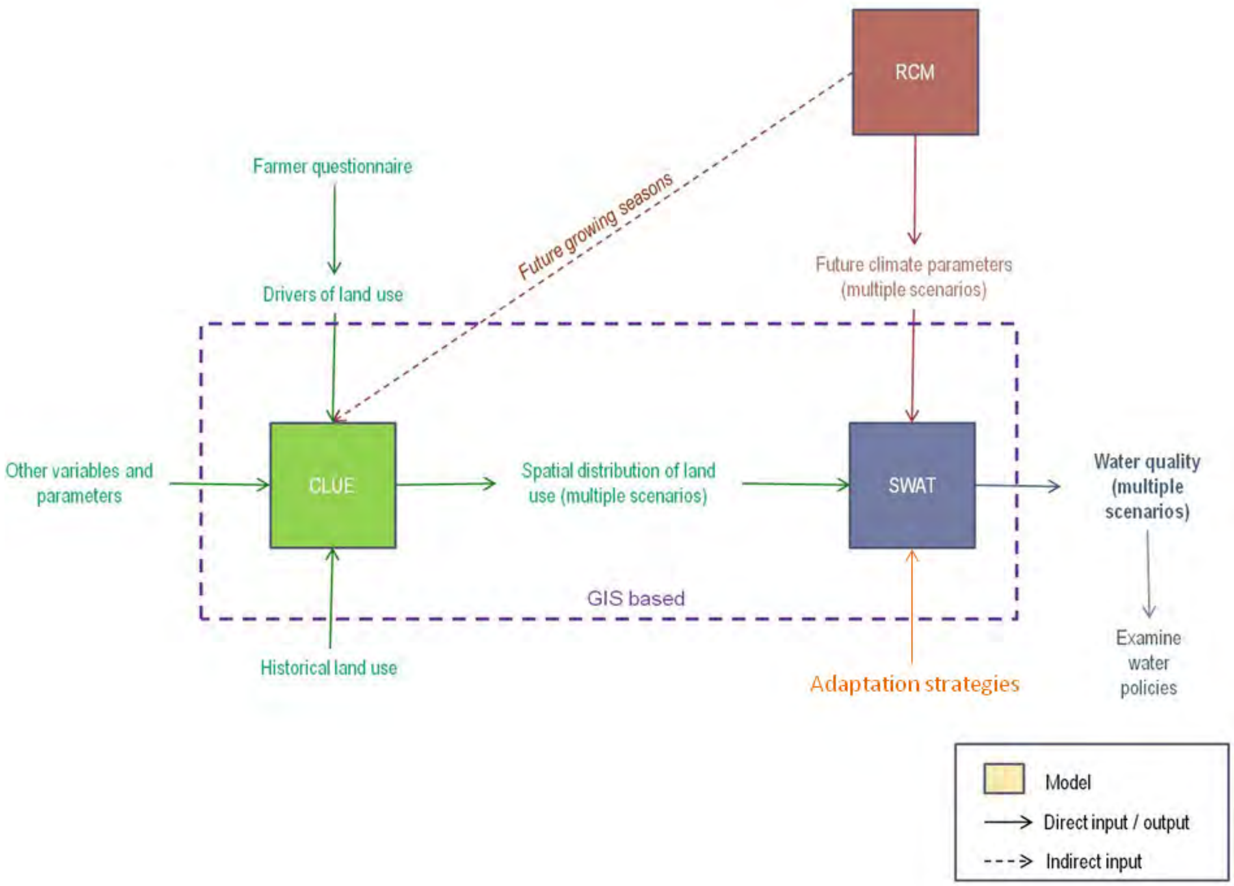


Figure 1. The conceptual framework (RCM = Regional Climate Model; CLUE = Conversion of Land Use and its Effects; SWAT = Soil and Water Assessment Tool); for further explanations of the model concepts see the Methodology (Chapter 5).

4.1. Study area

The Pike River watershed covers an area of 629 km^2 and straddles Québec and Vermont (99 km^2 of land is located in the State of Vermont). The Pike River flows from Lake Carmy in Vermont, through the town of Bedford and discharges directly into the Missisquoi Bay. The elevation in the watershed ranges from 710 m to 50 m AMSL. The soils are predominantly clays (gleysolic) of marine and lacustrine origin situated in the low-lying areas. Calcareous tills and shale tills (brunisolic and podzolic) are found in the higher elevations (Deslandes et al., 2007).

Approximately 54% (33 966 ha) of the watershed was under agricultural land use in 1999. A historic land use map of 1999 (from Landsat 7 ETM+ (Cattaï, 2004)) shows the watershed to be composed of 22% hay, 20% corn, 8% cereal, 2% soybean, 2% orchard, 40% forest, 5% water and 1% urban areas. In 2003, a total of 33 740 ha were under agricultural land. In 2011, the total agricultural land increased to 34 013 ha. Livestock occupy an important sector in the basin as well; the mean animal density in the watershed in 2001 was 1.3 (total animal units/total area of cropland), this is considered to be high; values <0.25 are low and values between 0.25 and 0.5 are medium. Of the livestock, 49% were swine, 35% were cattle, 7% were poultry, and 5% were other (Statistics Canada, 2002). In 2006, the mean animal density remained the same.

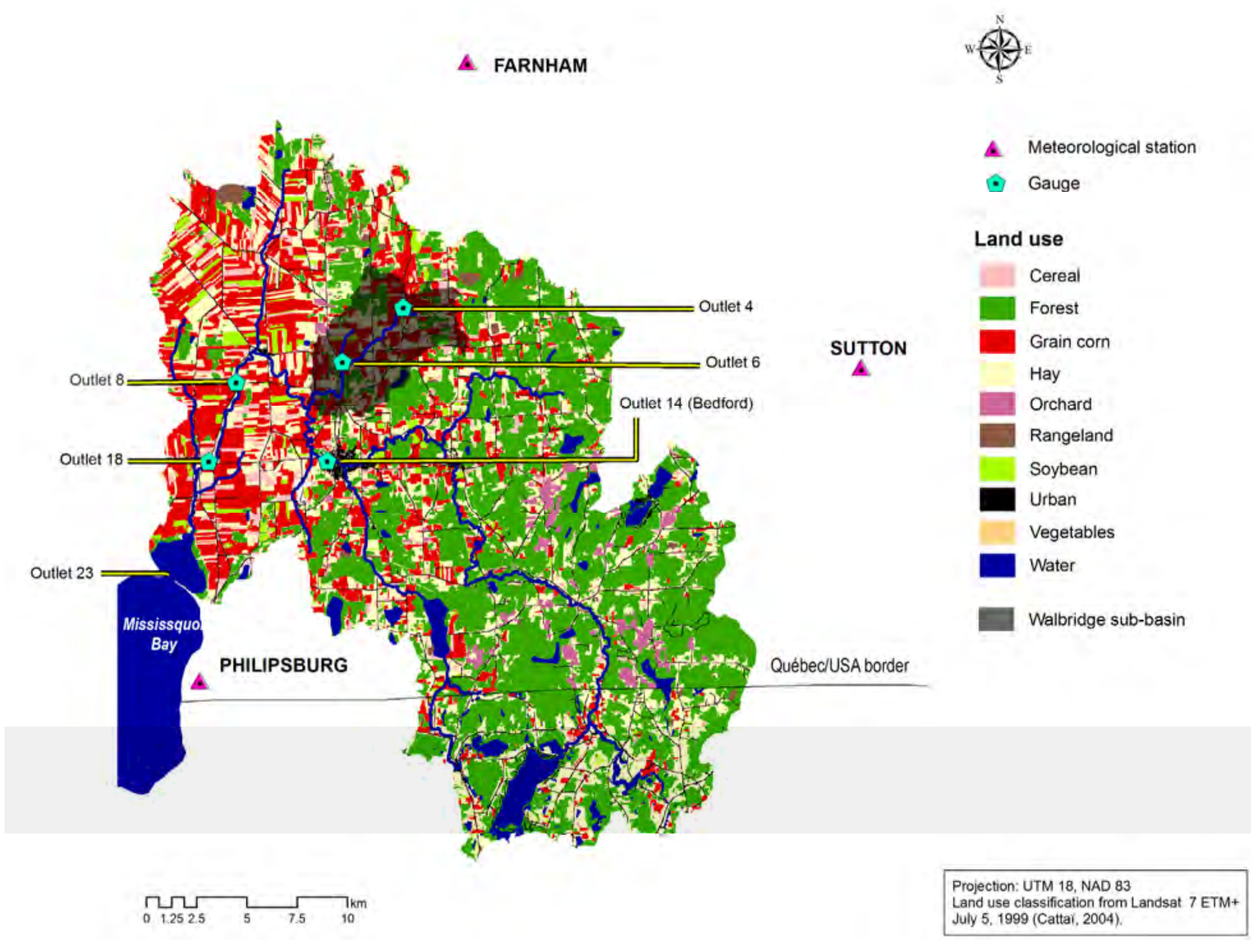


Figure 2. The Pike River watershed with land use from 1999. The shaded area (surrounding outlets 4 and 6) indicates the extent of the Walbridge sub-basin.

The area located in the lower part of the basin (west of the town of Bedford) is made up of mostly agricultural land; three-quarters is cultivated. This area contributes significantly to the export of phosphorus from fertilizers (Poirier et al., 2012; Simoneau, 2007). The high levels of phosphorus have contributed in part to the frequent outbreaks of cyanobacteria blooms (Blais, 2002).

The basin receives approximately 1 270 mm of precipitation annually, of which 235 cm is snow that falls mainly from November to April (Environment Canada, 2013). The hydrological regime of the basin is driven principally by snowmelt from March to April (Figure 3), with peak annual flows occurring in April and gradually decreasing to summer (June, July, August). The lowest flows occur during the peak growing season, in July, when evapotranspiration is highest. A normal growing season starts at the beginning of April and ends at the end of October. During the growing season the average surface air temperature is 14^{o}C, and average precipitation is 105 mm. Temperatures in mid-November drop to below freezing and remain so until March.

Table 2. Climate normals (1971-2000) from an average of Farnham, Philipsburg and Sutton stations (data from Environment Canada).

	April	May	June	July	August	September	October
Mean temperature (^{o}C)	5.7	13.0	17.8	20.3	19.1	14.4	8.1
Total precipitation (mm)	92.2	96.2	98.1	120.4	118.2	108.7	99.9

The monthly flow regimes of the basin, as well as the monthly nutrient transport graphs, are depicted in Figures 3-6. Due to spatially variable and temporally incomplete discharge and nutrient measurements available, different gauges were used to compare the observed values with the simulated variables. The reference simulation represents SWAT run with observed climate data from 1971-2000 and a land use layer from 1999. To demonstrate how the model simulated the variable for the entire watershed, each graph also depicts the SWAT simulated variable at the basin outlet (outlet 23).

Table 3. Outlet number and its upstream characteristics.

Outlet	Area drained (ha)	Sub basin main channel length; average channel slope; and land use
4	736	0.91 km; 0.6%; intensive agriculture with pockets of forest
6	752	1.91 km; 0.1%; intensive agriculture with pockets of forest
8	56130	2.22 km; 0.0%; intensive agriculture
14	38610	1.06 km; 0.2%; mainly urban
18	56800	6.24 km; 0.1%; intensive agriculture
23	63190	6.02 km; 0.0%; agricultural land with wetland and some forest

At the basin outlet 23, the mean annual simulated streamflow from 1971-2000, is 10.6 m^3/s (one reported comparable value is 8.9 m^3/s (OBVBM, 2011a)). The month of April has the highest mean streamflow of 29 m^3/s, and July the lowest mean flow of 2.5 m^3/s (Figure 3). Outlet 14 (located upstream in the basin (Table 3)) compares the time series of measured to simulated data.

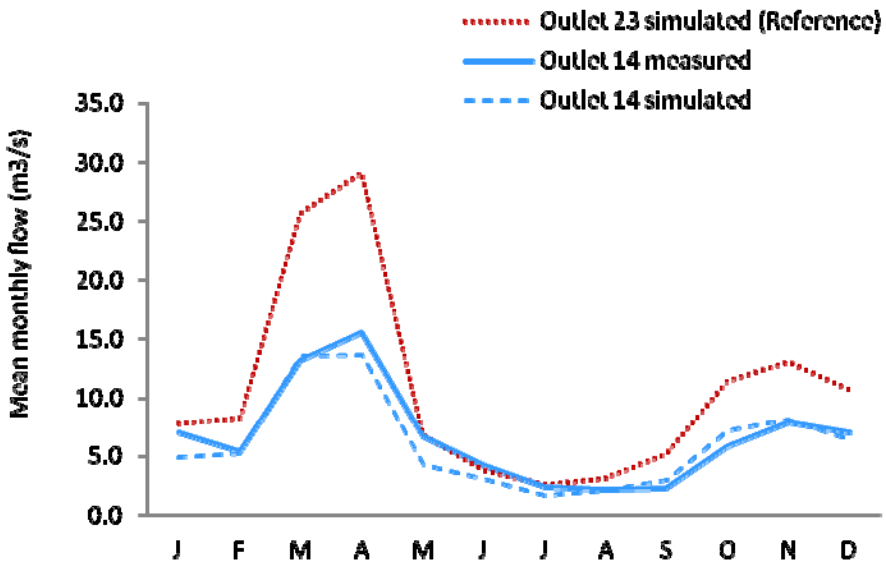


Figure 3. SWAT mean monthly streamflow (m^3/s) at outlet 23 for the reference simulation (1971-2000), compared to the observed and simulated mean monthly streamflow at outlet 14 (NSE=0.73) from 1979-2011.

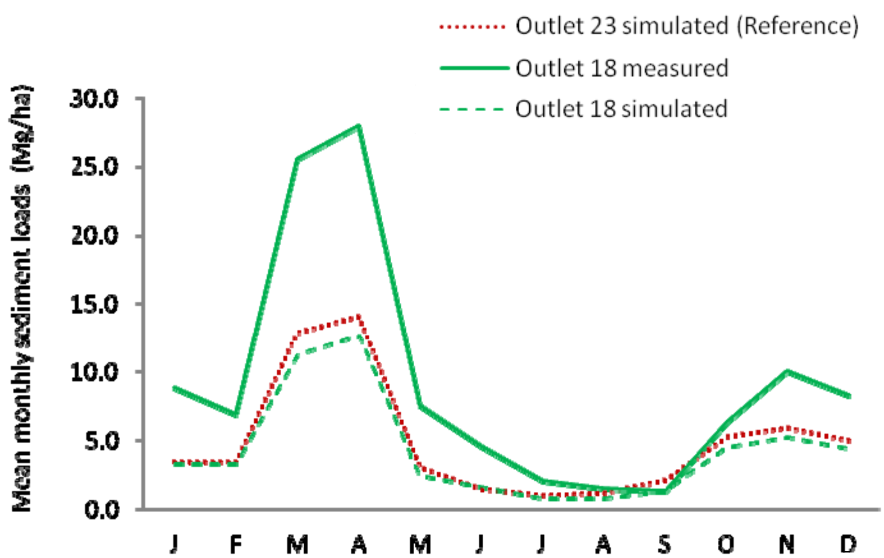


Figure 4. SWAT mean monthly sediments (kg/ha) at outlet 23 for the reference simulation (1971-2000), compared to the observed and simulated mean monthly sediments at outlet 18 (NSE=0.38) from 1979-2007.

The sediments are being underestimated by SWAT; this is evident by comparing the measured and simulated data at outlet 18. These values are also expected to be lower than in the reference simulation at outlet 23. Nevertheless, the timing of the events is satisfactory (Figure 4).

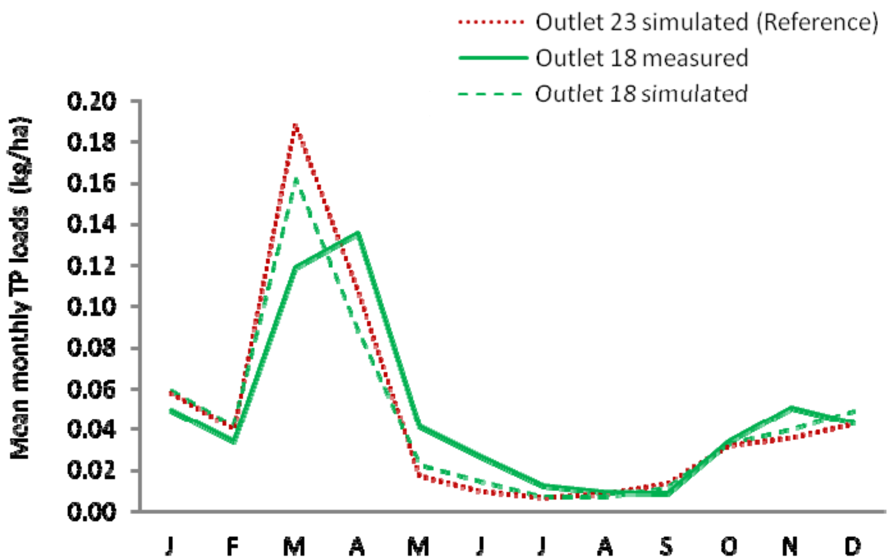


Figure 5. SWAT mean monthly TP (kg/ha) at outlet 23 for the reference simulation (1971-2000), compared to the observed and simulated mean monthly TP at outlet 18 (NSE=0.46) from 1979-2011.

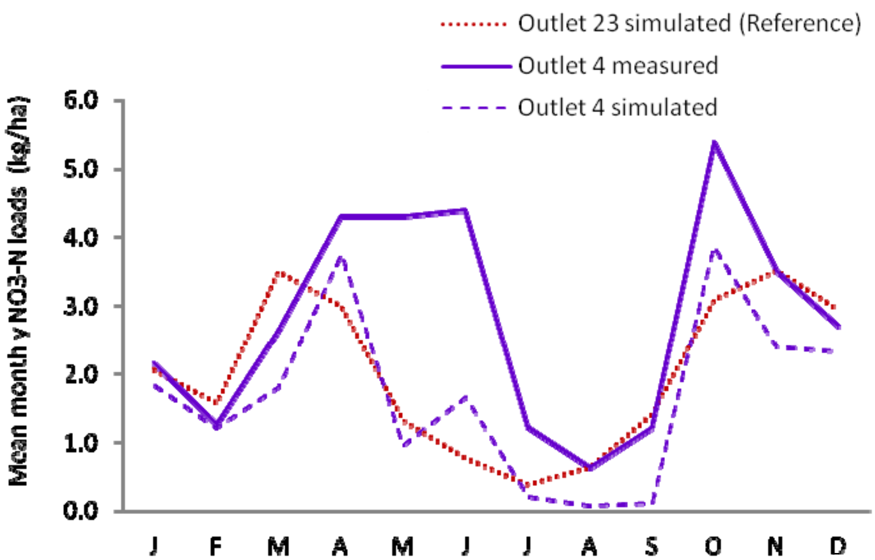


Figure 6. SWAT mean monthly NO_3^--N (kg/ha) at outlet 23 for the reference simulation (1971-2000), compared to the observed and simulated mean monthly NO_3^--N at outlet 4 from 2001-2003 (NSE=0.77) and from 2004-2006 (NSE=0.43).

The measured and simulated TP at outlet 18 shows the overall magnitude to be well reproduced for most months (Figure 5). SWAT underestimates TP slightly, and the peak transport occurs somewhat earlier (in March instead of in April). Most of the P is particulate P (Appendix 9).

Due to very sparse data available for NO_3^--N, the simulations represented the measured data the least well (Figure 6). Nitrate-N was underestimated for the most part and the timing of the peak nitrate transportation during May and June was not well captured

5. Methodology

This section outlines how the study will investigate nutrient transport and concentrations in the watershed due to climate change impacts alone, as well as due to the impacts of land use change alone. Then, it will outline the combination of climate and land use change impacts examined in the basin, and finally it will portray the adaptation strategies applied to examine improvements in water quality.

5.1. Future climate change scenarios

In collaboration with Ouranos, a suite of three climate simulations was selected (Table 4), each encompassing the periods 1971-2000 and 2041-2070 with a daily time step. The future period 2041-2070, representing the 2050 time horizon, was a medium time horizon chosen because the climate change signal only becomes apparent after 30 years (de Elía et al., 2013). Also, the 2050 horizon is relevant for the land use change scenarios because it is still close enough in the future that management decisions and policy actions remain applicable to the current generation of farmers and stakeholders.

To determine which climate simulations to choose, first the climate parameters that the hydrological model in this study (SWAT) is sensitive to were pinpointed. Based on past research (Gombault, 2012), the following climate variables were known to be sensitive in the SWAT model, and therefore considered when selecting the climate simulations: changes in minimum and maximum temperatures in winter and in spring; changes in total annual precipitation amounts. In addition, extreme precipitation events wanted to be considered, therefore changes to the 95th percentiles of precipitation in spring, summer and fall were also included. Ouranos focused on these 8 climate parameters when choosing the climate simulations for the project so that the climate simulations covered a broad range of these parameter values. The values of the climate variables were relevant for the south of Québec.

In this study, RCMs were selected to provide future climate simulations because they are dynamically downscaled from Global Climate Models (GCMs) to better represent the physical climate of the mesoscale watershed conditions. The cluster analysis method (Logan et al., 2011) enabled climate simulations to be chosen so that the variability of the future changes (with respect to the 8 defined climate variables above) covers approximately 50% of all 16 regional climate simulations available at Ouranos at this time. [Note that this calculation does not take into account the total variability which is better represented by a larger model ensemble (including the GCMs); if the GCMs were included, the 3 simulations would cover less than 50% of the known variability.] Thus, the three climate simulations selected all have different characteristics, and provide a large coverage of the available simulations, Figures 7 and 8 depict a few of these differences.

The three climate simulations were denoted according to their operational name used at Ouranos: ACU, AGR and AHI-AHK. In this report the following codes are used to denote the simulations: ACU, AGR and AHK, respectively.

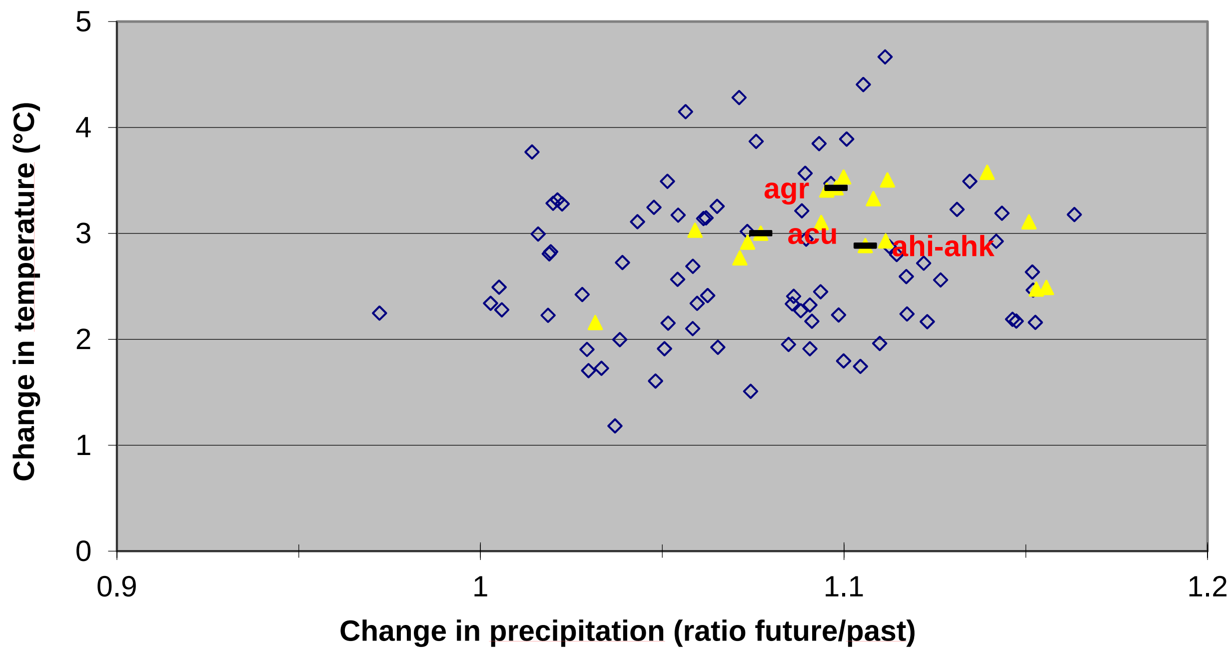


Figure 7. Climate simulations showing changes in annual precipitation and mean annual air temperature for the Pike River watershed, differences between 1971-2000 and 2041-2070. Yellow triangles are RCMs, blue diamonds are GCMs. [Figure courtesy of Ouranos].

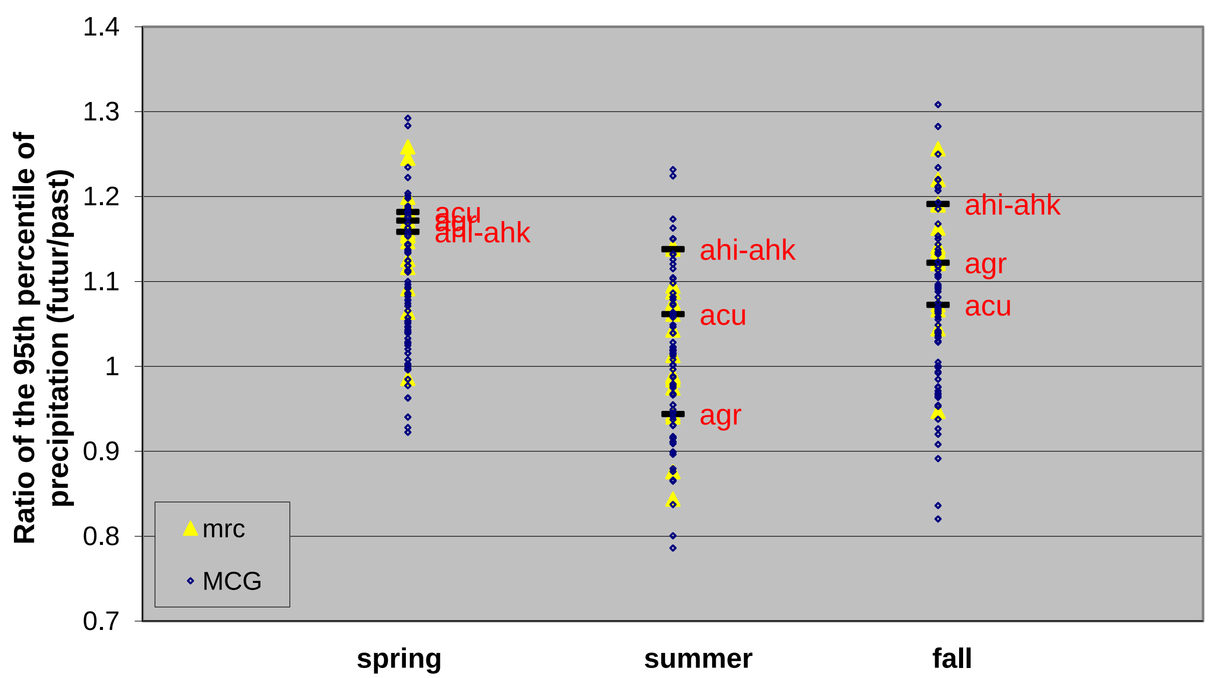


Figure 8. Climate simulations showing changes in the 95th percentile of daily precipitation for the Pike River watershed, differences between 1971-2000 and 2041-2070. Yellow triangles are RCMs, blue diamonds are GCMs. [Figure courtesy of Ouranos].

Different versions and domains of the Canadian Regional Climate Model (CRCM; Paquin 2010) were selected, each with a horizontal grid-size mesh of 45 km (true at 60° N). These were piloted by 2 different GCMs. All simulations used the A2 SRES greenhouse gas evolution scenario as developed by IPCC. The A2 scenario is a rather pessimistic scenario (but not the most pessimistic) in which expected CO_2 concentrations for the middle of the century are about 575 ppm (Nakicenvoic et al., 2000). Current concentrations of CO_2 have now surpassed 400 ppm (Monastersky, 2013).

The CRCM data has been generated and supplied by Ouranos. The temperature and precipitation in all of the simulations were bias corrected by Ouranos based on observed station data using the “daily translation” method by Mpelasoka and Chiew (2009). Two types of observed data were available to correct for the bias of the chosen climate simulations: the station data from Environment Canada (EC), and interpolated data from the National Land and Water Information Service (Hutchinson 2004). The data obtained from the EC stations provided the best outcomes when the measured streamflow and nutrient data were compared to SWAT simulations (streamflow, sediment transport, NO_3^--N and TP). Therefore, the EC station data from Philipsburg, Farnham and Sutton were chosen for the bias correction of the climate simulations, as well as for the SWAT calibration procedure. Using local weather stations for the bias correction procedure also provides a downscaling of the simulations from a regional to a local scale.

Table 4. Properties of the three climate simulations chosen for this study.

Name of simulation	Regional Climate Model	Piloted by Global Climate Model	Regional domain cell*cell	SRES	Characteristics
ACU	CRCM4.1.1	CGCM3-4	Québec 112*88	A2	Smallest changes in annual precipitation Largest changes in spring Tmin and Tmax
AGR	CRCM4.2.3	CGCM3-5	Québec 112*88	A2	Smallest changes in 95th percentile of summer precipitation Largest changes in winter Tmin and Tmax
AHI-AHK	CRCM4.2.3	ECHAM5-2	North America 182*174	A2	Greatest changes to annual precipitation Greater changes in 95th percentile of summer and fall precipitation Smallest winter and spring changes in Tmin and Tmax

The climate scenarios were used for two purposes:

1. to simulate future water quality in the basin, using the future climate variables as input to the SWAT model; and
2. to determine changes to the future growing season by calculating the cumulative degree days, and the start date of the future growing season. Here, the 1971-2000 simulations were compared with the 2041-2070 simulations to estimate the changes in the future. This information allowed choosing new crops which may be planted in the watershed in the future.

5.1.1. Calculating the growing degree days

The growing degree days (GDD) and the start of the growing season were calculated from the three future climate simulations. The GDD were computed using the method by Gordon and Bootsma (1993), which calculates GDD from April 1 to October 31. Daily GDD were summed from the time when daily mean temperature (T_{mean}) first exceeds the base temperature (T_{base}) in April until the last date of $T_{mean} > T_{base}$. These dates are considered to be approximate for the growing season of crops. The GDD were determined using base temperatures of 0^oC, 5^oC and 10^oC, respectively. Different crop types have different minimum temperatures when they start to grow, for example, wheat requires at least 5^oC to grown, so to estimate its GDD, the daily GDD were summed from the time when the mean daily temperature (T_{mean}) first exceeds 5.0^oC in April until the last day in October where $T_{mean} > 5.0^oC$.

$$\text{When daily } T_{mean} > T_{base,} \text{ then, } GDD = \sum_{April\ 1}^{Oct\ 31} \frac{T_{max} - T_{min}}{2} - T_{base}$$

This method precludes days when the growing season extends beyond the period of April 1 to October 31, which is especially relevant in a future climate. However, this method can nevertheless be used to compare the relative increase in GDD in the future to a reference climate.

Knowing the future amount of GDDs in a season allows determining the crops to be considered for seeding in the future. Besides the GDD, some crops, such as winter wheat or alfalfa, may be disadvantaged by the warmer temperatures, especially in winter if there is an absence of snow cover. However, this aspect was not examined in this study.

5.1.2. Start of the growing season calculation

The start of the growing season was computed using the method by Chmielewski and Köhn (1999) in which the growing season starts when the average daily temperature (T) is greater or equal to 5.0^oC, and the sum of the differences remains positive for the 29 subsequent days:

$$\Sigma_i (T_i - 5^oC) > 0^oC, (i = 2, 3, ... 30)$$

Similarly, the end of the growing season is defined as the day on which the average daily temperature is less than 5^oC, and the sum of the differences is negative for the rest of the year:

$$\Sigma_i (T_i - 5^oC) < 0^oC, (i = 2, 3, ... \text{end of year})$$

5.2. Future scenarios of land use

Several scales can be considered in the context of land use change, ranging from global to local (farm level). Most of the previous studies have focused on changes over larger scales (country or continent) to determine the future agricultural landscapes. In this report, the regional and local spatial scales (i.e. watersheds and agricultural enterprises) were examined to provide insights into the driving effects of change and elucidate the decision processes of farmers in order to relate them to land use changes.

5.2.1. Questionnaire to determine drivers of land use change at the farm level

The rate, quantity and location of land use change are affected by several driving factors, including demographic, economic, technological, cultural and biophysical factors. In small scale modelling, data for describing drivers and complex relationships is typically limited, so that proximate variations are often used to represent the driving forces instead of using the underlying driving factors (Verburg et al., 2002).

To describe future land use changes in the watershed, the current and future driving factors of crop land use change were determined based on local factors influencing the decisions made by producers in the watershed.

To gauge the decision-making factors of farmers, a questionnaire was compiled, together with stakeholders (*Union des Producteurs Agricoles* (UPA), *Ministère de l'Agriculture, Pêcheries et Alimentation* (MAPAQ), *Ministère du Développement durable, Environnement, Faune et Parcs* (MDDEFP) and the *Organisme de Bassin Versant de la Baie Missisquoi* (OBVBM)) active in the watershed.

The questionnaire consisted of 23 questions (see Appendix 2). It was constructed to gain insights into the historic and current decision making factors of farmers for crop land use, and to determine important factors of future change. Questions focused on why certain crop changes had taken place in the past on the farm, and what factors would bring about a future possible change of crops on their farm. Their responses were based on their experience and on their current practices. No future climate scenario was described to them. The questionnaire could be filled out anonymously and was estimated to be able to be completed in less than 30 minutes.

The questionnaire was sent to two independent groups of farmers. The first group were farmers with fields located in the Pike River watershed (n=210). The second group was a class of agricultural Diploma students in their third year at Macdonald Campus of McGill University (n=23). The purpose of questioning two groups was to capture differences with respect to two generations' outlook regarding current practices and with respect to the future of their farms.

The answers to the questions were used to guide the subsequently developed future land use scenarios in terms of types of the quantity of each crop type planted every year, the conservation practices used, and the future of the farm.

5.2.2. Scenarios of land use change in the watershed

To represent different future land uses in the study area, two "plausible" scenarios (see a and b) and two "extreme" scenarios (see c and d) were developed and subsequently modeled with CLUE-S and SWAT, respectively.

5.2.2.1. Land use change scenarios modelled with CLUE-S

The CLUE-S model (Conversion of Land Use and its Effects-Small scale; Verburg et al. (2002), see section 5.2.3) was chosen to simulate land use scenarios in the study area because it provides spatial distributions of crop land use in the near future by using historic drivers of change as input. Future scenarios focused on categories of land use that included: annual crops, permanent crops, bioenergy crops, pastures, fallow land, the potential for new crops, protected areas, forests and urban areas.

To determine the plausible land use scenarios in the basin, the following storylines were agreed upon to pursue with the land use model CLUE-S. The storylines were:

a) Historical trends will continue (or business as usual)
b) Expert guidance provided scenario (based on the farmer decisions and stakeholder input)

A description of each follows below.

a) Scenario "Historical Trends Continue" (HIST)

In this scenario, the historic land use change trends were extrapolated into the future which captured the recent past trends of land use and continues them into the future. To extrapolate these trends, the historical land use in the basin was determined from diverse sources of information. The main source was from digital maps from 2003 to 2011 containing the spatial distribution of crops, obtained from BDCG/BDCA data from the *Financière Agricole* (FADQ, 2008, FADQ 2005) for Québec. A digital layer of 2001 forest cover, obtained from the *Système d'information écoforestière* (SIEF, 2004) database, as well as digital layers for crops in the USA from the CropScape database (USDA-NASS, 2012) from 2008 to 2011 for Vermont were also used to create one raster layer for each year from 2003 to 2011 in ArcGIS.

Farm level data collected by MAPAQ (*données d'occupation du sol des fiches d'enregistrement* provided by Robert Laurin) was used to complement missing data in the BDCA/BDCG data from 2003 to 2011. However, in the BDCA/BDCG data, the land use type denoted as AGRL data was not able to be allocated to any specific crop since there was no information on these agricultural lands from the *Financière Agricole*, so it was left as "other agricultural land".

In this scenario, the historical evolution of agricultural crop areas during 2003-2011 was simply extrapolated quantitatively unto 2040 with regression equations. All trends were linear. Small manual adjustments were made to finally fit the crops in the watershed area. Overall, the total agricultural land increased by 0.4% during 2003 to 2011, while forest areas decreased by 0.47% and urban areas increased by 0.03% during this period.

The scenario was developed as a baseline to compare the other scenarios to (i.e. if farmers simply continue to do as they have in the past, this is what will happen). This scenario reflects the historic market trends, the past crop insurance available for farmers, and consequent choices of crops that result.

b) Scenario "Expert Guided" (EXP)

The second scenario is based on farmer decisions and drivers of land use change obtained from the questionnaire responses. The scenario was also developed from meetings held with MAPAQ, UPA, OBVBM, Ouranos, the *Institut de Recherche et de Développement en Agroenvironnement* (IRDA) and other researchers. Drivers for land use change were reflected in this scenario by altering the crop quantities and types over 30 years.

For this scenario, the results of the farmer questionnaire were mainly used to build the story line into the future. Thirty years is a recommended projection time limitation of the CLUE model (Verburg 1999; Veldkamp and Fresco 1996). The questionnaire answers (Appendix 3) provided qualitative data that guided which crops to diminish and which to increase in a future time line. For example, from question 6, we could gauge if the farmer was satisfied with the types of crops currently being grown. From questions 8, 10 and 11 we could determine some of the drivers of changes in the past. Questions 12 and 13 guided the future crops and knowing important drivers of land use change for the future, for example, if the growing season were 4 weeks longer.

Further regional drivers of land use change at the level of Québec were considered by conducting a literature review of existing policies and market forces (Appendix 4).

This scenario also reflects the changes in climate in the region by taking into account a study on analogue climates. Gagnon et al. (2013) show the future climate in the Montérégie to be similar to that of the US states currently in the "Corn Belt" (Iowa, Illinois, Indiana, Ohio and Pennsylvania). For the most part, the crops grown in these states are corn and soybeans (already present in the basin). However the study also suggests that vegetables, orchards and vineyards will be suitable grow in the future (2050 horizon).

The main characteristics of this scenario show the total agricultural land use area to remain constant over time. The amount of forested area decreases at the same rate as the rate of urban expansion. Within the agricultural areas however, there is a pronounced increase in corn production. Soybean areas increase as well. The amount of hay decreases. There is also more area allocated to niche crops, such as switchgrass, orchards and vegetables.

Given the above story lines, the CLUE-S model was used to spatially distribute the crops every year using the quantitative changes that took place in the story line. The resulting land use evolution over 30 years for both scenarios was presented to a group of experts to validate the scenarios. A meeting was held where the scenarios were presented to experts and stakeholders in the project (UPA, MAPAQ, Ouranos, ROBVQ, IRDA and CEHQ). A total of 10 participants evaluated the scenarios and provided input during a 3 hour long meeting. The refined and agreed upon HIST and EXP scenarios were then transferred to the SWAT model by means of applying the SWAT2009_LUC tool (see 5.2.3.1).

5.2.2.2. Land use scenarios modelled directly in SWAT

In addition to the above scenarios, two "extreme" scenarios were developed by changing the land use in SWAT. The first of the extreme scenarios assumes the entire watershed to be covered in forest, while in the second the watershed is entirely planted to corn. In both of these extreme scenarios, only the urban areas and open water areas are preserved. The extreme scenarios helped to define the outer limits of the water quality simulations in SWAT.

The extreme scenarios are not meant to necessarily be realistic, but were used to determine the limits of the SWAT model regarding the simulation of nutrient transport with the current SWAT set-up of the watershed.

c) Extreme scenario "Watershed Planted Entirely to Corn" (CORN)

In this scenario, the whole watershed is seeded to grain corn. The corn is planted on May 12 of every simulation year and fertilized with 130 kg N/ha/year and 66.7 kg P/ha/year (Table 5). These rates were used based on the average rate applied on the whole watershed for corn during the calibration and validation periods. The proportion of manure and mineral fertilizer applied is also representative of current practices in the watershed.

Table 5. Timing and quantity of fertilizer application for the CORN scenario.

Fertilizer application	N mineral (kg/ha)	N manure (kg/ha)	P mineral (kg/ha)	P manure (kg/ha)
April 23	22.0	38.7	-	20.0
May 12	-	-	22.2	-
June 10	22.0	31.0	-	16.0
October 22	-	16.3	-	8.5

d) Extreme scenario "Watershed Entirely Forested" (FOREST)

In this scenario, the only parameter that was changed is the initial concentration of NO_3^--N in the shallow aquifer. For the calibration, the best parameter values were deemed to be 25 or 72 mg/L, depending on the location of the HRU. The section of the watershed upstream from gauge 14 (mostly forested) was assigned 25 mg/L while the section downstream from gauge 14 (mostly agriculture) had a value 72 mg/L. Since it is unlikely that the concentration of NO_3^--N would remain high under the all forest scenario, the shallow aquifer NO_3^--N was reduced to the value found mostly under the forested section, which was 25 mg/L, this was applied to the whole basin.

It should be noted, the extreme scenarios were not ideally represented in SWAT, since no new model set-up was performed. Only the curve numbers (SCS-CN) in each of the extreme scenarios were adjusted according to the vegetation type. All the other parameters were left as in the calibrated model for the reference land use of 1999. Had a new set-up been carried out, the number of hydrologic response units (HRUs; explained in Section 5.3.1.1) would have been greatly reduced in both cases, and the parameters corresponding to each extreme scenario would have better represented the forest or corn cover, respectively (i.e. the model would have been calibrated for the corresponding extreme scenarios). We assume that this representation of the extreme scenarios attenuates the amplitude of the SWAT modelling results, i.e. a true 100% corn cover would lead to more extreme results.

5.2.3. The CLUE-S model

The CLUE model (Veldkamp and Fresco, 1996) is a descriptive model to simulate the spatial distribution of land use patterns in the near future based on present and historical land use, and on competition between land use in space and time. It was developed as a discrete finite state model for watersheds in which agriculture is the predominant land use occupancy. The model has evolved to take into account a greater number of driving factors and to project to a longer time horizon of several decades (Veldkamp and Fresco, 1997; Verburg et al., 1999; Verburg and Veldkamp, 2004). The model has been fairly widely applied to several parts of the world, including China, the Philippines, Costa Rica, Ecuador, and Honduras.

The CLUE-S model (version Dyna-CLUE) (Verburg et al., 2002) is suitable for small scale applications (less than 1 km by 1 km resolution); and is thus also suitable for heterogeneous landscapes. Each pixel is assigned a dominant land use type.

CLUE-S is a hybrid model because it simulates land use change by using empirically quantified relationships (logistic regressions) between land use and the historic driving forces of changing land use patterns (e.g. soil type, distance to market, demographics, etc.), in combination with dynamic modelling (using iterations of land use competition based on user-defined elasticity of change and logistic regressions). Future driver of land use change are used to build scenarios of how the quantity of each crop in the watershed may change each year.

The CLUE-S model has two distinct modules; a non-spatial demand module (where the user defines the quantitative crop changes each year), and a dynamic spatial allocation procedure (where qualitative relationships are respected):

The first module is the land use demand module. The user specifies the quantity of change in each land use category independently of the spatial distribution of the categories. The results of this module specify at a yearly time step (or bi-yearly; see Verburg and Veldkamp (2004)) the area covered by different land use types. The quantities are a direct input for the second, spatial allocation module.

The second module is the spatial allocation, which uses a combination of empirical, spatial analysis and dynamic modelling. The empirical analysis looks at the relationship between the spatial distribution of historical land and the drivers and constraints of this land use. The location preferences, or suitability, for change are defined by using empirically derived relations (logistic regressions) of location factors and past land use (Verburg et al., 2004a). These results are used when simulating the competition between land use types for a given location.

The stability and resilience of land use to change can also be modelled. The CLUE-S model is able to account for these through elasticity of land use change, which allows the user to define how adverse the land use is to change. This is based on expert knowledge and user defined land conversion times. Land use constraints and restrictions can also be specified by the user. These are areas which are considered to be static and do not change (much) over time (e.g. parks, urban, water, etc.).

For grid cells that are allowed to change, the total probability is calculated (from logistic regression equations) for each of the land use types using an iteration variable specific to the land use. Competition for land and actual allocation for change is an iterative process in the model. Using the probability maps (from the logistic regressions), the decision rules in combination with the actual land use map, and the demand for different land use types, the most suitable location is chosen for each land use. When allocation equals demand, the final map is saved and the calculations continue for the next time step (Verburg et al., 2002).

Veldkamp and Fresco (1996) and Verburg et al. (1999) recommend that the “realistic” time horizon for running CLUE-S should be limited to no more than 30 years into the future. The principal reasons are that technology, crop varieties and other changes may occur beyond this time period, which the model is not able to capture. Furthermore, the logistic regressions in the model do not evolve with the land use changes over time, hence the assumption that the logistic regressions relationships will still remain valid over long periods of time is not realistic (see Heistermann et al., 2006).

5.2.3.1. Inserting the land use scenarios from CLUE-S into SWAT

The two “plausible” land use scenarios that were developed and applied to CLUE-S (HIST and EXP) were subsequently implemented in the SWAT hydrological model to determine the impacts of land use change on surface water quality. The coupling of CLUE-S results and SWAT was carried out using the beta version of a black box tool from the University of Arkansas, called SWAT2009_LUC (Pai and Saraswat, 2009). This tool is able to accept CLUE-S raster layers as input and spatially allocate new land use configurations to existing HRUs in the SWAT model as described below (see also further discussion in 6.3.2.1).

A spatial raster layer is produced by CLUE-S corresponding to one map of crop land use distribution in each year of simulation, from 2011-2040. These 30 maps are read by the SWAT2009_LUC tool. All pixels with the same future slope, soil and land use characteristics as an existing HRU in the basin are re-allocated into the raster layer’s corresponding HRUs. This reorganization is performed in order to assign the new land uses onto existing HRUs so that no existing HRU changes its land use. This reallocation changes the individual areas of the existing HRUs in each sub-basin, but it allows the SWAT model to retain the parameters for which it was calibrated and keep its hydrological cohesiveness. SWAT2009_LUC calculates the changed area of each HRU for every layer within the 30-year period and transmits this information to SWAT. SWAT then simulates land use change by increasing or diminishing the area of the initial HRUs as stipulated in each of the future land use layers.

The two land use scenarios depicting “extreme” land use changes (FOREST and CORN) were executed directly in SWAT (i.e. not developed in CLUE-S and did not necessitate the use of SWAT2009_LUC) by altering the land cover in the watershed as prescribed; 1) the whole watershed was converted to forest and 2) the whole watershed was planted to corn. The “extreme” scenarios were implemented by using the management files (.mgt) to convert all HRUs to the corresponding extreme land use, except for the urban and open water areas.

5.3. Modelling the quality of surface water

5.3.1. The SWAT model

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) was used to assess the quality of surface water. SWAT is a freely available hydrological model developed by the United States Department of Agriculture-Agricultural Research Service: USDA-ARS (see www.brc.tamus.edu/swat). It is a comprehensive physically based, semi-distributed, continuous model designed to simulate water quality of intensive agricultural watersheds. It accounts for the long term impact of watershed management practices. Its ability in simulating field management practices makes it highly suitable if climate change adaptation strategies need to be developed (Borah and Bera, 2004).

The hydrological model SWAT was developed specifically for the purpose of being able to allow for considerable spatial detail and is capable of simulating land-management scenarios to determine agricultural management effects on water quality (Arnold et al., 1998). SWAT has been applied to a wide range of studies, with watersheds of varying sizes ranging from the field level (Gollamudi et al., 2007) to macroscale basins (Jha et al., 2006). Researchers have used SWAT to examine a myriad of issues, including the impacts of climate change on surface- and on ground-water quantity and quality in North America (Gassman et al., 2007).

5.3.1.1. Background on nutrient modelling in SWAT

The SWAT model has three major forms of nitrogen that it models in mineral soils: organic N associated with humus; mineral forms of N held by soil colloids; and mineral forms of N in solution (Neitsch et al., 2011).

There are five main nitrogen pools that are associated with the nitrogen forms: two inorganic pools (NH_4^+ and NO_3^-) and three organic pools (fresh plant residue, stable humic substances and active humic substances). Parameters that are relevant for these soil N pools are related to the initial soil nitrogen content; mineralization (and decomposition/immobilization); as well as denitrification (and nitrification) processes.

The main processes for modelling nitrogen transport towards the stream are governed by parameters pertaining to the amounts of N added to the soil (e.g. fertilization amounts and mixing), and the amounts of N initially in the soil, as well as the transformation and transportation processes of nitrogen in the soil towards the water body. Nitrates can be transported by surface runoff, lateral flow, or percolation.

Mineralization and decomposition are dependent on water availability and temperature; they only occur when soil temperature is above 0^oC. Nitrification/volatilization only occurs when the soil temperature layer is greater than 5^oC (Neitsch et al., 2011).

Nitrates in the groundwater are also taken into account through recharge from the soil profile. Any water moving as percolation or bypass flow from the lowest depth of the soil profile and flows through the vadose zone becomes shallow and/or deep aquifer recharge. An initial nitrate load (kg N/ha) can be specified for the shallow aquifer in regions where nitrate loadings are high.

The phosphorus cycle contains three major sources in mineral soils: the organic pool associated with humus; a plant-available pool in the soil solution; and an insoluble mineral component.

SWAT models six different pools of P in the soil; three pools are associated with the inorganic forms of P (solution, active and stable) and the other three with the organic P forms (fresh, stable and active) (Neitsch et al., 2011). The fresh organic pool is associated with the crop residues and microbial biomass. The active and stable organic P pools are both associated with the soil humus, which is partitioned into these two pools to allow for P to transform from humic substances to mineralized substances. The P mineralization algorithms are net mineralization algorithms which take into account immobilization. Mineralization and decomposition depend on water availability in the soil and on soil temperature. Both are only allowed to occur if the soil temperature is above 0^{o}C and both are controlled by the decay rate constant, which as well as being controlled by temperature and water is also a function of the C:N and the C:P ratios of the residues.

The inorganic P in solution is the available form of P that plants can take up. This pool is in rapid equilibrium with the active pool. The equilibrium is governed by the P availability index. The active pool however is in slower equilibrium with the stable pool because SWAT simulates slow P sorption. At equilibrium, the stable mineral P pool is four times the size of the active mineral pool.

The primary movement of soluble P in the soil is by diffusion due to a concentration gradient in the soil. SWAT allows soluble P to leach from the top 10 mm into the first soil layer; this is governed by the P percolation coefficient. Organic and mineral P may be transported through attachment to soil particles.

The shallow aquifer can also contain soluble P. To account for this, a value must be specified to account for groundwater loadings of P, which may be especially relevant in agricultural intense areas. Any groundwater flow that enters the main channel from the shallow aquifer will have a specified value in mg P/L.

The SWAT model in this project was always run with a minimum of 3 years warm-up period to initialize the soil nutrients. A more detailed description of the model processes is given by Neitsch et al. (2011).

5.3.1.2. SWAT model set-up

ArcSWAT2009 version 458, modified for Québec (Michaud et al., 2008), was run on an ArcGIS 9.3.1 (ESRI 2009) platform. SWAT requires a number of physical and spatially distributed data to compute the hydrological and erosion processes involved in water quality simulations. For a summary of the data inputs see Table 6.

In this project, SWAT delineated 30 sub-basins for the Pike River, which was less than the previous set-up from Gombault (2012) of 99 sub-basins. The goal of this study is to examine land use change, rather than to pin-point the transportation of sediments, nutrients at a fine scale. For a watershed size of 630 km^2, 30 sub-basins appeared to be an acceptable number for our study.

The base data required to set-up SWAT consists of a digital elevation map (DEM) layer, a soil map, and a land use map. The DEM used had a 30 meter resolution (Deslandes et al., 2002) to which all subsequent layers were matched (i.e. the resolution of the model set-up was the same as the DEM). The soil information was obtained from various soil surveys and studies of the region (Thériault et al., 1943; Cann et al., 1948; Bernard, 1996; USDA-NRCS, 1999; USDA-SCS, 2006; Tabi et al. 1990). A historic land use map from July 5, 1999 was obtained from a Landsat 7 ETM+ image (Cattaï, 2004).

Hydrologic Response Units (HRUs), which form the spatial units of the SWAT model, are based on similar slopes, soil types, and land uses. This project had 13 crop types, 77 soil types and 4 slope classes. To minimize the number of HRUs, a threshold can be specified whereby minority slope, soil and/or land use areas below a given threshold are not considered in the sub-basins. In this set-up, threshold values of 0%, 5%, and 0% were used for slope, soil and land use respectively, to delineate a total of 2786 HRUs in SWAT.

All SWAT computations were calculated at the HRU level, based on a daily soil water balance. The water balance accounts for daily precipitation, evapotranspiration, return flow of groundwater to the stream, surface runoff, initial soil water content and any water leaving the soil profile to the vadose zone. Results at the HRU level are aggregated at each sub-basin and transferred into the reach to be routed through the hydrological network. For a detailed description of SWAT processes see Neitsch et al. (2011).

The observed daily precipitation and temperature input necessary for SWAT stemmed from three meteorological stations: Philipsburg (45.03^{o}N, 73.08^{o}W), Sutton (45.07^{o}N, 72.68^{o}W), and Farnham (45.30^{o}N, 72.90^{o}W) (Figure 1). Each sub-basin in SWAT obtains its meteorological data from the weather station located nearest to its centroid. For the climate simulations, data generated from the CRCM from three tiles each at a horizontal resolution of 45 km (true 60^{o}N) (Plummer et al., 2005) were used to obtain a complete coverage of the Pike River watershed. The bias corrected climate data from each of the CRCM tiles was relegated to the corresponding nearest meteorological station, so that the CRCM tile with centroid [44.80^{o}N, 73.05^{o}W] was allocated to Philipsburg; the CRCM tile with centroid [45.07^{o}N, 72.71^{o}W] was allocated to Sutton; and the CRCM tile with centroid [45.32^{o}N, 73.10^{o}W] was allocated to Farnham.

Table 6. Sources of data used for modelling the Pike River watershed.

Data	Source	Type	Time period	Scale/ resolution	Reference
Digital Elevation Model	*Banque Nationale Données Topographiques; Plans des cours d'eau du MAPAQ*; National Elevation Data (USGS)	Raster		30m horizontal (±1.3m vertical accuracy)	Deslandes et al., 2002
Initial land use layer	Landsat ETM 7 +	Raster	July 5 1999	30m	Cattaï, 2004
Quebec other land use data	*Banque de données des cultures généralisées* and *Banque de données des cultures assurées* (BDCG/BDCA)	Shape file	2003-2011		FADQ, 2008; FADQ, 2005
Vermont land use data	CropScape	Raster	2008-2011	30m	USDA http://nassgeodata.gmu.edu/CropScape Han et al., 2012.
Forest cover	*Système d'information écoforestière* (SIEF)	Shape file	2001	1:20 000	MNRQ http://www.mrn.gouv.qc.ca/forets/connaissances/connaissances-inventaire-cartes-sief.jsp
Soil layer	Québec: IRDA Vermont: Soil Survey Geographic (SSURGO) Database	Raster		1:63 300	Grenon, 1999; Cann et al., 1948; Thériault et al., 1943. (see Deslandes et al., 2002) ; USDA-NRCS, 1999.
Soil properties	*Inventaire des problèmes de dégradation des sols du Québec*	Text file			Tabi et al., 1995 Bernard, 1996 Wischmeier et al., 1971
River network	*Système d'information écoforestière*	Shape file	2001		MNRQ http://www.mrn.gouv.qc.ca/forets/connaissances/connaissances-inventaire-cartes-sief.jsp

Streamflow data	CEHQ	Excel file	1980-2011	Gauge	CEHQ, 2013 http://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/default.asp
Walbridge water quality data	IRDA	Excel file	2001-2003 2004-2006	Gauge	Michaud et al., 2004
Pike River water quality data	*Banque de donnée sur la qualité du milieu aquatique* (BQMA)	Excel file	1980-2007	Gauge	Direction du suivi de l'état de l'environnement/MDDEP 2008
Meteorological data	National Climate Data and Information Archive	Excel file	1971-2011	Station	Environment Canada, 2011 http://climate.weatheroffice.gc.ca/climateData/canada_f.html
Manure inputs	*Fiches d'enregistrement des exploitations agricoles de la Montérégie*	Excel file	1998	Farm scale	MAPAQ, 2000
Field Management Operations	Reports on *L'état des cultures*	Text file	1998-2011	Regional scale	FADQ, 2011 http://www.fadq.qc.ca/fr/acces_medias/evenements/etatsdes_cultures/etat_des_cultures_2011.html

For this project, the SWAT model set-up for the Pike River was updated from Gombault (2012) since additional data, or more recent and more suitable data was available to observe the effects of land use change (Table 7). As well, longer time series of streamflow data were available which were incorporated into the model calibration and validation steps. Finally, more recent fertilization practices and best management practices were extracted from data of the "*Suivi 2007 du Portrait agroenvironnemental des fermes du Québec*" (BPR, 2008) and incorporated into the model.

Table 7. Supplemental SWAT input data used for this project, in addition to previous data.

Data Type (see Table 6 for sources)	Previous data periods used in Gombault (2012)	Additional data for this project
Streamflow	1979 to 2007	2007 to 2011
Water quality	2001-2003; 2004-2007	-
Agricultural land use	1999	2003 to 2011
Field management practices	1998 to 2006	2006 to 2011
Fertilizer amounts, animal units	1998	2003 to 2007
Conservation practices	-	2003 to 2007

5.3.1.3. Management operations implemented in SWAT

The following management operations were implemented in SWAT and kept constant (unless stated otherwise) throughout all of the simulations. The fertilizer types and amounts per HRU in each sub-basin from the set-up of Gombault (2012) were redistributed proportionally onto the corresponding HRUs in each of the 30 sub-basins in this project. Details on the crop fertilization can be found in Deslandes et al. (2007), Michaud et al. (2006), and Levesques (2003). The amount of fertilizer applied to each crop is provided in Table 8.

Table 8. Average N and P fertilizer application per crop for the watershed.

	N mineral	N manure	P mineral	P manure	**Total N**	**Total P**
Corn	80.0	48.6	7.7	61.4	**128.6**	**69.1**
Hay	0	116.4	0	61.0	**116.4**	**61.0**
Cereals	78.8	32.2	15.4	35.5	**111.0**	**50.8**
Orchard	50.0	0	45.0	0	**50.0**	**45.0**
Vegetables	35.0	0	0	0	**35.0**	**0**
Switchgrass	0	25.0	0	0	**25.0**	**0**
Soybeans	0	0	0	0	**0**	**0**
Berries	80	0	40	0	**80**	**40**

Farm management practices in the watershed, such as the type and date of field operations, were collected from reports of the *Financière Agricole du Québec* (FADQ, 2011) on regional crop facts and from partners' knowledge of the basin (IRDA, MAPAQ). The antecedent precipitation was taken into account by respecting a minimum of 48 rain-free hours before implementing seeding dates, soil tillage and manure spreading operations in SWAT. Initial soil nutrient values were left as default values.

Prior to 2003, no residue management practices or incorporation of manure were modelled in the watershed because in 2004 only 2 to 3% of the cropped area was under reduced tillage (Frère, 2004), and there was no spatial data available for the watershed. Thus, it was assumed that prior to 2003 almost none of the watershed had reduced tillage. From 2003-2006, the manure incorporation practices were included as documented in the "*Suivi 2007 du Portrait agroenvironnemental des fermes du Québec*" (BPR, 2008). For example, 38% of the applied manure volume was incorporated. The dates of operation related to manure application and tillage to incorporate manure were selected to ensure that no rain fell 48 hours prior to and post operation (whenever possible).

Soil conservation operations were also implemented from 2003 to 2006 as according to Frère (2004), so that 3% of the fields in the Pike River watershed were under reduced tillage and 2% under no tillage. Soils under hydrological group D (according to SCS method; SCS, 1972) were exempted of no-till practices because the soil was considered to be too wet for this type of practice.

In our set-up, buffer strip widths of 0 m, 1 m, and 3 m were applied to row crops, hay and orchards, reflecting the presence of ditches. The width was selected according to data in the "*Suivi 2007 du Portrait agroenvironnemental des fermes du Québec*" (BPR, 2008) so that 16% of the crop area in the watershed had a 0 m buffer strip, 74% had a 1m buffer strip and 10% had a 3m buffer strip.

For the period from 2007-2011, the management operations were updated to include new legislation, known as the PAEF (*Plan Agroenvironnemental de Fertilisation*). Tillage practices were updated to reflect changing trends, such as an increase in reduced tillage practices. A new management scenario was therefore developed by Aubert Michaud from IRDA, and approved by Richard Lauzier from MAPAQ, which was based on the "*Guide de reference en fertilization*" (CRAAQ, 2010). For details on management practices implemented in SWAT see Appendix 5.

5.3.1.4. SWAT calibration and validation

The Sequential Uncertainty Fitting algorithm (SUFI-2; Abbaspour et al., 2004) is a tool found in SWAT-CUP version 4.3.2 (Abbaspour, 2011). SWAT-CUP is a package containing several calibration tools and is available to download with the SWAT model.

SUFI-2 is a semi-automated inverse modelling procedure that was used for calibrating and validating the SWAT model to the available time series data of streamflow, sediments, TP and NO_3^--N loads. SUFI-2 finds a best solution of the parameter sets to optimize simulated SWAT variables with the least possible deviation between the corresponding observed variables. The ensemble of parameter sets that meet a specified objective function were retained as behavioural parameter sets for implementation in SWAT. The parameters used for the calibration process were chosen based on a sensitivity analysis of SWAT. Next, a sequential calibration was carried out for: streamflow, sediments, TP, and finally for NO_3^--N.

Although the Pike River is perhaps one of the most instrumented and well-monitored watersheds in Québec, there remain sparse and incomplete datasets, especially for water quality data, for a thorough calibration and validation of SWAT. Multiple gauges were used to calibrate/validate during various time periods and for different variables. Missing data was previously interpolated by IRDA using the FLUX5.0 software (Walker 1998). Table 9 provides an overview of the gauges and their variables used to calibrate/validate SWAT.

Streamflow was first calibrated at the yearly, monthly, and daily time step for the entire Pike River watershed. Two CEHQ gauges located on the main stem of the river at Bedford (model outlet 14) and further down the river at outlet 8 were used to simultaneously calibrate for streamflow from 2001-2006. The validation took place from 2006-2011 at the same outlets. For a final evaluation of the model performance of streamflow, outlet 8 was used with data from 1980-2011. At outlet 14, about 75% of the watershed is drained, while 88% is drained at outlet 8.

After streamflow was satisfactorily calibrated and validated (as per Moriasi et al., 2007), the SWAT model was calibrated (2001-2003) and validated (2004-2006) for water quality variables (sediments, TP and NO_3^--N) at the monthly time step. The sub-basin Walbridge was used to calibrate and validate water quality because it had the most reliable data and the longest time series of available measured water quality data in the Pike River watershed. Two IRDA gauges in the sub-basin Walbridge were used for simultaneous calibration: outlet 4 and outlet 6. The water quality data was measured simultaneously with streamflow mainly during high and low flow events, so that approximately 30-50 samples were taken per year (Michaud et al., 2004). To fill the missing data at the outlets, IRDA applied the FLUX5.0 software of the US Corps of Engineers (Walker, 1998) to attribute sediment, TP and NO_3^--N loadings to hydrological conditions through experimental rating curves linking water quality to discharge, in order to obtain a complete monthly time series of sediments, TP and NO_3^--N.

The upstream part of the Walbridge sub-basin has a rolling terrain, and a higher percentage of well-drained soil than the downstream part (44% compared to 17%). The downstream part has a higher water table, and more frequent surface runoff (Michaud et al., 2008). Thus, the upper part of Walbridge (although located in the downstream part of the entire Pike River basin) is more hydrologically representative of the upper part of Pike River, and the lower part of the Walbridge sub-basin is more representative of the lower part of the watershed. Due to these characteristics of the Walbridge sub-basin, when the water quality was satisfactory simulated, the water quality parameters for outlet 4 were applied to the upstream section of the Pike River watershed while the water quality parameters found for outlet 6 were applied to the downstream section of the watershed as per Michaud et al. (2008).

Finally, using BQMA data from the MDDEFP (Table 10), the sediments and TP for most of the basin (90% of the area) were evaluated at outlet 18, from 1979-2007. The measured data at outlet 18 stemmed mainly from grab samples taken randomly, at best twice per month for sediment; but in several months no samples were taken, especially at the beginning of the season. For TP, sampling was performed 1-2 times per month. Again, IDRA used the FLUX5.0 software (Walker, 1998) to create a complete monthly time series for sediments and TP (NO_3^--N was not prepared).

Table 9. Measured surface water discharge data available (from CEHQ and IRDA) for calibration and validation of SWAT.

Gauge	Calibration	Validation
Outlet 14	1 Nov 2001 to 31 Oct 2006	1 Nov 2006 to 21 Nov 2011
Outlet 8	1 Nov 2001 to 31 Oct 2006	1 Nov 2006 to 21 Nov 2011
Outlet 4	1 Nov 2001 to 27 Apr 2004	1 Nov 2004 to 1 Nov 2006
Outlet 6	1 Nov 2001 to 27 Apr 2004	1 Nov 2004 to 1 Nov 2006
Outlet 8		1 Sept 1979 to 21 Nov 2011

Table 10. Measured water quality data available for calibration and validation (from MDDEFP and IRDA).

Gauge	Calibration	Validation
Outlet 4	1 Nov 2001 to –May 2003	1 Nov 2004 to 1 Nov 2006
Outlet 6	1 Nov 2001 to –May 2003	1 Nov 2004 to 1 Nov 2006
Outlet 18		1 Nov 1979 to 1 Sept 2007

5.3.2. Scenario development to implement in SWAT

This section provides an overview of what type of scenarios were implemented using SWAT. A justification of why a particular scenario was chosen is provided in the corresponding section, later on. A warm-up period of 5 years was implemented in each simulation in SWAT, to initialize soil nutrient levels.

A variety of SWAT runs were performed to investigate the different impacts of climate change and of land use change, both one-at-a-time and then combined. First, SWAT was applied using historical meteorological data for 1971-2000 and a static current agricultural land use map layer (from 1999) for the Pike River to determine the baseline quality of surface water. This was henceforth called the **reference simulation** and was used to compare all the future simulations to, in order to determine any changes in water quality.

Second, SWAT was applied with each of the **three selected climate scenarios for 2041-2070**, and with the static agricultural land use map of 1999 (i.e. without the scenarios of land use) for the entire simulation period. This allowed determining the impacts of climate change alone on the water quality at the outlet of the basin.

Third, SWAT was run with each of **four land use scenarios for the period 2011-2040**: the two “plausible” scenarios of land use developed by the stakeholders and spatially represented by CLUE-S; and the two “extreme” scenarios (all forest and all corn). The land use scenarios were applied with the observed (1971-2000) meteorological data, in order to isolate the effect of land use change in a current climate. Each of the scenarios was compared with the reference simulation to quantify the changes in water quality at the outlet of the river.

Fourth, **four combinations of choices between two climate scenarios (AGR and AHK) and two scenarios of land use (HIST and EXP)** were applied to represent the future 2050 horizon (note that the land use change scenarios span 2011-2040, and the climate scenarios span the period of 2041-2070; see section 5.3.2.1 below for further comments on this issue). These scenarios were chosen based on the interests of stakeholders. The matrix of four possibilities of climate and land use change (AGR_HIST, AGR_EXP, AHK_HIST, AHK_EXP) was applied in the hydrological model SWAT to determine the potential quality of surface water representing the future horizon 2050.

And finally, a range of adaptation strategies were developed together with stakeholders based on future potential changes in the watershed. **Three storylines of strategies of adaptation were developed. These were tested in combination with one of the previous matrix results (AHK_EXP)** to quantify the effect of the proposed adaptations towards mitigating the deterioration or even improving the quality of surface water in the watershed.

5.3.2.1. Combining the land use change scenarios with the climate scenarios

The land use scenarios were developed for a near- to mid-term future from 2011-2040. This was mainly done because of the constraint of developing land use scenarios beyond a 30 year time horizon, as the drivers of change are probably no longer relevant. Veldkamp and Fresco (1996) and Verburg (1999) recommend the "realistic" time horizon for running CLUE and CLUE-S should be limited to no more than 20 to 30 years in the future because technology, crop varieties and other changes may occur beyond this time period, which the model is not able to capture. Furthermore, the logistic regressions in the model do not evolve with the land use changes over time, and hence the assumption that the relationships will still remain valid over long periods of time is not realistic (see Heistermann et al., 2006). Nevertheless, the land use scenarios are useful to determine "hot spots" of change that may affect surface water quality.

One limitation of applying a near-term land use scenario to a mid-term horizon (2050), is that the land use changes may be regarded as conservative estimates only, and hence may not manifest themselves very prominently amongst other changes in the basin.

The land use scenarios represent a range of changes that may plausibly occur to crop land use in the basin during a 30 year time period. Since the scenarios have been developed as an evolving trend over 30 years, they may also be interpreted as representing a time horizon of the 2020s. This time horizon is significantly closer than the 2050 horizon of the climate scenarios. However, since they are only scenarios of possible change (i.e. not specific predictions), and in the absence of more realistic scenarios for a longer-term future, we consider these scenarios to also be a plausible proxy for a more distant time frame in which land use may change within a similar range. We are particularly interested in the variability that agricultural land use change can present with a changing climate, and not so much the absolute changes themselves. The land use change scenarios developed from 2011-2040 were therefore applied unaltered to the 2050 horizon (i.e. to 2041-2070) to match the climate change scenarios.

Each land use change scenario was applied as a sequence of 30 individual representations of land use (one layer for each year) to capture the variability rather than implementing only a static land use. Additionally, each year of land use simulation is dependent on the previous year to a certain extent (soil moisture conditions, soil nutrient residuals, organic matter decomposition, crop rotations all carry over from one year to the next). Climate simulations are similar in that each year of climate depends on the previous year of simulation (greenhouse gas concentrations, air masses, convective systems, radiation budgets, precipitation patterns are all related from one year to the next). In the model runs we then combined land use with climate change by applying the sequence of land uses (in yearly steps) to the given time series of the climate scenarios. The same methodological approach was applied e.g. in Park et al. (2011).

For the scenarios involving a combination of climate change and land use change, the specific fertilizer and planting dates were adjusted for a future climate as follows:

Due to warmer temperatures, the growing degree days will increase in the future. The growing season was calculated to increase by a minimum of up to 2 weeks in spring, indicating the possibility to seed earlier in spring (see Section 6.1). In eastern Canada, corn has the potential to grow for a longer time, and therefore yield higher biomass in the future (Pearson et al., 2008). Farmers may adjust their fertilizer application amounts as a result. Thus, when implementing the combined adaptation scenarios in SWAT, the fertilization and seeding operations of corn was altered to reflect these changes.

Preliminary tests in SWAT were undertaken in a future climate (AHK) to determine which crops yielded higher biomass in a longer growing season, with and without additional fertilizer. The tests showed that by planting 2 weeks earlier and adding 50% more N and P fertilizer, the annual mean corn biomass increased by 1.47 Mg/ha. The other crops did not show a yield response (or only a very small response) to an increase in fertilizer. We assume that over the 30 years of simulation, the farmers will adapt the fertilizer amounts to meet the maximum potential yields of the crops, therefore the fertilizer rates for corn were adjusted, but not for the other crops.

The N and P fertilizer amounts applied varied per soil type, thus per HRU. Hence for corn, new fertilisation rates were calculated by taking into account the ratio of historic fertilizer applied per unit biomass of corn obtained per HRU, and applying that ratio to the future (it was assumed that an increase of 50% N fertilizer application produced the maximum attainable biomass). This same equation was used to adjust the amounts of phosphorus fertilizer for corn:

$$New\ Napp = \frac{Napp\_hist}{Biomass\_hist} * MaxBiomass\_fut$$

where, *New Napp* is the amount of adjusted N fertilizer applied; *Napp_hist* is the previous amount of N applied; *Biomass_hist* is the previous mean biomass attained; and *MaxBiomass_fut* is the biomass achieved with the 50% increase in N fertilizer. Overall, this change applied to 123 977 ha that were planted to corn (or 18% of the basin area).

To account for the effect of a warmer climate and an extended growing season, it was decided to shift the seeding date of corn 12 days earlier (based on Deryng et al., 2011), however harvest dates were kept the same. In addition, hay was cut four times a year instead of 3 times a year (the manure application remained the same, since we assumed the livestock densities would not increase in the watershed).

An independent t-test of the AHK_EXP scenario before and after implementing the changes to the seeding dates and fertilization regimes showed no significant difference in the transport of sediments, or of TP or NO_3^--N in any of the months. This was mainly attributed to the relatively small management changes made to only certain areas in the watershed (but it could also have been due to the crops taking up more nutrients because of the increase in biomass, or because of the greater soil coverage of the increased biomass which may lead to less surface runoff after rainfall events, or a combination of all of these).

5.3.3. Adaptation strategies to improve surface water quality

The *Organisme de Bassin Versant de la Baie Missisquoi* (OBVBM) has conceived a water management plan (PDE; OBVBM, 2011b) as part of the Québec Water Policy. The plan defines several actions to improve surface water quality in the basin. For this study, the PDE was used as a basis to initiate a discussion with stakeholders on targeted actions that can be implemented in the watershed to reduce the vulnerability of the basin to deteriorating water quality under potential climate variability and change conditions.

Our project targeted adaptation strategies strictly linked with agricultural field practices and did not include more comprehensive strategies in terms of watershed land use planning. For example, in the PDE, strategic actions to reduce non-point source P contamination include increasing the area under conservation tillage, adding buffer strips, or stabilizing and vegetating river banks. We focused only on adaptations related to the management practices of fields and local lands. These actions can also be interpreted as being land use changes. They are physically based and can be modeled in SWAT to determine their impact on improving water quality.

Three adaptation scenarios were drawn up with the assistance of stakeholders (UPA, OBVBM, MAPAQ, IRDA, CEHQ, Ouranos). Each scenario contained several actions for improving water quality which were modeled in SWAT by adjusting the necessary parameters. The adaptation strategies were based on actions that were considered in the PDE of the OBVBM, and that were of interest to the stakeholders. It was also important that the proposed strategies could not only be implemented in the basin but could also be modelled in SWAT.

The three adaptation scenarios can be summed up as focusing on:

1) a strategic solution to target a reduction in TP transport from the most vulnerable lands (those that are erosion prone and transport the most TP);
2) a feasible scenario where the easy to implement management strategies are implemented in the short-term by farmers in the watershed; and
3) an optimistic scenario implementing the best knowledge on management strategies to reduce non-point source pollution.

Each of the three scenarios is described below:

1) **<u>Strategic scenario (STRAT)</u>**

This scenario aims to reduce non-point source pollution from the most problematic lands. In a previous study by IRDA (Michaud et al., 2007) SWAT was implemented to achieve a reduction in TP in the basin. ArcSWAT was used as a decision support system to define optimal land uses and field management changes that would target at least a 41% reduction in TP loads that drain into the Missisquoi Bay, to achieve an acceptable water quality criterion at the basin outlet.

The aim of the STRAT scenario in this project is to replicate the same management strategies that were most effective in the Michaud et al. (2007) study, but this time with the future climate and agricultural land use changes. This approach allows determining whether these strategies are also effective in light of the potential changes that may take place in the basin.

The following adaptation strategies were implemented in the STRAT scenario based on reconstituting the major elements of scenario #21 in Michaud et al. (2007), which resulted in the most reduction in TP (reductions of 41%):

i. Ten percent of the cultivated areas (not including hay) which were most susceptible to TP export (1794.63 ha) were converted to prairie (tall fescue that was not harvested and had no manure application).
ii. Next, soil conservation practices were randomly implemented on 45% of cultivated areas (7874.63 ha) as follows: corn, soybeans, and cereals on soils pertaining to hydrological groups A and B were converted to no-tillage. The same crops on soils pertaining to hydrological group C and D were converted to reduced tillage.
iii. Buffer strips (filter strips) 3 m wide were implemented on all HRUs adjacent to a stream or to a river.
iv. All manure application was incorporated within 24 hours of being spread (for the whole watershed).
v. Lastly, a 4% reduction of TP and a 5% reduction in sediment loads at the basin outlet were applied to simulate the implementation of runoff control structures called Hickenbottom inlets.

2) **<u>Feasible scenario (FEASB)</u>**

This scenario was developed to implement practices that were deemed to be the most practical for the agricultural sector to apply in the short term, by targeting the “low hanging fruits”. The practices were as follows:

i. On the 10% of cultivated areas (not including hay) which export the most TP (1794.63 ha), a cover crop was implemented after the harvest as follows: corn was intercropped with rye-grass in June; summer cereals were intercropped with clover in May; and soybeans were intercropped with rye cereal in September (after the leaves dropped).
ii. The next most problematic 10% of cultivated areas prone to erosion (i.e. transport of sediments), were taken out of production and converted to switchgrass (1967.42 ha). Switchgrass was harvested once a year and 25 kg/ha of mineral N were applied after harvest in May.
iii. Buffer strips 3 metres wide were implemented on all HRUs adjacent to a reach or to a river.

In addition to these three practices, the protection of floodplains, as well as the implementation of sediment retention basins were discussed with the stakeholders and were proposed for implementation, but they were not modelled in SWAT because of major constraints encountered. For detailed explanations see Appendix 6.

3) **<u>Optimistic scenario (OPTIM)</u>**

This scenario focused on integrating all of the best management practices (to our knowledge) that are able to reduce non-point source pollution, including undertaking organic farming on all of the crops, to achieve a good water quality. Thus, for this scenario, the management practices in SWAT were modified as follows:

i. The application of mineral fertilizers did not take place; only organic fertilizers (swine manure) were applied. Furthermore, the manure was incorporated within 24 hours after being spread.
ii. Conventional tillage was replaced with reduced tillage on soil hydrological classes C or D, and by no-tillage on soil hydrological classes A and B.
iii. A cover crop (red clover) was seeded after the corn was harvested. After cereals were harvested, alfalfa was seeded in late summer; this was cut 3 times during the following growing season and left over-winter and killed before seeding corn in spring.
iv. All cash crops had the following rotation: corn – soybean - summer cereals - alfalfa.
v. Buffer strips (3 me wide) were implemented in all HRUs that were adjacent to the river.
vi. Agro-forestry (poplars, 20% biomass harvested every 4 years) was undertaken on all slopes greater than 9% in the watershed (as determined from the DEM with ArcGIS, which represented 2693.80 ha or 4.3% of the watershed area).

In addition to these practices, the protection of drinking water sources was discussed and proposed for implementation; however this was not modelled in SWAT because of limitations encountered in the modelling process. For detailed explanations see Appendix 6.

5.4. Summary and overview of procedure

In this project, SWAT is applied with a multitude of scenarios as summarized below:

Reference simulation:

REF: The reference simulation representing the period from 1971-2000 (with a prior 5 year warm up period), using a static land use layer of 1999 for the simulation period, and observed daily climate data that matches the period 1971-2000.

Climate change scenarios:

ACU: The climate change simulation "ACU" applied in SWAT for the period 2041-2070 (with a prior 5 year warm up period), with static land use layer from 1999 and modelled daily climate data for the period 2041-2070.

AGR: The climate change simulation "AGR" applied in SWAT for the period 2041-2070 (with a prior 5 year warm up period), with static land use layer from 1999 and modelled daily climate data for the period 2041-2070.

AHK: The climate change simulation "AHK" applied in SWAT for the period 2041-2070 (with a prior 5 year warm up period), with static land use layer from 1999 and modelled daily climate data for the period 2041-2070.

Land use change scenarios:

HIST: The static land use layer of 1999 is replaced with the land use change scenario "Historical Trends Continue" with 30 years of changing land use. The scenario is applied in SWAT with the help of the SWAT2009_LUC tool and SWAT is run from 1971-2000 with the observed daily climate data from 1971-2000 (with a prior 5 year warm up period).

EXP: The static land use layer 1999 is replaced with the land use change scenario "Expert Guided" with 30 years of changing land use. The scenario is applied in SWAT using the SWAT2009_LUC tool and SWAT was run from 1971-2000 with the observed daily climate data from 1971-2000 (with a prior 5 year warm up period).

FOREST: Extreme land use change scenario, where all land other than urban and water is vegetated to forest. This was simulated directly in SWAT by adjusting the land use, and SWAT was run from 1971-2000 using observed daily climate from 1971-2000 (with a prior 5 year warm up period).

CORN: Extreme land use change scenario, where all land other than urban and water is planted to corn. This was simulated directly in SWAT by adjusting the land use, and SWAT was run from 1971-2000 using observed daily climate from 1971-2000 (with a prior 5 year warm up period).

Combination of climate change and land use change scenarios:

Two of the climate simulations and two of the land use scenarios were chosen in consultation with the project partners and stakeholders. The following four combinations resulted:

AGR_HIST: Simulated in SWAT from 2041 to 2070 (with a prior 5 year warm up period), with the climate simulation "AGR" and with the land use change "Historical Trends Continue".

AGR_EXP: Simulated in SWAT from 2041 to 2070 (with a prior 5 year warm up period), with the climate simulation "AGR" and with the land use change "Example of Plausible".

AHK_HIST: Simulated in SWAT from 2041 to 2070 (with a prior 5 year warm up period), with the climate simulation "AHK" and with the land use change "Historical Trends Continue".

AHK_EXP: is simulated in SWAT from 2041 to 2070 (with a prior 5 year warm up period), with the climate simulation "AHK" and with the land use change "Expert Guided".

Adaptation scenarios:

One of the combined scenarios (AHK_EXP) was then chosen with the input of the stakeholders, to test a suite of the following adaptation strategies:

STRAT: Simulated with adaptation strategies that reduce the watershed TP loads by 41% at the outlet of the basin.

FEASB: Simulated with adaptation strategies that target the implementation of practical best management options that farmers can undertake in the short-term.

OPTIM: Simulated with adaptation strategies that target the implementation of the largest amount of best management practices that are possible to model.

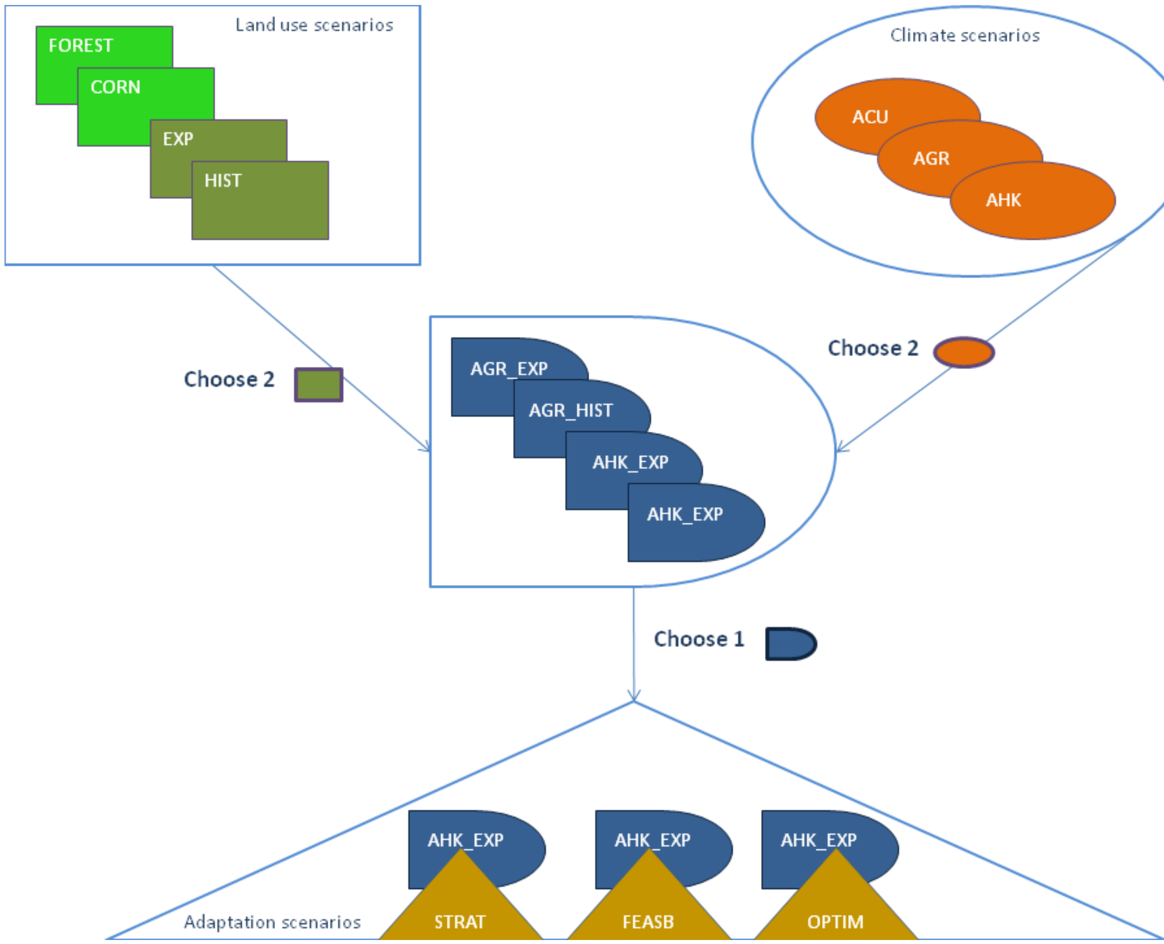


Figure 9. Schematic overview of the methodology, depicting that SWAT will be applied to every one of the coloured shapes.

6. Results

6.1. Expected future climate changes

The minimum and maximum temperature differences and the precipitation changes between the reference climate simulations (from 1971-2000) and future climate simulations (2041-2070) are shown in Figures 10 to 12. The three climate simulations demonstrate somewhat dissimilar projections in precipitation and minimum and maximum temperature ranges.

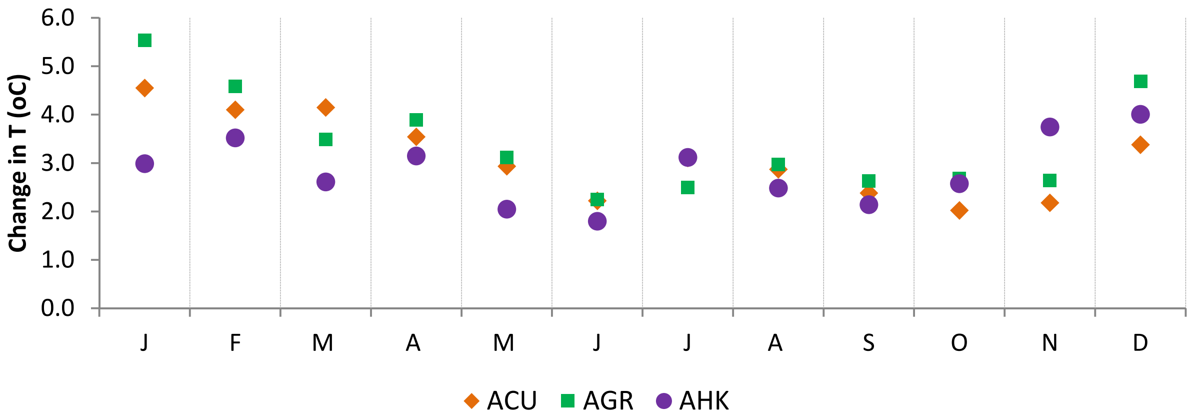


Figure 10. Expected mean daily minimum temperature changes from climate simulations ACU, AGR, AHK for each month (difference between 1971-2000 and 2041-2070).

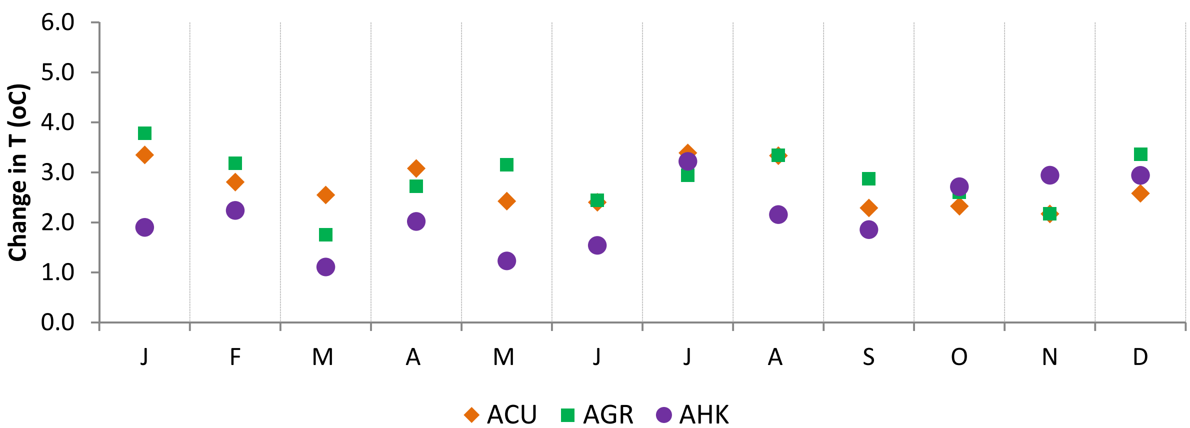


Figure 11. Expected mean daily maximum temperature changes from climate simulations ACU, AGR, AHK for each month (difference between 1971-2000 and 2041-2070).

All of the climate simulations have a greater increase in T_{min} than in T_{max}. Generally, the mean monthly T_{min} increase the most for the AGR simulation, and least for the AHK, with the greatest differences (up to 3 degrees) occurring from November to March. The mean monthly T_{max} increases most for the AGR and least for the AHK, with differences in the range of 2^{o}C, or less.

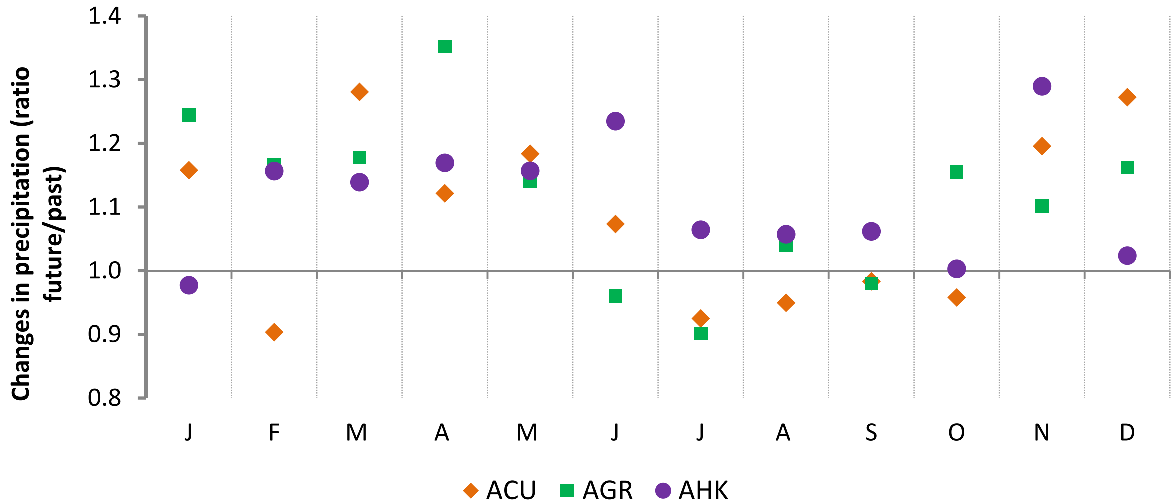


Figure 12. Expected changes in the ratio of future (2041-2070) mean monthly precipitation to observed mean monthly precipitation (1971-2000) for the climate simulations ACU, AGR, AHK. A ratio of 1.0 is equal to no change.

The precipitation for the three simulations will provide more precipitation into the watershed. Average yearly increases for ACU are 66.4 mm; for AGR 98.4 mm; and for AHK 101.9 mm. However the increases are not evenly distributed throughout the year. Most of the mean monthly precipitation increase takes place in March, April, May, November and December. In the months from July to September few changes takes place, and some precipitation decreases occur from June to October and from January to February.

6.1.1. Future growing degree days

By comparing the three climate simulations from the period 1971-2000 with the future period 2041-2070, a potential increase in the GDD base 0° of 482 to 606 was calculated for the future period (Tables 11-13).

As the base temperature increases, the gain in GDDs in the future becomes less. An increase in 443 to 563 of the GDD base 5°, and an increase in 365 to 476 for the GDD base 10° were calculated.

These increases indicate a longer growing season (with higher temperatures). Potentially, a fourth cut of hay is possible, or another crop of strawberries or planting new varieties that necessitate more plant heat units.

It should be kept in mind that these are conservative estimates, since the GDD were calculated for the period between April 1 to October 31. In the future, the growing season may start up to 14 days earlier (see section 6.1.2).

Comparing the mean annual GDDs calculated from the climate simulations to the observed data (Table 11), the climate simulations give similar values as the observed, but consistently underestimate the mean annual GDDs, in spite of being bias corrected. The residuals are in the order of 4 to 7.5%. According to Ouranos, this is due to approximations used in the bias correction method, such as the number of quantiles used to describe the distributions, which attenuates the tail ends of the distribution (the extremes).

Table 11. Number of mean GDD/yr (and standard deviations) for the reference period (1971-2000) from Philipsburg station data and from the climate simulations.

	GDD base 0^o	GDD base 5^o	GDD base 10^o
Philipsburg station data	3145 ± 127	2125 ± 118	1237 ± 99
ACU	3020 ± 171	2013 ± 147	1145 ± 117
AGR	3020 ± 127	2015 ± 114	1148 ± 98
AHK	3020 ± 176	2014 ± 161	1150 ± 130

Table 12. Number of mean GDD/yr (and standard deviations) for the future period (2041-2070) from the climate simulations.

Climate scenario	GDD base 0^o	GDD base 5^o	GDD base 10^o
ACU	3598 ± 158	2548 ± 155	1604 ± 147
AGR	3626 ± 169	2577 ± 167	1624 ± 151
AHK	3503 ± 178	2458 ± 175	1515 ± 154

Table 13. Additional mean GDD/yr simulated for the future period 2041-2070.

Climate scenario	GDD base 0^o	GDD base 5^o	GDD base 10^o
ACU	578	535	458
AGR	606	563	476
AHK	482	443	365

The increase in GDD calculated concord well with those found in the Agroclimate Atlas of Québec (*Atlas agroclimatique du Québec, 2012*) which applied the same methodology as here, and used 15 climate simulations (instead of three); they report an additional GDD base 0°C of 351 to 393 for the lower range (10% percentile) of future climate change simulations, and increases of 563 to 605 for the upper range (90% percentile) of simulated change. For GDD base 10°C, the low range increased by 229 to 274; and the upper range by 412 to 458 GDD.

6.1.2. Start of the future growing season

The mean growing season start date for 2041-2070 is expected to occur up to 14 days earlier compared to the period 1971-2000. This is significantly earlier ($p < 0.001$) for all of the climate simulations, compared with their reference period.

A 14-day earlier growing season corresponds to a date near the end of March for the 2050 horizon. Although this may indicate the start of the growing season, the field conditions may be too wet in some years to allow for proper seeding, as farmers regularly experience, despite the start of the season. This may be particularly relevant in the future, given the expected wetter climate scenarios in April and May for ACU, AGR and AHK.

Overall, the growing season results also compared well with the average increase in days for future growing seasons indicated in the Agroclimate Atlas of Québec (*Atlas agroclimatique du Québec, 2012*), which predicts an earlier start of the growing season by 15 to 17 days (note that they calculate the start date when the 5-day moving average temperature is greater than 5.5^{o}C).

Table 14. Start of the growing season (and standard deviations) for the reference period (1971-2000) based on the climate simulation data.

Climate simulation	Julian Day	Mean Date
Philipsburg station data	90 ± 8	April 1
ACU	93 ± 10	April 3
AGR	96 ± 8	April 6
AHK	96 ± 11	April 6

Table 15. Start of the growing season (and standard deviations) for the future period (2041-2070), based on the climate simulation data.

Climate simulation	Julian Day	Mean Date
ACU	78 ± 12	March 19
AGR	80 ± 9	March 21
AHK	84 ± 8	March 25

These results reflect a potential increase in GDDs as well as an earlier start of the growing season; yet they do not take into consideration soil temperature or soil humidity, to which farmers need to adjust their planting practices.

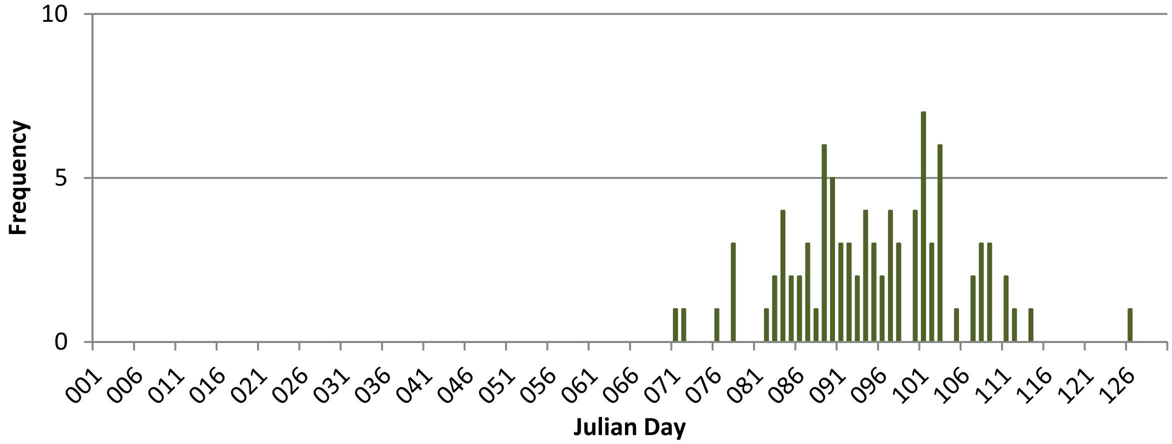


Figure 13. Start of the growing season in the reference period (1971-2000) calculated from ACU, AGR and AHK simulations.

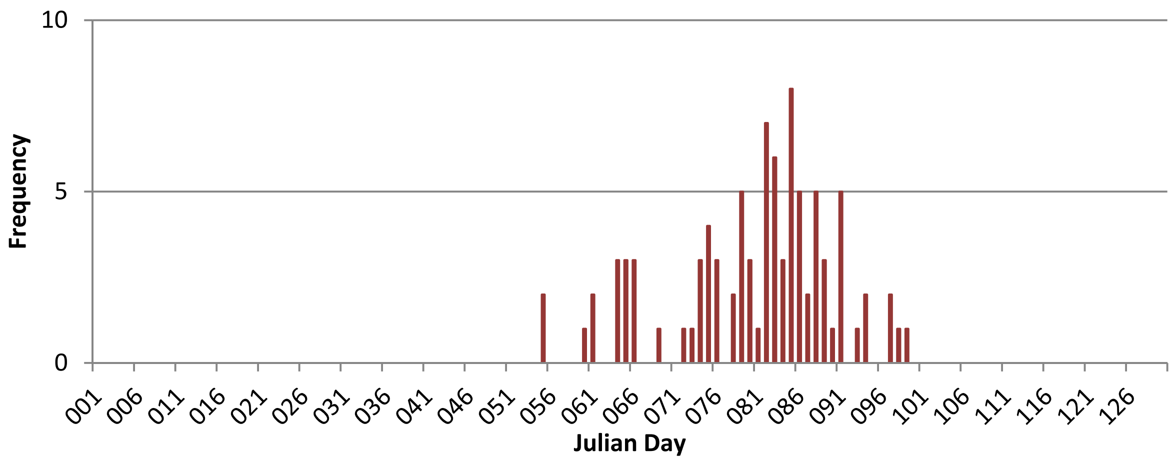


Figure 14. Start of the growing season in the future period (2041-2070) calculated from ACU, AGR and AHK simulations.

6.2. Land use change scenarios

6.2.1. *Results of the questionnaires*

The questionnaires were sent to two groups of farmers.

Group 1 consisted of farmers in the Pike River watershed (area 630 km^2). The questionnaires were sent directly to farms in the watershed by the local office of the *Ministère de l'Agriculture des Pêcheries et de l'Alimentation* (Bedford). In total, 210 questionnaires were sent to full-time farmers. A response rate of 24% was obtained, which was considered to be quite high.

Group 2 consisted of 23 young (under 25 years old) farmers enrolled in their last year of the Farm Management Technology Program at Macdonald College (McGill University), in Ste-Anne-de-Bellevue, Québec. Only one of the students had a farm located in the Pike River. Approximately ¼ of the students were from Ontario, and the remaining students were from Québec (from the border of the USA to approximately Trois Rivières). All of the students were either from a farm, or worked on a farm. The second group had a 100% response rate since the questionnaires were handed out and filled in during one of their classes.

Group1 and Group 2 differed in terms of their average experience in farming: 33 versus 10 years, respectively; and in the size of the farms they worked on: 93 versus 168 ha, respectively.

The results of the questionnaires showed little variability between the two groups. No matter if they were from one generation or another, or from different regions, farmers ranked the factors governing their choice of land use in very similar ways. Another interesting finding was that the economic factors, although important, were not the only driver for their choice of crop land use.

The major crops grown in 2011 for Group 1 were: corn 51%, soybeans 22% and hay 12%. The remaining land use areas were divided between forest, cereals, and pasture. The younger Group 2 presented a greater variation in crops. The main crop grown was still corn, but a smaller proportion (33%), hay was second (26%) before soybeans (18%). There was also more area devoted to vegetables, pasture, cereals and alfalfa. The results showed the younger group tended to produce a wider range of crops. Their main crop grown on the farm was either corn or hay, and their secondary crop varied between corn, soybeans or hay.

For Group 1, 43% of producers abandoned a crop due to a direct financial factor. All remaining categories: demand for the product, rotations, diseases, climatic factors, and other factors (i.e. needing specialized equipment, finding no buyers, their age, end of a contract, abandoned production type, fragile crop, too many chemicals required, etc..) together represented the majority of the reasons that led to an abandonment of a crop (57%).

For the younger Group 2, it was the category: other factors (mentioned here as being: equipment required, soil conditions, time investment, abandoned production, costs of production) which made up 33% of the reasons. The direct financial factor in turn accounted for 17% of the reasons for abandoning a crop for Group 2. The remaining 50% was split between the demand for the product, rotations, climatic factors, insects and disease, and favouring biofuel production.

Finally, 56% of Group 1 and 78% of Group 2 indicated that they would adapt their practices to a longer growing season. The first adaptation measure was to change the crop variety to accommodate a longer season. As a second measure, Group 1 chose to implement more crop rotations, while Group 2 indicated that there would implement more cuts of hay. These results show the ability on the part of producers to adapt if the growing season proves to be longer. In addition, the questionnaire also highlighted that many farmers are sensitive to climate change and that these changes are an important factor in their decision to change crop land use.

For the detailed results of the questionnaires, see Appendix 3.

6.2.2. Land use change scenarios modeled with CLUE-S

a) Scenario "Historical Trends Continue" (HIST)

Historically, the amount of agricultural land in the basin has increased slightly from 53.4% of the total area in 2003 to 53.8% in 2011. Therefore, in this scenario the total area of agricultural land increases at the same pace, to occupy 55.9% of the area in the basin when extrapolated to 2040 (or by an increase of 833 ha over the 30 years). Also, urban areas continue to increase as in the past, from 2.4% in 2011 to 2.6% in 2040 (or 110 ha over the 30 year simulation period).

By extrapolating the historic trends of land use change in the watershed from 2003-2011 to 2012 until 2040, a new land use layer for the entire watershed was created each year. By 2040, this scenario presents a large increase in the area of soybean (11%) and a slight decrease in the area of corn (3.7%). As well, the area under hay decreases somewhat (<1%) at the expense of cropland. Forested areas decline by approximately 2%, whereas urban areas expand by 0.2%.

Soybeans were introduced quite recently in Québec (in the past 20 years). The success of soybean is due to its introduction to farmers by MAPAQ, as well as due to an available market, and to a successful insertion into the crop rotation with corn. The areas of soybean have therefore increased quite rapidly in the watershed. However, the balance between soybean/corn may have been reached in the basin by now. Therefore, it is unlikely that the areas of soybean will continue to increase by much more in the future. Nevertheless, this scenario simply portrays the evolution and trends of the crop areas in the basin. It could also be assumed that soybean is a proxy for other alternative cash crops that may rapidly expand in the future in the watershed at the expense of currently established ones.

Overall, cash crops occupy a dominant role in this scenario by 2040, whereas the niche crops (e.g. berries and wheat) are no longer present by 2040. The category "Other ag land" may include any agricultural land. There was no specific information available for which one.

It should be noted that the described scenario areas were somewhat modified when they were coupled to the SWAT model, by using the SWAT2009_LUC tool (for more details see 6.3.2.1).

Table 16. Scenario "Historical Trends Continue" (HIST), percentages of crop areas in the watershed.

	Other ag land	Orchard	Hay	Forest	Rangeland	Corn	Cereal	Soybean	Vegetables	Urban	Berries	Switchgrass
2011	14.0	1.6	12.8	38.4	2.0	16.7	1.1	5.1	0.4	2.4	0.0	0.2
2040	11.7	1.3	12.1	36.7	0.00	12.4	0.0	16.7	1.6	2.6	0.1	0.1

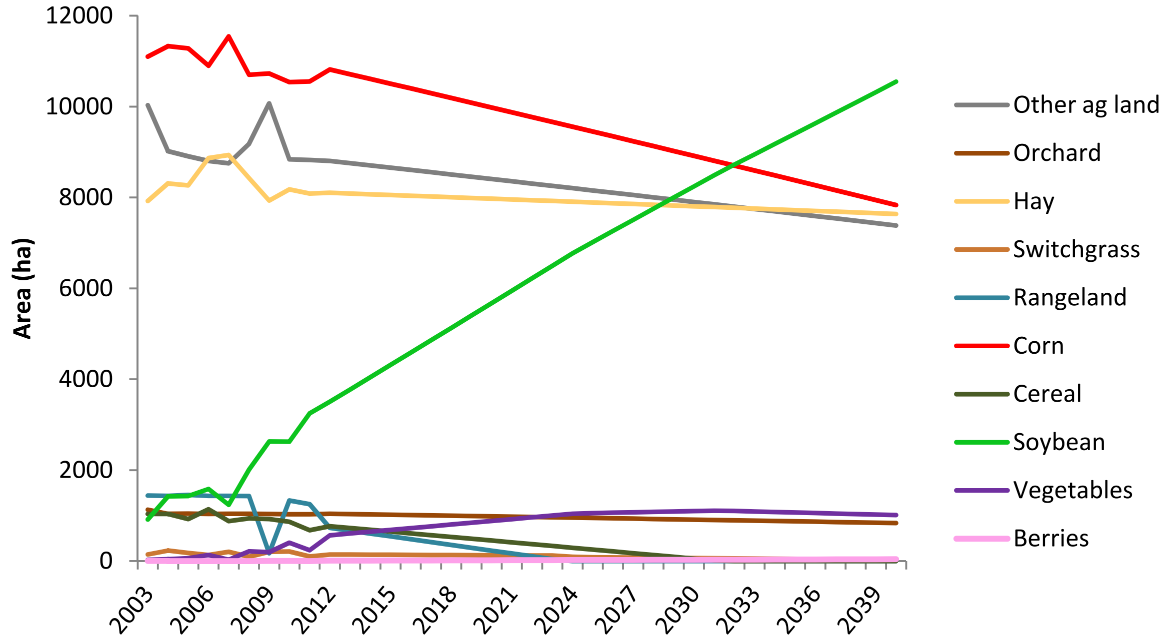


Figure 15. Land use trends in Scenario “Historical Trends Continue” (HIST).

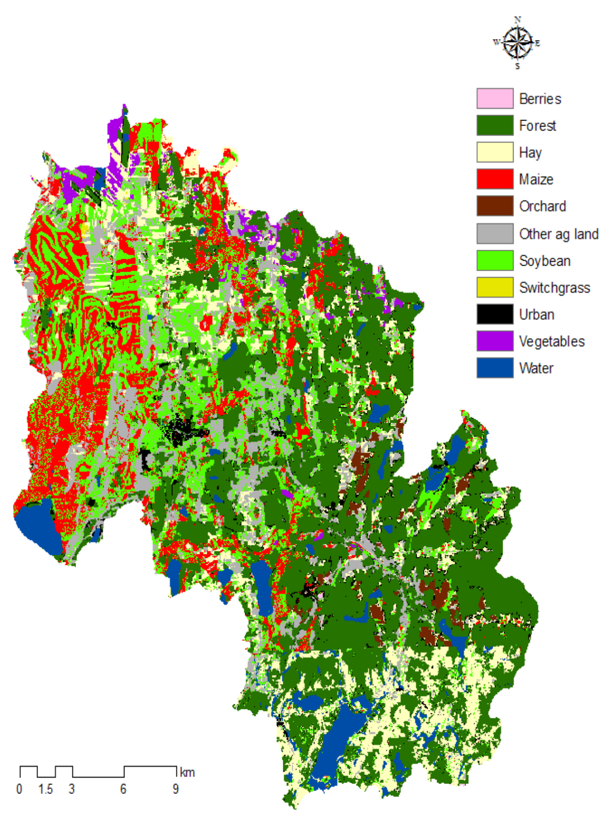


Figure 16. Scenario “Historic Trends Continue” (HIST) spatial distribution of crops in 2040.

b) Scenario "Expert Guided" (EXP)

Contrary to the HIST scenario described, this scenario has no increase in the total amount of agricultural land. The quantity and distribution of crops alters, but the total agricultural land area remains constant throughout the simulation period mainly because the area of forest is protected by a law introduced in 2004 that prevents deforestation (*Loi sur l'aménagment et l'urbanisme*, articles 6, 8, 79.1, 113 and 233.1). By 2040, there is a relatively large increase in corn (4%) caused by its profitability in a warmer climate (see analogous climate study from Gagnon et al., 2012).

By 2040, the soybean area increases (0.4%) but at a lesser amount than in the HIST scenario since the amount of new soybean planted will likely stabilize. Other increases in crop areas include cereals (0.1%) as farmers indicated a willingness to plant more; and are also interested to grow more vegetables (sweet corn, squash), orchards (yet with cherry trees replacing apple trees), and "other crops" such as willows, hops and tree nurseries. There is less area under hay (-0.7%) since farmers will be able to harvest 4 cuts of hay instead of the usual 3, and therefore less land for the same amount of hay is required. The amount of switchgrass area decreases (0.1%) in the basin since the subsidies to plant this crop as a buffer strip no longer exist. The decrease in forested area mirrors the expansion of the urban areas.

Overall, cash crops remain important crops in the basin; however there is more diversity in the type of crops and increases in niche market crops driven by the young entrepreneurs. The category "Other ag land" may include any agricultural land. There was no specific information available for which one.

Again, as with the HIST, it should be noted that the above described scenario areas were somewhat modified when they were coupled to the SWAT model, by using the SWAT2009_LUC tool (for more details see 6.3.2.1).

Table 17. Scenario "Expert Guided" (EXP), percentages of crop areas in the watershed.

	Other ag land	Orchard	Hay	Forest	Rangeland	Corn	Cereal	Soybean	Vegetables	Urban	Switchgrass
2011	14.6	1.6	12.8	38.8	2.0	16.7	1.1	5.1	0.4	2.4	0.2
2040	10.9	1.6	12.1	38.2	2.0	20.6	1.2	5.5	0.6	2.6	0.1

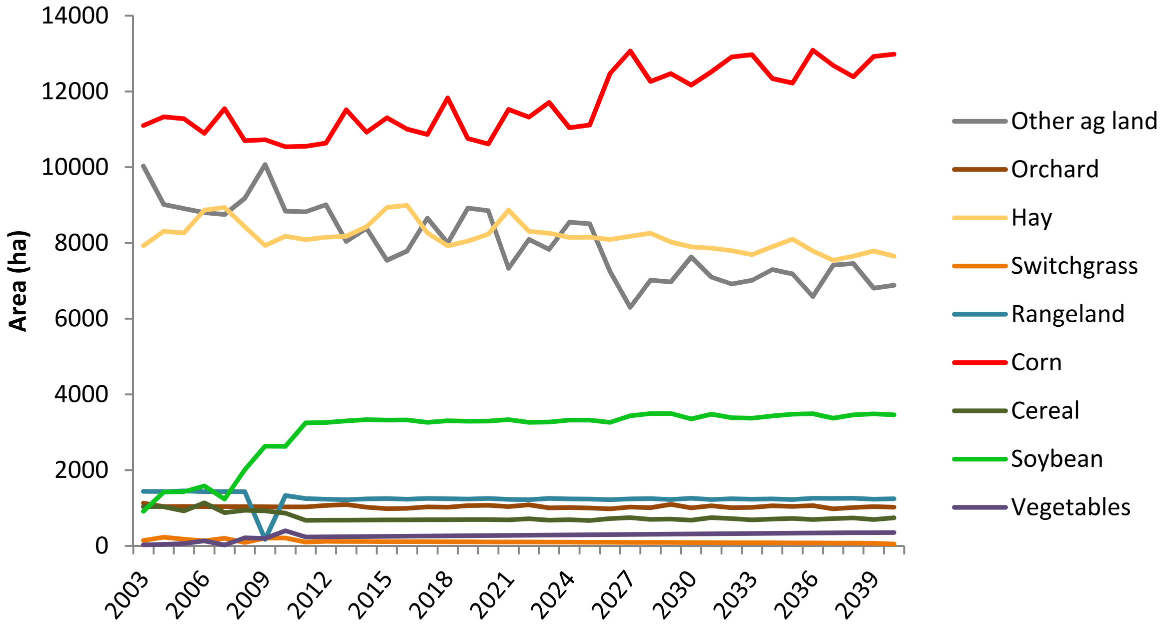


Figure 17. Land use trends in Scenario "Expert Guided" (EXP).

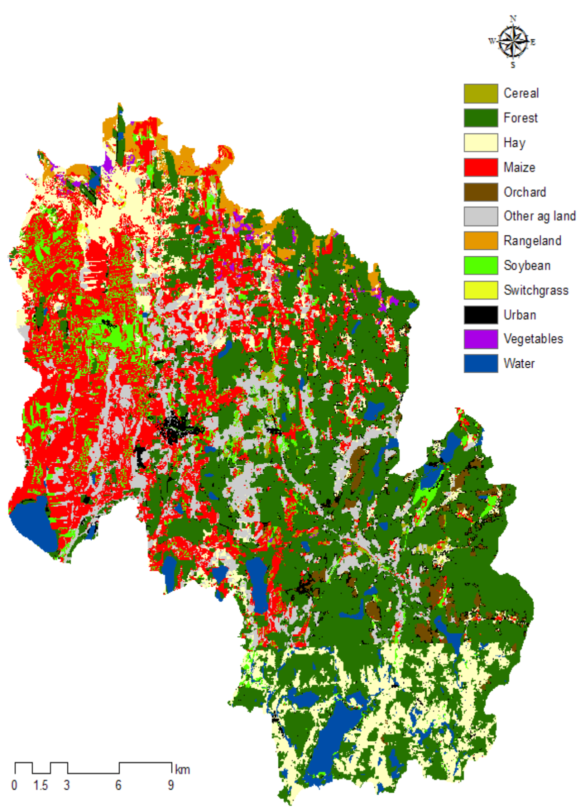


Figure 18. Scenario 'Expert Guided" (EXP) spatial distribution of crops in 2040.

6.2.3. Results of the SWAT model calibration and validation

With the SUFI-2 method (Abbaspour et al., 2004), an optimum set of parameter values that minimize the difference between observed and simulated output variables is determined (this is known as the best set of parameters).

In this study, a Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) was chosen as the primary objective function for calibration. The NSE is a statistical criterion that determines the relative magnitude of the variance of the residuals compared to the variance of the observed data. It is very commonly used in hydrological studies to evaluate model performance, and therefore previous studies can easily be compared to this one.

$$NSE = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$

where *NSE* is the Nash-Sutcliffe Efficiency, *O* is the observed value, and *P* is the predicted or simulated value.

In this study, the objective function was a minimum NSE = 0.5.

A particularity of the NSE, is that it is sensitive to high peak values due to the squared differences (Moriasi et al., 2007). Using a single goodness-of-fit measure is inappropriate to evaluate model performance alone, due to the restrictions any single measure carries with it. Thus, several other statistical criteria (RSR, Pearson's R, R^2, PBIAS) were used to evaluate the model performance. This way a variety of criteria were used to assess SWAT simulations based on observed data (Tables 18-20). A brief description of each follows with a mention of the thresholds used (based on a broad literature review) to gauge a satisfactory model performance.

The RMSE-observation standard deviation ratio (RSR) is calculated as the ratio of the RMSE to the standard deviation of observed data. The optimal value is 0.0 which indicates no residual variation. Values range from 0.0 to large positive values. The larger the RSR, the lower the model simulation performance (Moriasi et al., 2007). An RSR ≤0.7 was deemed to be satisfactory.

The Pearson's correlation coefficient (Pearson's R) describes the degree of linear association between the observed data and the simulated values. R values range from -1.0 to 1.0, with 1.0 being the most positive relationship, and -1.0 the most negative relationship, and 0.0 indicating no relationship (Chu and Shirmohammadi, 2004). A Pearson's R >0.5 was judged satisfactory.

The coefficient of determination (R^2) is the square of the Pearson's R and describes the proportion of the observed variance that can be captured by the simulations. Values range from 0.0 to 1.0 (Legates and McCabe Jr, 1999). A value >0.5 was considered to be satisfactory.

The percentage bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than the observed data. Values range from low negative to large positive numbers. A value of 0.0 is strived for. Negative values indicate the simulation overestimates the observed values, and positive values indicate an underestimation of the model to observed values (Gupta et al., 1999). The values were considered satisfactory were < ±25 for streamflow; < ±55 for sediment; and < ± 70 for nutrients.

Table 18. SWAT performance criteria for simulated streamflow during calibration and validation. Values in green boxes highlight a satisfactory model performance.

	Calibration (2001-2006)			Validation (2006-2011)		
	Yearly	Monthly	Daily	Yearly	Monthly	Daily
			Outlet 8			
NSE	0.80	0.83	0.62	0.63	0.78	0.44
RSR	0.45	0.55	26.65	0.61	0.47	31.24
Pearson's R	0.93	0.91	0.80	0.84	0.91	0.72
R^2	0.86	0.84	0.64	0.70	0.82	0.52
PBIAS	4.48	7.76	16.41	4.25	9.77	11.59
			Outlet 14			
NSE	0.58	0.83	0.67	0.34	0.75	0.67
RSR	0.65	0.41	25.08	0.61	0.50	31.27
Pearson's R	0.84	0.92	0.82	0.70	0.87	0.82
R^2	0.70	0.85	0.68	0.49	0.79	0.68
PBIAS	6.42	10.39	16.53	6.04	12.43	14.04

Table 19. SWAT performance criteria for simulated water quality variables during calibration and validation at the monthly time step. In addition, the NSE for streamflow is provided. Values in green boxes highlight a satisfactory model performance.

	Calibration (2001-2003)			Validation (2004-2006)		
	Sediment	TP	NO_3^--N	Sediment	TP	NO_3^--N
			Outlet 6			
NSE	0.16	0.67	0.72	-0.24	0.16	0.26
RSR	0.92	0.58	0.53	1.11	0.92	0.86
Pearson's R	0.79	0.92	0.90	0.29	0.45	0.59
R^2	0.63	0.85	0.82	0.08	0.20	0.35
PBIAS	61.24	35.47	16.41	7.61	17.86	-1.91
Flow NSE	0.64	0.64	0.64	0.42	0.42	0.42
			Outlet 4			
NSE	0.66	0.38	0.77	-1.26	-0.12	0.43
RSR	0.59	0.79	0.48	1.60	1.06	0.76
Pearson's R	0.90	0.90	0.88	0.35	0.43	0.72
R^2	0.81	0.81	0.78	0.13	0.18	0.51
PBIAS	30.48	49.31	0.38	-42.64	-5.48	28.35
Flow NSE	0.67	0.67	0.67	0.42	0.42	0.42

Table 20. SWAT performance criteria for simulated sediment and TP during evaluation at the monthly time step from 1979-2007 at outlet 18. In addition, the NSE for streamflow is provided at outlet 14 (the only long-term series available in the watershed). Values in green boxes highlight a satisfactory model performance.

	Sediment	TP
NSE	0.38	0.46
RSR	0.79	0.74
Pearson's R	0.81	0.76
R^2	0.66	0.57
PBIAS	53.22	4.78
Flow NSE (outlet 14)	0.73	0.73

The results of the calibration and validation of streamflow (Table 18) showed a very satisfactory SWAT performance. At the daily time step, the model did not perform quite as well as at the yearly or at the monthly steps, however this is fairly common with SWAT (Gassman et al., 2007; Moriasi et al., 2007). We used SWAT at a monthly time step, so the performance at this time step was most important. It is imperative to simulate streamflow well so that the transport of nutrients can consequently be properly simulated since they are highly dependent on streamflow and snowmelt processes.

To our knowledge, all three variables of sediments, TP and NO_3^--N have not been satisfactorily calibrated/validated in SWAT with the same model set-up. The performance criteria pertaining to SWAT's simulation of nutrients (Table 19) were quite satisfactory during the calibration stage; except for the sediment values which were underestimated by SWAT compared to observed values. The validation stage showed a rather poor model performance, and was attributed to the weak simulation of streamflow during this time period.

During the evaluation time period (Table 20) the performance criteria for sediments and for TP improved somewhat.

An overall improvement to the SWAT model performance was nevertheless able to be carried out compared to the previous model set-up of Gombault (2012). The discrepancies that remain were also attributed to the fact that missing gauge data was interpolated using FLUX software.

Figures 19 - 22 depict the observed streamflow and nutrient fluctuations with time, compared to the SWAT simulations that were produced using observed meteorological data for the corresponding time periods.

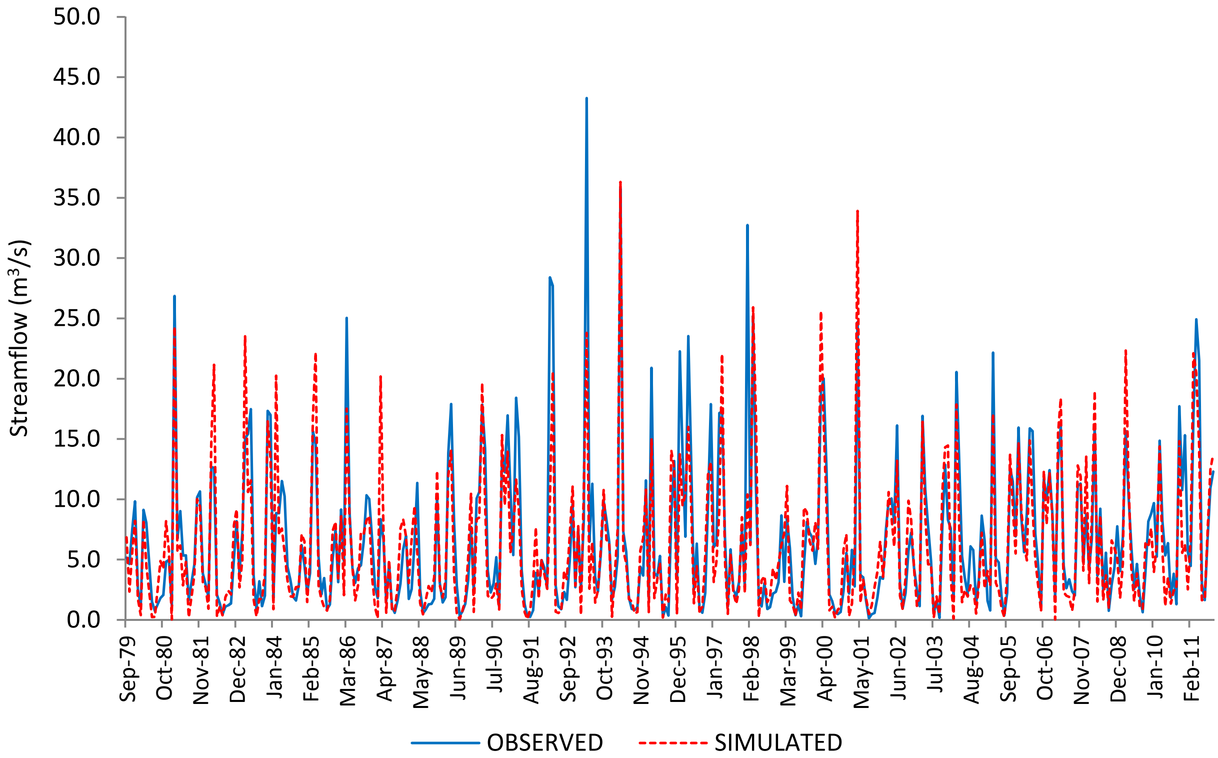


Figure 19. Observed and simulated monthly streamflow at outlet 14 (NSE=0.73; R^2=0.74; PBIAS=7.7) for the period 1979-2011.

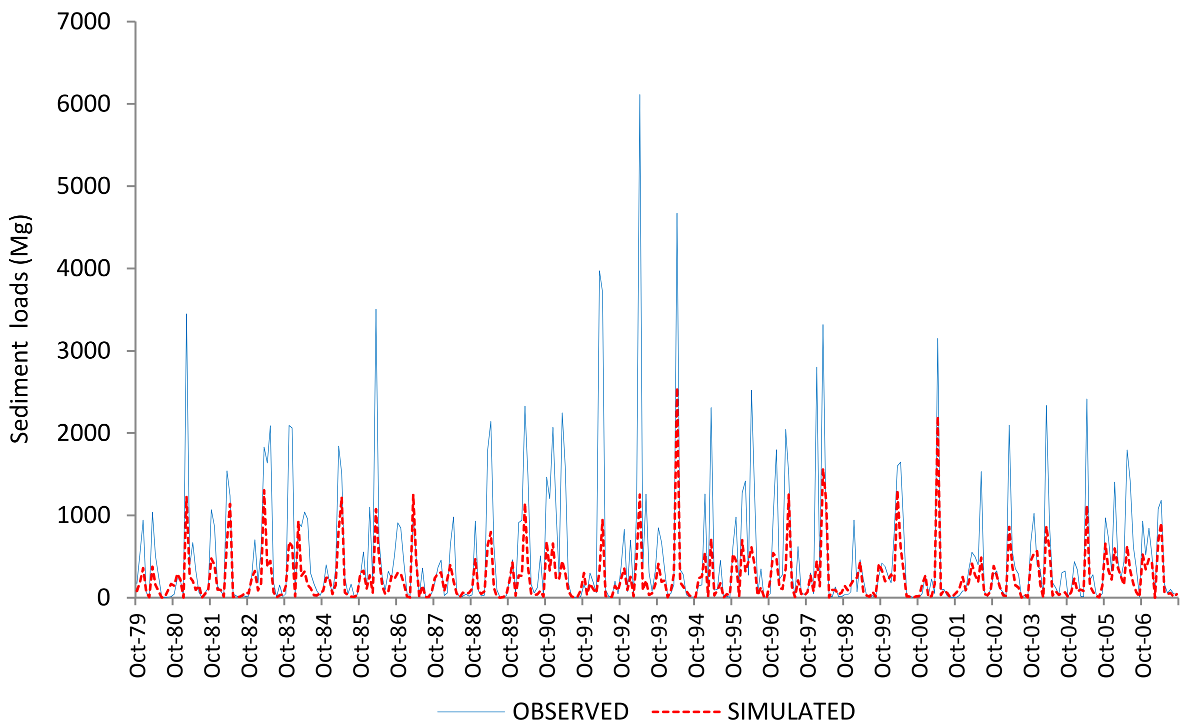


Figure 20. Observed and simulated monthly sediment loads at outlet 18 (NSE=0.38; R^2=0.66; PBIAS=53.2) for the period 1979-2007.

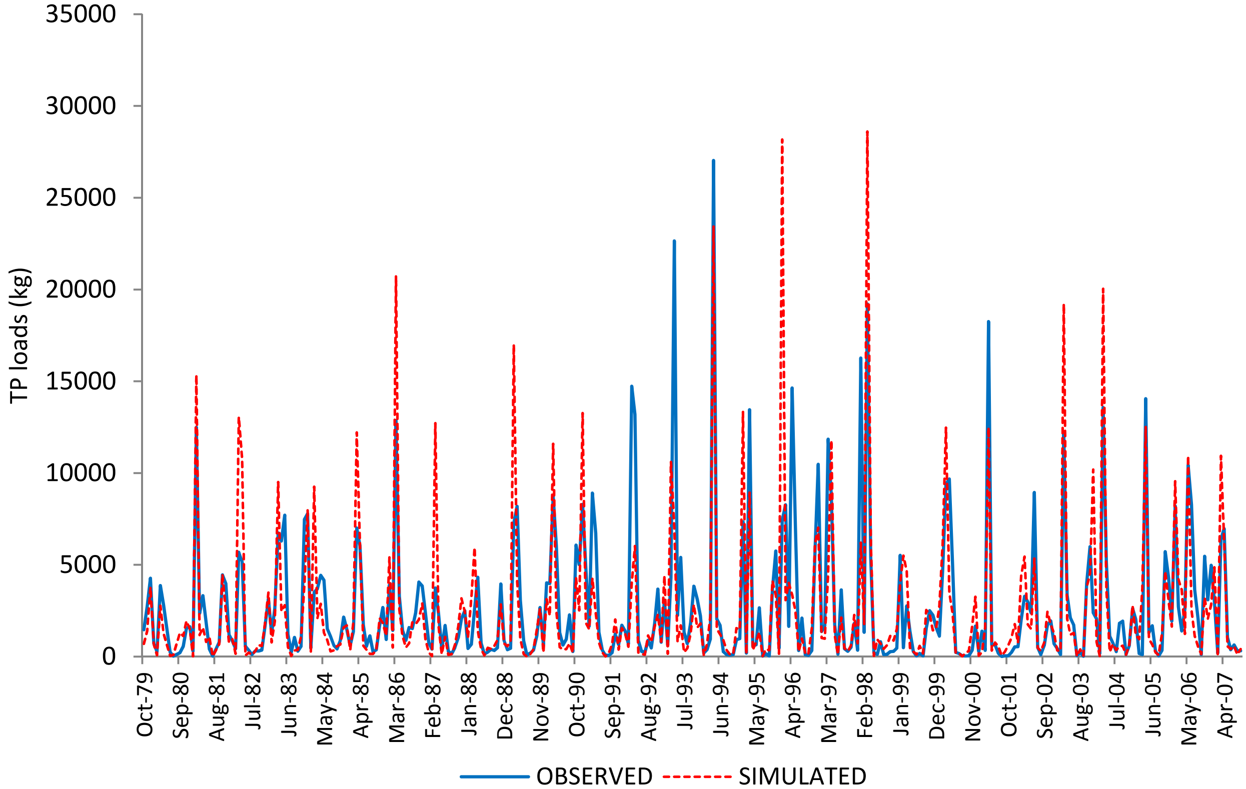


Figure 21. Observed and simulated monthly TP loads at outlet 18 (NSE=0.46; R^2=0.57; PBIAS= 4.8) for the period 1979-2007.

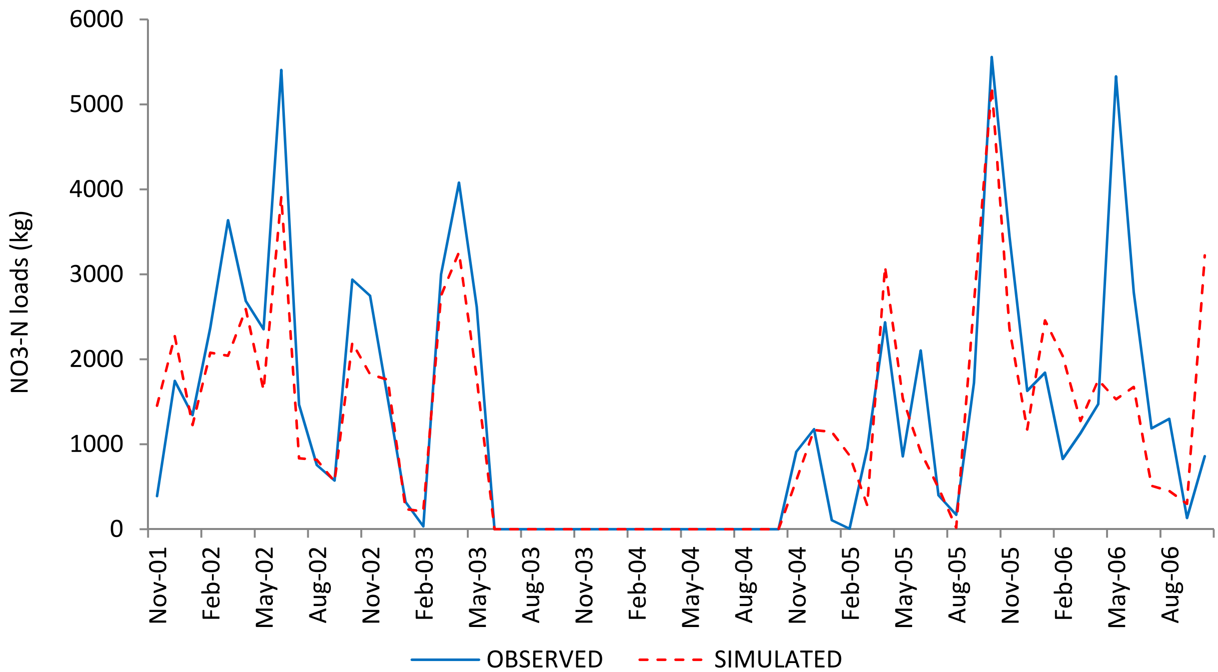


Figure 22. Observed and simulated monthly NO_3^--N loads at outlet 4 for the period 2001-2003 (NSE=0.77; R^2=0.78; PBIAS=0.38) and 2004-2006 (NSE=0.43; R^2=0.51; PBIAS=28.4).

6.3. Simulated water quality with SWAT

In the following sections, the SWAT outputs for streamflow, sediment, TP and NO_3^--N are mostly shown as changes in the monthly means of the simulated scenarios compared to the reference simulation in SWAT. The absolute monthly values for the reference simulation are given in Table 21. This approach of analysing changes rather than showing the absolute future values reduces the hydrological model prejudice related to systematic biases in the results (i.e. SWAT has PBIAS values ranging from -40 to 53 (Tables 18-20), indicating a systematic over- or under-prediction compared with observed values). For this reason, in this report we mostly refrain from discussing the absolute values of sediment loads or nutrient concentrations. Instead, the results are portrayed as differences from the reference simulation. Or, if absolute values are depicted, they are presented as boxplots with standard deviations, outliers, and with the reference simulation as a comparison.

Table 21. Absolute monthly values for the reference simulation (1971-2000).

Month	Flow (m^3/s)	Sediments (kg/ha)	TP (kg/ha)	NO_3^--N (kg/ha)
1	7.84	3.45	0.06	2.05
2	8.34	3.45	0.04	1.57
3	25.66	12.92	0.19	3.50
4	29.10	14.15	0.11	3.00
5	6.85	3.08	0.02	1.31
6	3.73	1.51	0.01	0.77
7	2.54	1.01	0.01	0.38
8	3.10	1.21	0.01	0.65
9	5.18	2.15	0.01	1.42
10	11.48	5.29	0.03	3.09
11	13.15	5.96	0.04	3.52
12	10.70	5.02	0.04	2.95

6.3.1. Water quality changes with climate change simulations

The three climate simulations were applied to SWAT, in lieu of the observed meteorological data to determine the impact of climate change alone on the watershed. Overall, an average of 66 to 102 mm more precipitation per year is simulated to fall in the watershed in the future (Table 22). The climate change simulations increase the mean annual flow (in the order of 1 m^3/s), and the mean annual sediment loads (Table 23). The mean annual TP loads remain for the most part unchanged, however the mean annual nitrate loads increased substantially.

Table 22. Mean annual water balance (WB) for the reference simulation and climate change simulations in SWAT: WB=Precipitation – evapotranspiration - surface runoff – subsurface flow - percolation to deep aquifer. (All simulated WBs are listed in Appendix 7).

	Precipitation (mm)	Evapo transpiration (mm)	Surface runoff (mm)	Subsurface flow (mm)	Percolation to deep aquifer (mm)	Water balance (mm)
Reference	1184.1	566.6	29.1	511.0	118.0	-11.5
ACU	1250.5	606.3	24.8	532.3	125.7	-13.6
AGR	1282.5	608.1	25.3	562.2	130.6	-18.4
AHK	1286.0	614.3	24.3	549.0	132.9	-10.2

The negative annual water balances indicate an overestimation of the evapotranspiration +surface runoff +subsurface flow +percolation to deep aquifer components. It is difficult to pinpoint which component it is, and is probably a combination of factors. Disparities in total water balances are generally due to lag times being greater than a year of water movement through one or more components; or soil water storage processes not accounted for; or other processes not accounted for, such as snow sublimation, or evaporation from lakes and rivers.

Table 23. Mean annual simulated streamflow, sediment, TP and NO_3^--N loads (with standard deviations) for the reference simulation (1971-2000) and for the three climate change simulations (2041-2070), at outlet 23.

	Flow (m^3/s)	Sediments (Mg/yr)	TP (Mg/yr)	NO_3^--N (Mg/yr)
Reference	10.6 ±2.1	3740.8 ±885.3	35.5 ±13.2	1530.4 ±289.5
ACU	11.1 ±1.7	3767.4 ±570.3	35.3 ±12.6	1683.3 ±282.7
AGR	11.7 ±1.9	4007.2 ±642.3	37.7 ±12.4	1743.4 ±284.6
AHK	11.5 ±2.2	3843.2 ±784.2	36.3 ±16.8	1757.3 ±293.6

As seen in Figure 12, future precipitation increases take place in March, April and May. Yet, in all simulations, the month of April has a significant decrease in streamflow. This indicates an earlier spring peak flow, shifting from April to March in the future. There is less snowfall overall (Appendix 8) creating less snowpack, and the snowmelt is more gradual and takes place over the months of February and March, with the peak occurring one month earlier than in the reference simulation, and is lower (mean monthly values ranging from 20 – 25m^3/s in March, instead of almost 30m^3/s in April).

Increases in future streamflow for ACU and AGR from December to February were simulated to be significantly higher than in the reference simulation, by 65% to 102%. For AHK, the future streamflow in February, September, November and December was significantly higher; by 40 to 111% (Table 25).

During the months from May to September few changes to streamflow were simulated to take place in the future. This is also the period during which precipitation has the least relative changes, compared to the reference simulation.

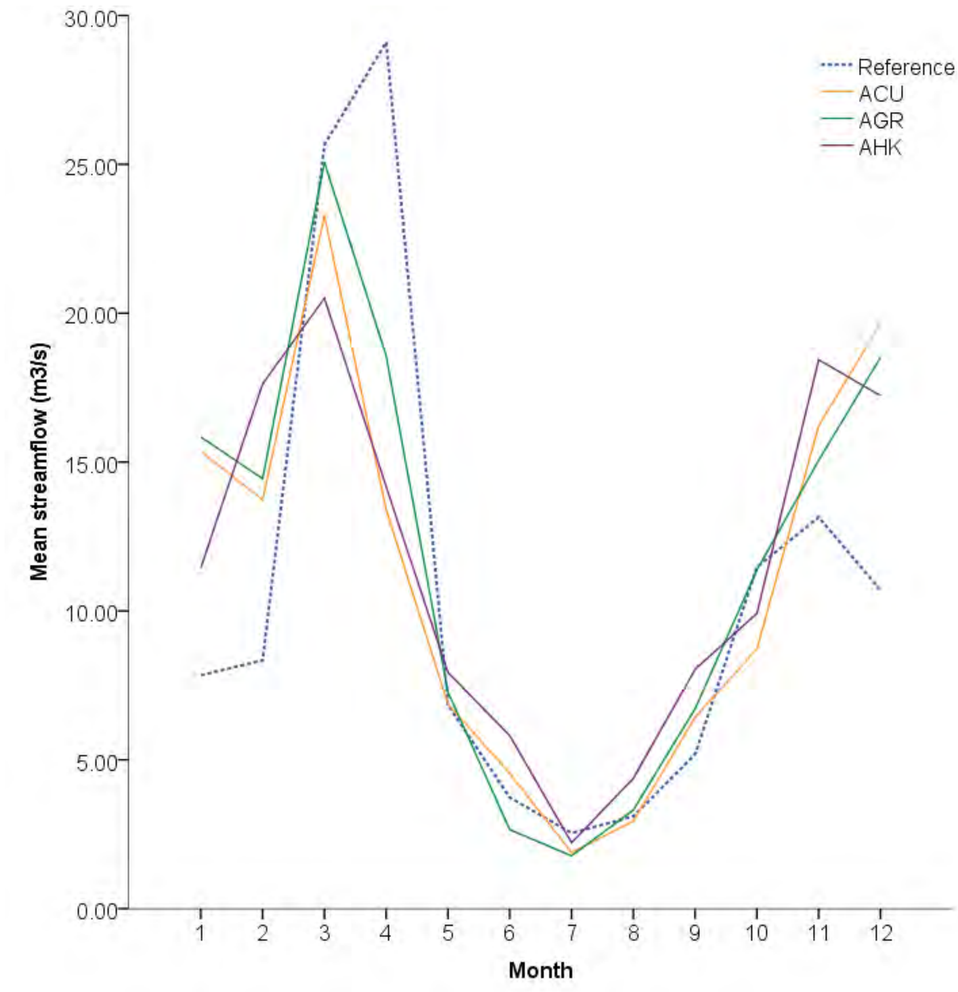


Figure 23. SWAT simulated streamflow for the reference simulation (1971-2000) and the future climate simulations (2041-2070).

Table 24. Absolute changes in mean streamflow, mean sediment and mean nutrients for the watershed due to future climate simulations (2041-2070), compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow (m3/s)	Sediments (kg/ha)	Total P (kg/ha)	NO_3^--N (kg/ha)
ACU	1	7.51	3.58	0.04	1.56
	2	5.39	2.30	0.03	0.73
	3	-2.39	-2.04	-0.06	-0.62
	4	-15.72	-7.91	-0.07	-1.31
	5	0.02	0.02	0.00	-0.07
	6	0.81	0.29	0.01	0.12
	7	-0.65	-0.32	0.00	-0.08
	8	-0.16	-0.06	0.00	0.02
	9	1.25	0.64	0.00	0.21
	10	-2.76	-1.32	0.00	-0.68
	11	3.07	1.38	0.01	0.72
	12	8.94	3.86	0.05	1.81
AGR	1	8.00	3.78	0.05	1.53
	2	6.10	2.67	0.05	0.87
	3	-0.60	-1.00	-0.03	-0.45
	4	-10.54	-5.89	-0.06	-0.97
	5	0.42	0.18	0.00	0.08
	6	-1.08	-0.50	0.00	-0.19
	7	-0.77	-0.36	0.00	-0.10
	8	0.21	0.12	0.00	0.14
	9	1.53	0.73	0.00	0.34
	10	-0.10	0.09	0.00	0.06
	11	1.91	0.71	0.01	0.36
	12	7.81	3.69	0.03	1.70
AHK	1	3.60	1.82	0.03	0.71
	2	9.29	4.12	0.06	1.30
	3	-5.16	-3.46	-0.09	-0.88
	4	-14.93	-7.92	-0.07	-1.23
	5	1.08	0.46	0.01	0.11
	6	2.08	0.84	0.01	0.36
	7	-0.33	-0.25	0.00	-0.02
	8	1.28	0.55	0.00	0.31
	9	2.85	1.35	0.02	0.63
	10	-1.56	-0.91	0.00	-0.35
	11	5.29	2.13	0.02	1.24
	12	6.53	2.90	0.02	1.41

Table 25. Relative changes (%) in mean streamflow, mean sediment and mean nutrient loads for the watershed due to future climate simulations (2041-2070), compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow	Sediments	Total P	NO_3^--N
ACU	1	96	104	64	76
	2	65	67	81	47
	3	-9	-16	-34	-18
	4	-54	-56	-69	-44
	5	0	1	5	-6
	6	22	19	68	16
	7	-26	-32	-27	-21
	8	-5	-5	2	4
	9	24	30	35	15
	10	-24	-25	-10	-22
	11	23	23	27	20
	12	84	77	111	62
AGR	1	102	110	81	74
	2	73	77	116	55
	3	-2	-8	-16	-13
	4	-36	-42	-58	-32
	5	6	6	8	6
	6	-29	-33	-26	-25
	7	-30	-36	-34	-26
	8	7	10	6	22
	9	30	34	35	24
	10	-1	2	-1	2
	11	15	12	15	10
	12	73	74	61	58
AHK	1	46	53	56	35
	2	111	119	151	82
	3	-20	-27	-45	-25
	4	-51	-56	-66	-41
	5	16	15	33	8
	6	56	56	120	46
	7	-13	-25	-18	-5
	8	41	45	44	48
	9	55	63	119	44
	10	-14	-17	-5	-11
	11	40	36	58	35
	12	61	58	43	48

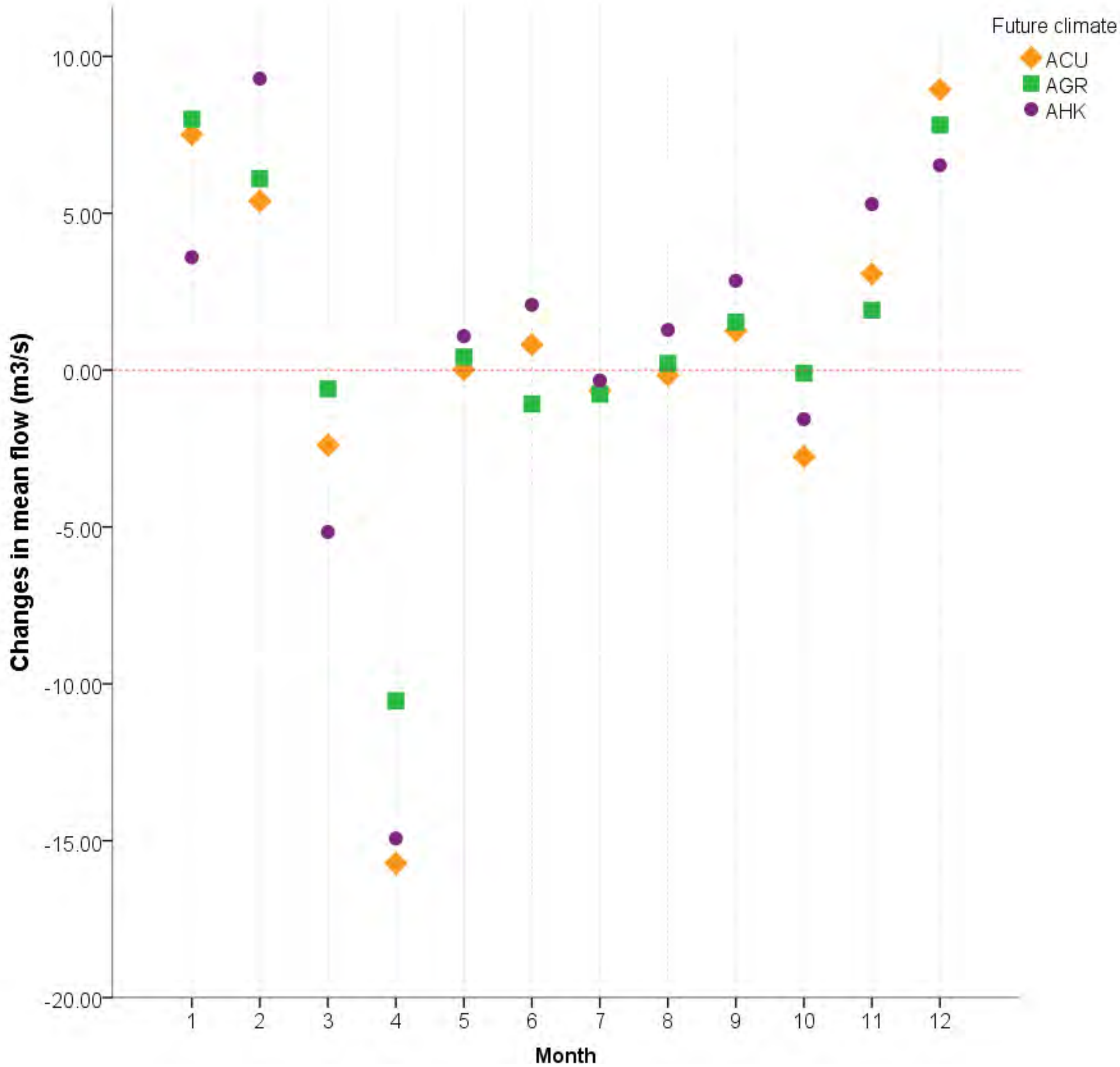


Figure 24. Changes in SWAT simulated mean monthly streamflow (m^3/s) for climate change simulations (2041-2070), compared to the reference simulation (red zero line), at the basin outlet.

The greatest increase in streamflow (65% to 111%) compared to the reference simulation (red line; for the absolute reference values, refer to Table 21) was simulated in the month of February while the month of April had the greatest decrease (36% to 54%). These results concord well with the *Atlas hydroclimatique du Québec méridional* (CEHQ, 2013) which portrays future (2050 horizon) hydrological discharges stemming from the Hydrotel model (Fortin et al., 1995) simulations using climate change data; generating 435 hydro-climatic simulations to calculate the statistics. The Atlas also projects the greatest increases to take place in January and February, with mean discharges 30% to 60% higher for watersheds near our study area. The watersheds corresponding to our study area in the Atlas are *Rivière Châteauguay* (2490 km^2) and *Rivière des Anglais* (643 km^2). Also, for both of these watersheds, the future spring melt is projected to occur two weeks earlier, with the greatest increases in discharges taking place in February of nearly 170% and 200%, respectively. Changes in mean monthly discharges for April were projected to decrease by 12% to 36%. In the Atlas, other large reductions in mean discharges took place in September and October, ranging from 25 to 35% (CEHQ, 2013), which was not the case here (Figure 24) because the SWAT model reacts to sub-surface drainage being modelled at the field level. This causes the precipitation in autumn, after most of the crops are harvested (September), to move preferentially into the reach via the drains, so that the precipitation is moved rapidly into the reach. Also, in SWAT, the CN adjusts to accommodate any changes in soil cover and tillage, so that after harvest, the ground usually has a higher CN than before (especially if no residues are left). This yields less infiltration and higher surface runoff volumes.

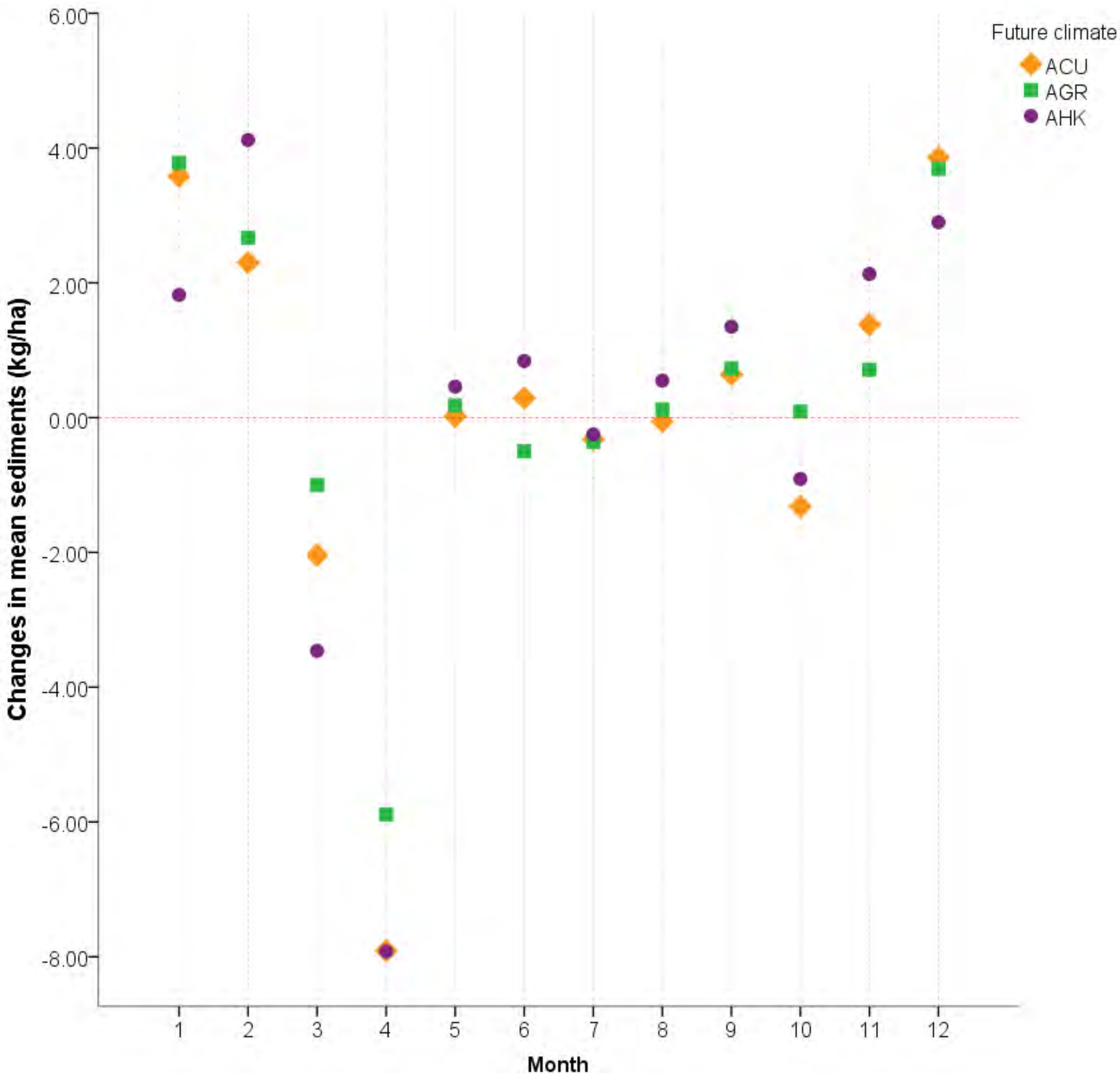


Figure 25. Changes in SWAT simulated mean monthly sediments loads (kg/ha) for climate change simulations (2041-2070), compared to the reference simulation (red zero line), for the watershed.

Compared with the reference simulation, the future climate simulations cause significantly greater mean sediment loads for the months of January, February, September, November and December. A significant decrease in mean sediment transport is simulated to occur in April. The changes in mean monthly sediments loads closely mirrored the changes simulated for mean streamflow (Figure 24). A significant increase in streamflow always brought about a significant increase in sediment loads, and vice versa. A regression equation explaining sediment transported by flow was found to be: *sediment (kg/ha) = 0.46*flow* (m^3/s) *- 0.19* (Pearson's R = 0.99, p<0.0001).

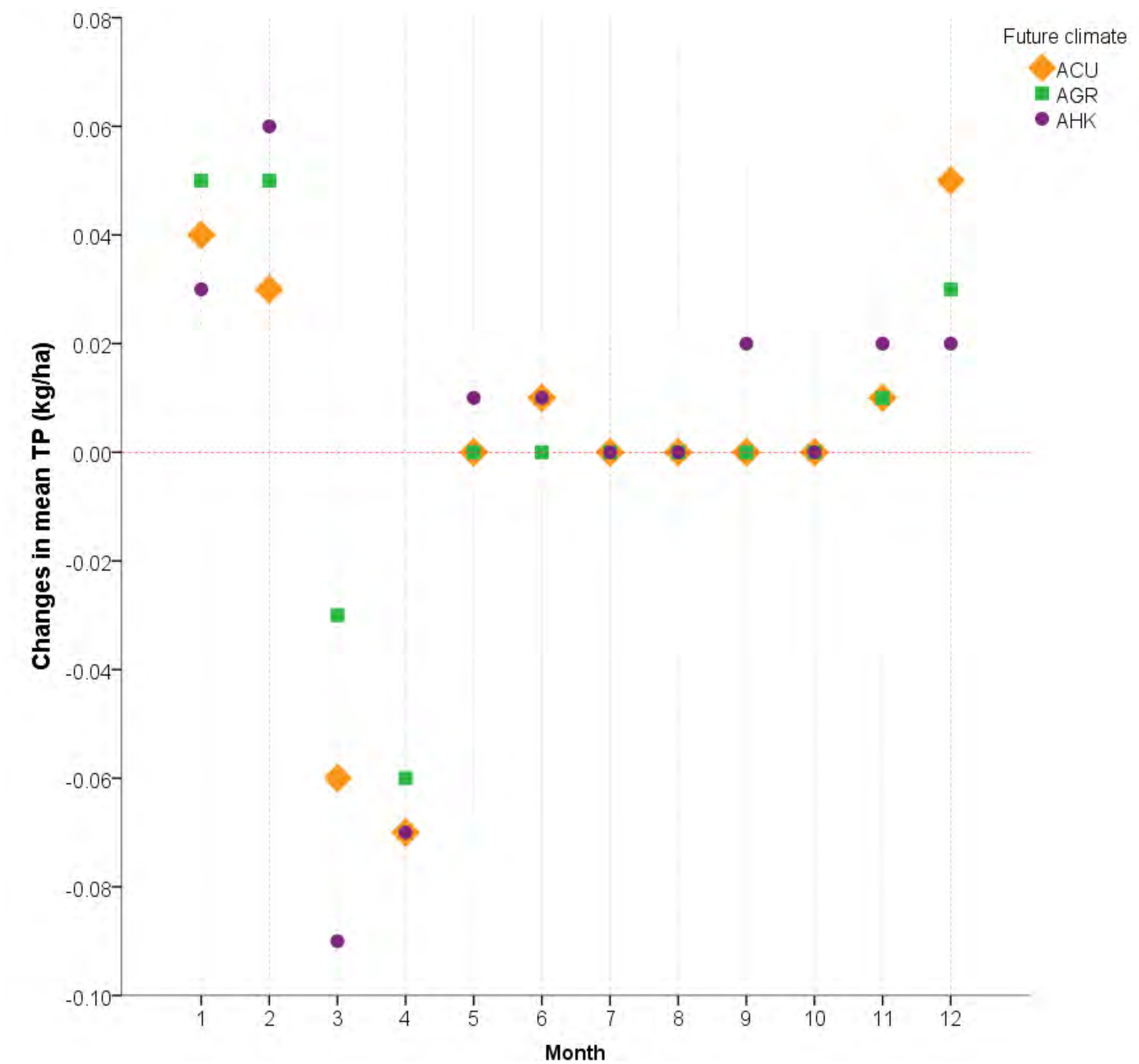


Figure 26. Changes in SWAT simulated mean monthly TP loads (kg/ha) for climate change simulations (2041-2070), compared to the reference simulation (red zero line), for the watershed.

Compared to the reference simulation, significant increases in mean TP loads are shown (in at least one of the climate simulations) during the months of January, February, September, November and December. Significant mean decreases were simulated in March and April. Hardly any changes in mean TP loads were simulated during the months of May to September.

Total phosphorus is made up of particulate and soluble P. In our SWAT simulations, approximately 70% of the TP stemming from annual crops is in the form of particulate P and 30% is soluble (Appendix 9). The particulate P binds to soil particles, especially the fine and medium size particles (Beaudet et al., 2008). Erosion usually entails the transport of the fine soil particles. The main driver of TP transport is surface runoff, therefore during periods of snowmelt the greatest increase in TP are simulated (65% to 111%).

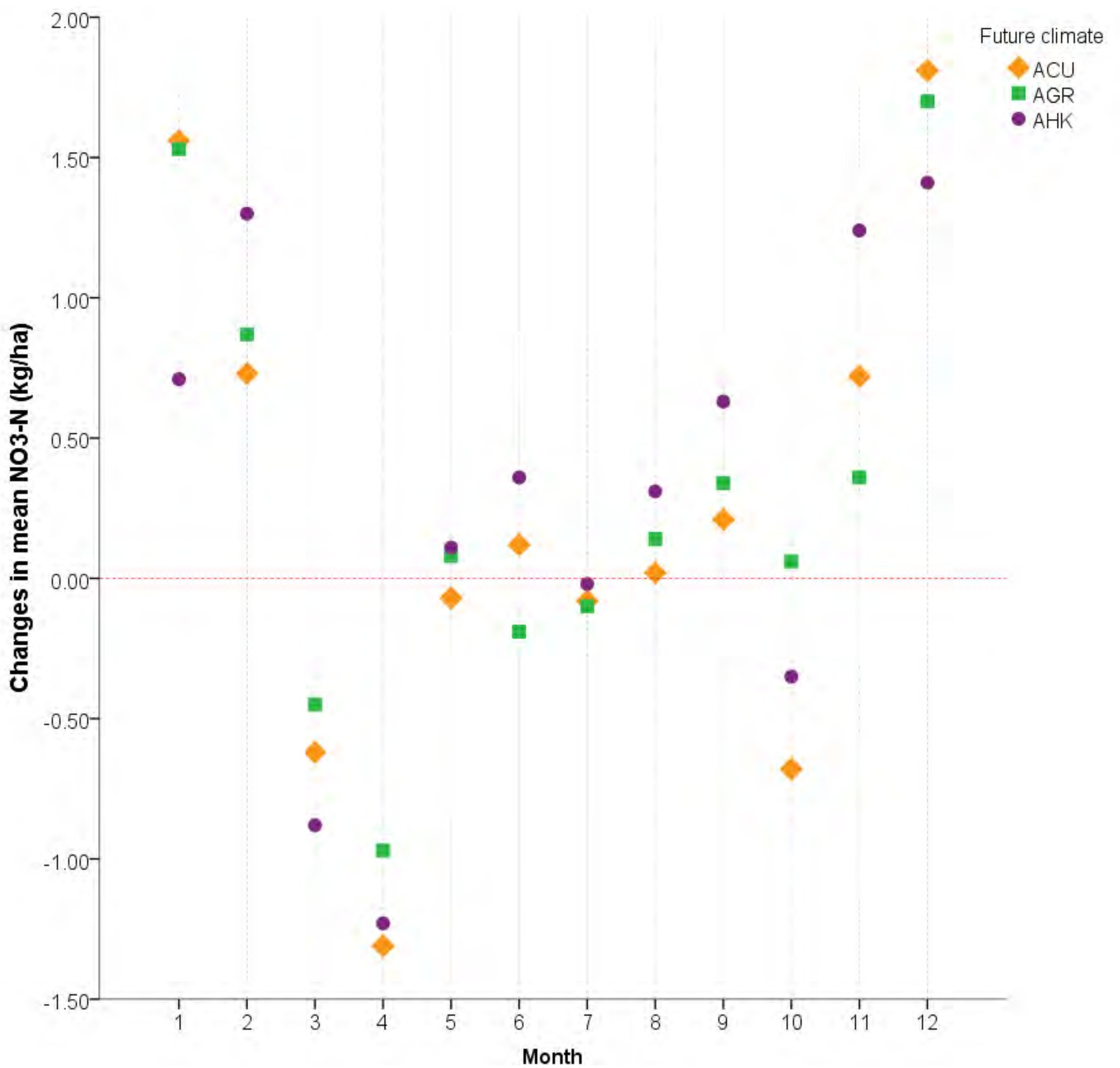


Figure 27. Changes in SWAT simulated mean monthly NO_3^--N loads (kg/ha) for climate change simulations (2046-2070), compared to the reference simulation (red zero line), for the watershed.

Climate change impacted changes to the mean NO_3^--N loads somewhat greater than the mean loads of TP. Nitrate-nitrogen is more labile than phosphorus, because the NO_3^- molecule is highly soluble in water, whereas mineral phosphorus binds to soil particles. Thus, NO_3^--N loads are not only driven by surface flow, but also by infiltration and throughflow. Hence, NO_3^--N loads are more sensitive to precipitation and infiltration changes, as can be seen by the higher variability, and they do not follow the same general pattern as the changes in sediment or TP loads which tend to increase the most with greater streamflow (i.e. during snowmelt in February). The NO_3^--N loads increased during January, February, November and December, which are the months with the greatest increases in percolation compared to the reference simulation (Appendix 8).

In summary, due to climate change impacts, the increases in mean streamflow were simulated to be greatest in February with an additional 5.31 (±2.09) to 9.29 (±2.21) m^3/s of flow, and decrease the most in April by 10.54 (±3.89) to 15.72 (±3.67) m^3/s. The mean sediment loads are simulated to increase the most by 2.30 (±0.92) to 4.12 (±0.97) kg/ha in February, and decrease by the most by 5.89 (±2.06) to 7.91 (±2.00) kg/ha in April. The mean TP loads are simulated to increase by at most 0.05 (±0.02) to 0.06 (±0.02) kg/ha in February and decrease the most by 0.06 (±0.02) to 0.07 (±0.02) kg/ha in April. The mean NO_3^--N loads are simulated to increase the most by 1.41 (±0.39) to 1.81 (±0.39) kg/ha in December and decrease the most by 0.88 (±0.35) to 1.31 (±0.29) kg/ha in April.

Our results concord well with the timing of changes found by Gombault (2012); a study in which four (non-bias corrected) climate change simulations (ADC, ACU, AFA-AFD and ARP) were provided by Ouranos. She found precipitation increased the most in March and April, with the greatest mean increase ranging from 14% to 38%. A decrease in precipitation was also projected for the summer month (June to August) with the greatest mean decrease ranging from 8% and 18%. As a result, her simulations with SWAT (using a finer set-up and a different calibrated model than ours) showed increases in streamflow from November to March with the highest mean increase in March being between 16 m^3/s to 18 m^3/s (58% to 215%), and a decrease from April to August with the greatest mean decrease in April being between -11 m^3/s to +3 m^3/s (-24% to +5%). Sediment, TP and total nitrogen (TN) loadings followed the same trend. The highest mean increase in sediment loadings ranged from 1 kg/ha to 72 kg/ha (2% to 234%) in March while the highest mean decrease ranged from -31 kg/ha to -70 kg/ha in April (-27% to -69%). Similarly, the highest mean increase in TP loadings ranged from 0.04 kg/ha to 0.21 kg/ha (24% to 148%) in March while the highest mean decrease ranged from -0.10 kg/ha to -0.17 kg/ha in April (-27% to -50%). Finally, the highest mean increase in TN loadings ranged from 1.7 kg/ha to 3 kg/ha (65% to 220%) in March while the highest mean decrease ranged from -0.49 kg/ha to -2.29 kg/ha in April (-5% to -33%).

The differences in the magnitude of changes found by Gombault (2012) was mainly due to the unbiased climate simulations used, where during the reference period (1970-2000) in winter, the climate simulation's air temperature was lower than the calibrated snowmelt threshold (therefore less melting took place), while for the future period the air temperatures were warmer and did reach the snowmelt threshold (of $1^{o}C$), so significantly more melting took place in the future. If the data were unbiased, the snowmelt threshold would have been met more often in 1970-2000, generating more runoff.

Examining nutrient loads transported from the land only tells part of the story. A primary concern is to meet set water quality criteria. Here, the Québec criteria for surface water quality (MDDEF, 2002) were used because the discharge at watershed outlet (outlet 23) reflects the quality of water in the Pike River and its tributaries, and not the water quality of the Missisquoi Bay per se. The concentrations of TP and NO_3^--N at outlet 23 were therefore examined and reported. The concentration of nutrients (mg/L) in a river reach depends on how much flow is available in the reach; concentrations are related to the quantity of flow.

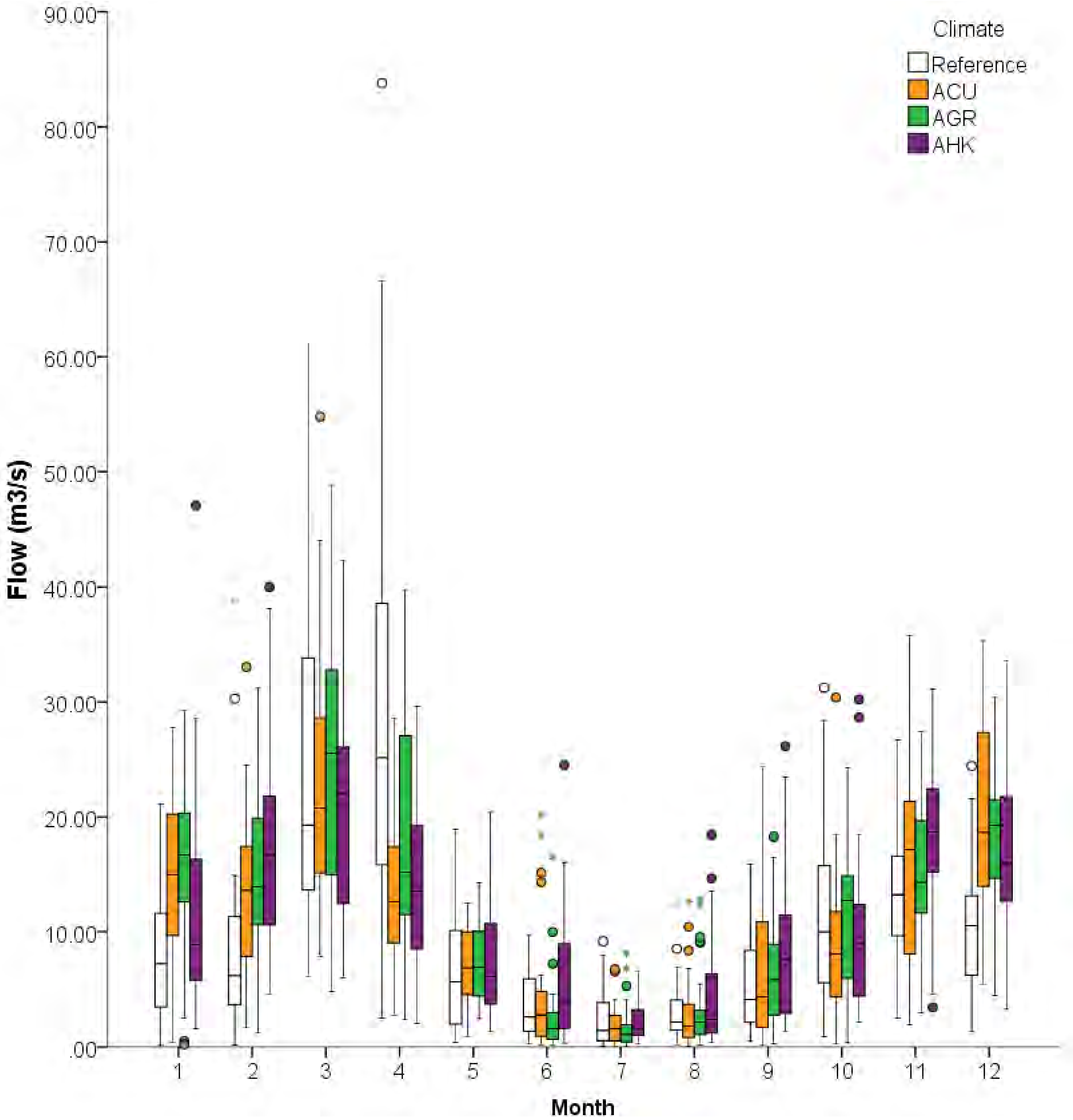


Figure 28. SWAT simulated streamflow (m^3/s) at the basin outlet for the climate change simulations (2041-2070; colored boxes), compared to the reference simulation (white boxes).

Boxplots show the central mark as being the median, the upper and lower edges of the box are the 75th and 25th percentile, respectively and the whiskers extend to the values that lie inside one and half box lengths from the quartiles. The circles represent values which lie one and a half box lengths away from the quartile (considered outliers), and the smaller, pale markers are values that lie more than three box lengths away from the quartile (considered extremes).

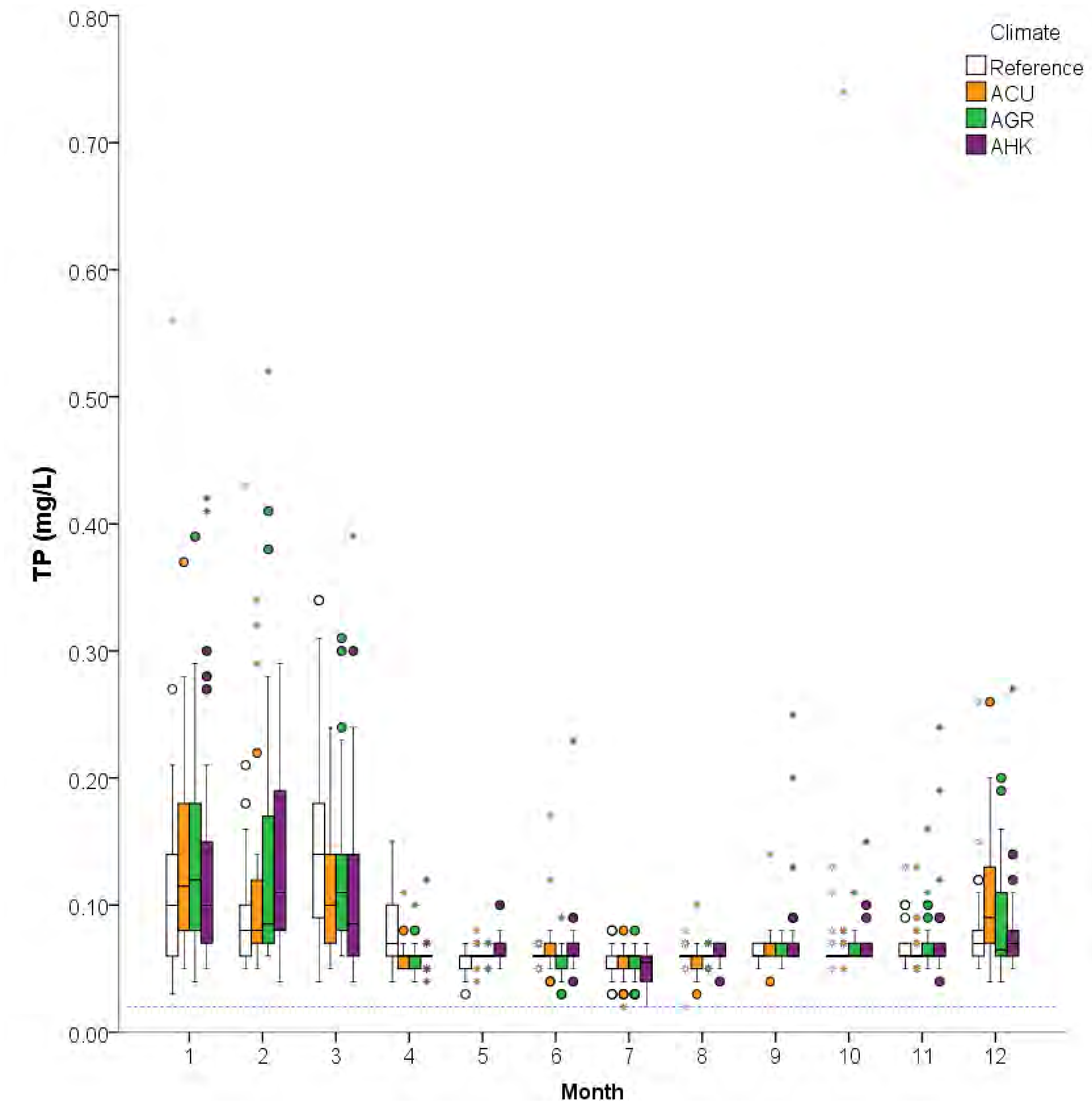


Figure 29. Concentration of SWAT simulated TP (mg/L), at the basin outlet for the climate change simulations (2041-2070; coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 0.02 mg/L.

Only in three months was the median concentration of TP negatively impacted by climate change (January, February and December). The increased mean loads of TP stemming from the land in

December, January and February lead to greater TP concentrations at the outlet for at least one of the simulations, and this despite the increases in mean flow during these months. However, in March, the increased future median flow (Figure 28) coupled with similar mean TP loads as during the reference simulation, caused the future TP concentrations to be reduced. In April, when both the mean streamflow and the mean TP loads were significantly lower, the overall monthly median TP concentration was not affected by climate change.

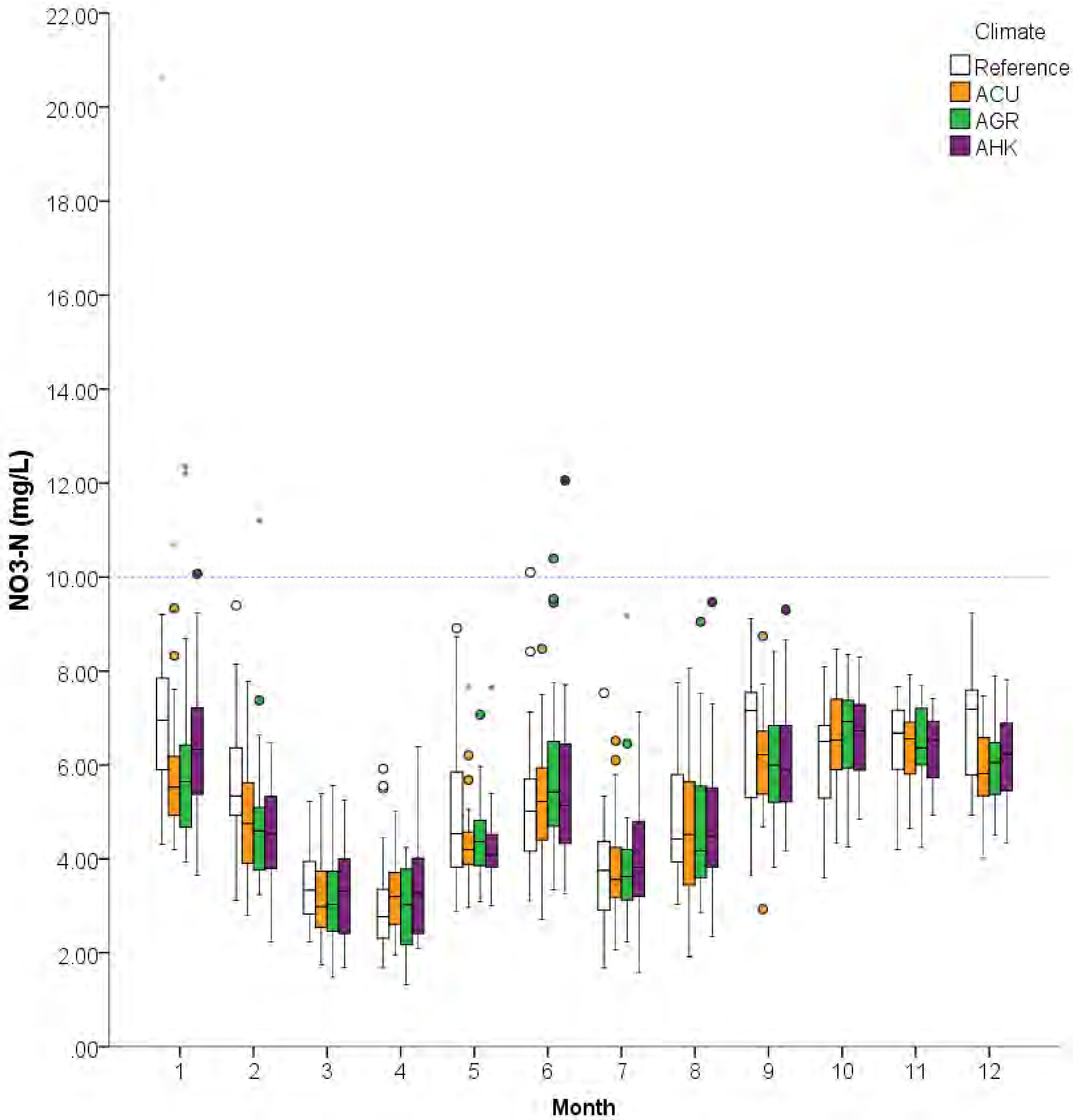


Figure 30. Concentration of SWAT simulated NO_3^--N (mg/L), at the basin outlet for the climate change simulations (2041-2070; coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 10.0 mg/L.

Generally, the months with the highest increase in flow (December, January and February) also showed a decrease in median NO_3^--N concentrations, compared to the reference simulation. In

April, the median NO_3^--N was slightly higher than the reference, despite the significantly lower streamflow and lower NO_3^--N loads. For the remaining months, the variability of NO_3^--N remained within the same range as the reference scenario. The climate change simulations did not alter the fact that the concentrations of NO_3^--N rarely exceeded the water quality criterion of 10 mg/L (in 8 of 1080 mean monthly values). In contrast, the TP concentrations almost never met the water quality criterion of 0.02 mg/L (in 2 of 1080 mean monthly values).

The sediments modelled in SWAT consist of coarser sediments (such as sand) as well as of finer sediments (such as clay) that are transported overland and deposited into the reach. To show a sediment concentration, would involve describing suspended sediments transported by a water column. This would require knowing the quantity of finer particles (silt and clay), which are determined from water samples that are filtered. Since this was not undertaken, only sediment loads are presented and discussed.

In summary, simulated climate change impacts did not consistently increase the concentrations of nutrients at the outlet of the watershed, compared with the reference simulation. The months in which median TP concentrations were most negatively affected were in winter (December, January, February). Yet, during the months of March, the median TP concentrations are lower than in the reference simulation, and for the rest of the year they remain relatively unchanged. The water quality criterion of 0.02 mg/L for TP was almost never attained. For NO_3^--N concentrations, climate change decreased concentrations in December, January, and February. In April, the NO_3^--N concentrations were higher than the reference simulation. Otherwise, they remained for the most part unchanged. Overall, the water quality criterion of 10.0 mg NO_3^--N /L was rarely exceeded.

Table 26. Median nutrient concentrations (mg/L) at the outlet for the reference simulation (1971-2000) and the future climate simulations (2041-2070).

	Month	Total P (mg/L)	NO_3^-N (mg/L)
Reference	1	0.10	6.96
	2	0.08	5.34
	3	0.14	3.33
	4	0.07	2.77
	5	0.06	4.53
	6	0.06	5.03
	7	0.05	3.76
	8	0.06	4.42
	9	0.06	7.16
	10	0.06	6.51
	11	0.06	6.68
	12	0.07	7.14
ACU	1	0.12	5.53
	2	0.08	4.75
	3	0.10	2.99
	4	0.06	3.19
	5	0.06	4.20
	6	0.06	5.23
	7	0.06	3.56
	8	0.06	4.52
	9	0.07	6.22
	10	0.06	6.53
	11	0.06	6.56
	12	0.09	5.82
AGR	1	0.12	5.65
	2	0.90	4.60
	3	0.11	3.03
	4	0.06	3.02
	5	0.06	4.37
	6	0.06	5.43
	7	0.06	3.63
	8	0.06	4.18
	9	0.07	6.00
	10	0.06	6.92
	11	0.06	6.37
	12	0.07	6.06
AHK	1	0.10	6.34
	2	0.11	4.54
	3	0.09	3.32
	4	0.06	3.27
	5	0.06	4.08
	6	0.06	5.13
	7	0.06	3.82
	8	0.06	4.49
	9	0.06	5.89
	10	0.06	6.72
	11	0.06	6.53
	12	0.07	6.23

6.3.2. Water quality changes due to land use change scenarios

6.3.2.1. Water quality changes due to the "plausible" land use scenarios

Due to the coupling of the CLUE-S raster layers in SWAT with the SWAT2009_LUC tool, some of the desired land use changes did not occur in SWAT as prescribed by CLUE-S. According to the developers of the coupling tool SWAT2009_LUC (Pai and Saraswat, 2011), a certain amount of deviation in the area of land use per sub-basin may occur when HRU thresholds are defined in the model set-up. In this case, Pai and Saraswat (2011) indicated that the deviation that may occur in a sub-basin can be in the range of 5-10% per land use. However in this study, deviations of up to 30% occurred in some sub basins.

In the HIST scenario most of the transferred land use changes were lower than those originally prescribed by CLUE-S. After transferring to SWAT, the decrease in corn area was 150 ha less; as well, there were 1115 ha less for "other ag land"; 572 ha less for rangeland; and 555 ha less for forest areas. The prescribed increases in land use were also reduced, by 574 for vegetables and by 2540 ha for soybeans. Relative to the watershed area, these errors represent 0.2%, 1.8%, 0.9%, 0.9%, 0.9%, and 4.0%, respectively. Despite these deviations, the HIST scenario remains primarily driven by changes in corn and soybean as prescribed, but to a lesser extent (Figure 31).

The land use changes of the EXP scenario show more erratic alterations when transferred into SWAT, with respect to the originally prescribed CLUE-S changes; the direction of change was sometimes contradictory and the differences were irregular. For example, the area under soybean was prescribed to increase by 211 ha, but instead the transferred area had a decrease of 76 ha. Similarly, the area under cereals (wheat, barley and oats) was prescribed to increase by 65 ha, but it diminished by 245 ha. The categories of orchard and rangeland had similar but smaller absolute divergences and the forest area was reduced by an additional 161 ha. The largest inaccuracies between the prescribed and transferred areas were the under-representation of 1496 ha in the increase of corn area (2.4% of the watershed area), followed by a missing 1338 ha (2.1%) in the decrease of "other ag land", and an absent 437 ha (0.7%) of declining hay area.

The originally prescribed land use in the EXP scenario was driven mainly by changes in corn and "other ag land", which during the transfer both experienced the highest absolute alterations by the transfer tool. It is important to note, however, that the category "other ag land" represents unknown agricultural land, therefore it was modeled in SWAT in exactly the same way as corn (to represent the highest fertilized crop). The originally prescribed combined land use changes for corn plus "other ag land" had a net increase of 489 ha, and the transferred land changes for corn plus "other ag land" to SWAT showed a net increase of 332 ha. The main trends in the EXP scenario thus remain comparable and are still driven by the changes in corn and in "other ag land" (Figure 32).

Evidently, the transferred scenarios do not represent the exact magnitudes of land use change as originally prescribed. Nevertheless, they represent the closest possible match that could be achieved in the coupling process by using the transfer tool SWAT2009_LUC. Despite its limitations and obvious distortions, this tool ensures that the overall hydrological model consistency remains intact and that no re-calibration is required, which would alter the existing SWAT model set-up and consequently limit the interpretation of the results. The transferred scenarios still represent plausible pathways of future land use change following the prescribed HIST and EXP trends

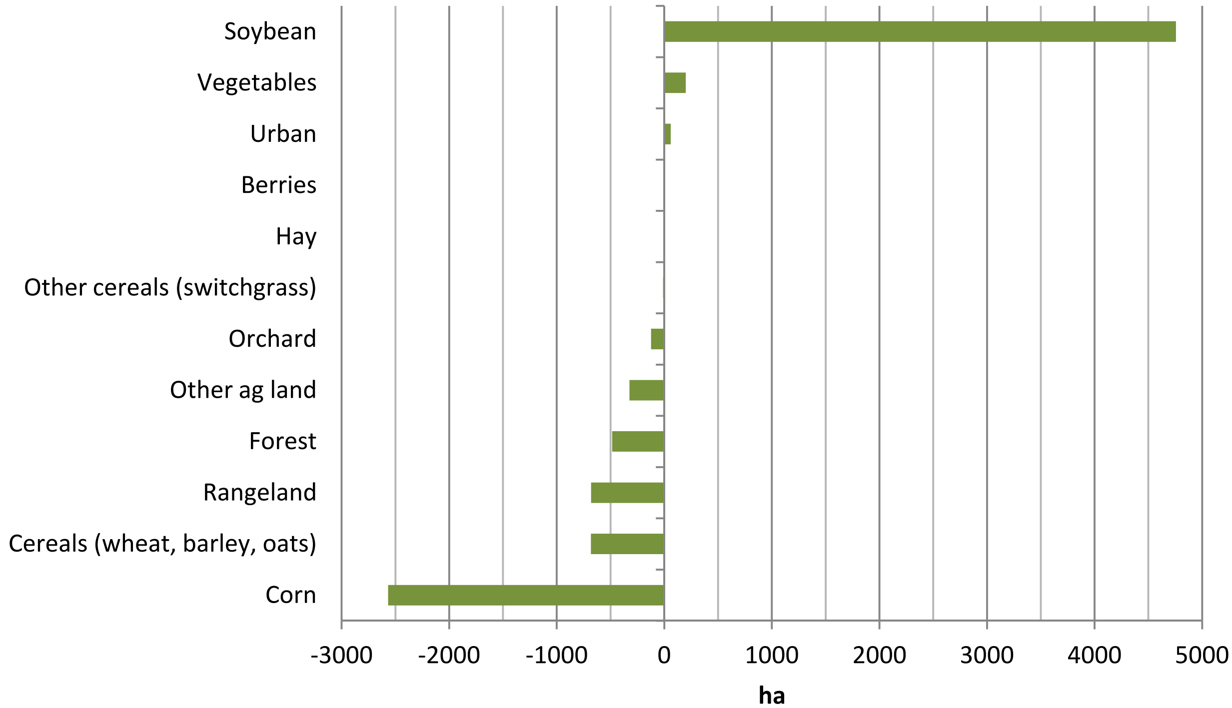


Figure 31. Crop changes after 30 years of simulation for the scenario "Historical Trends Continue" (HIST).

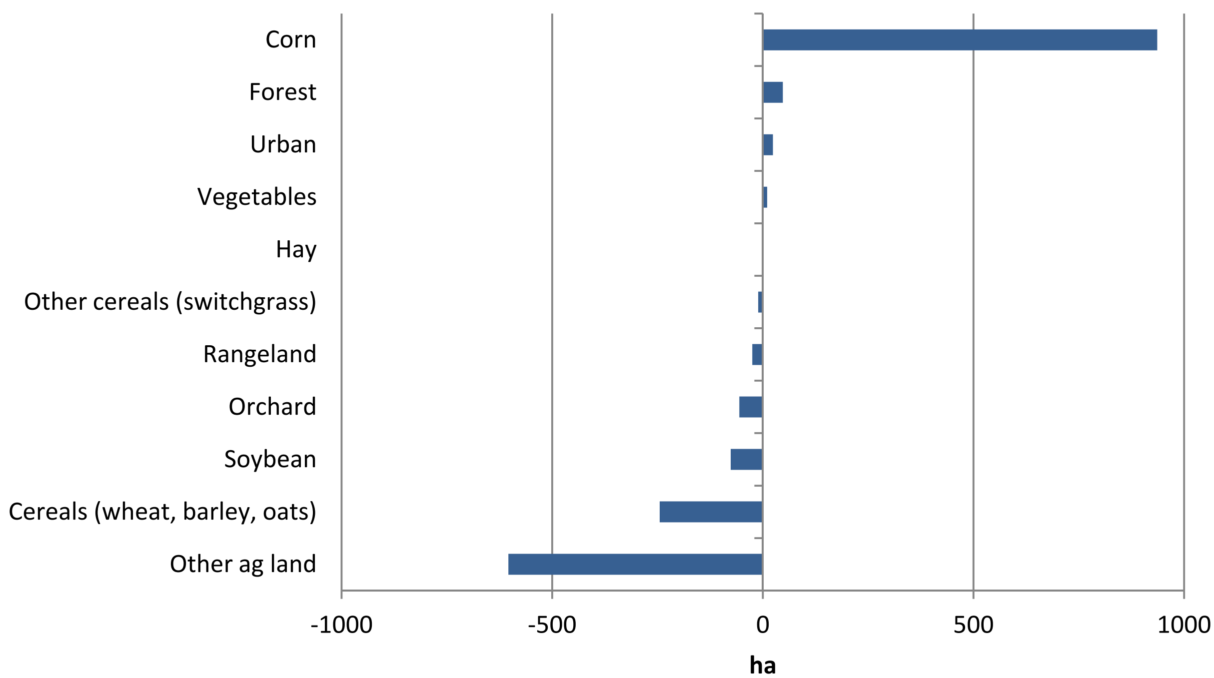


Figure 32. Crop changes after 30 years of simulation for the scenario "Expert Guided" (EXP).

The mean annual streamflow from the land use scenarios (HIST and EXP) compared to the reference simulation, was not greatly impacted. Although the land use changes brought about an increase in mean annual sediment and TP loads, it was not significant due to the high standard deviations. There was no significant change in mean annual NO_3^--N loads.

Table 27. Mean annual simulated flow, sediment, TP and NO_3^--N loads (with standard deviations) at outlet 23, for the reference simulation and land use change scenarios (1971-2000).

	Flow (m^3/s)	Sediments (Mg/yr)	TP (Mg/yr)	NO_3^--N (Mg/yr)
Reference	10.6 ±2.1	3740.8 ±885.3	35.5 ±13.2	1530.4 ±289.5
HIST	10.8 ±2.1	3794.1 ±902.9	42.8 ±16.3	1512.1 ±282.3
EXP	10.7 ±2.1	3767.9 ±896.8	41.8 ±16.0	1552.7 ±291.8

The changes in the HIST land use scenario after 30 years of simulation show a large decrease in the area of corn (2568 ha) as well as a decrease in “other ag land” (324 ha) which represents unknown agricultural land and is fertilized according to the same regime as corn in SWAT. The amount of soybean which is also a wide-row crop increases by 4757 ha. Overall, the total area of agricultural land increases by 1247 ha which continues to contribute to non-point source pollution. Land which is relatively non-polluting, such as forest and rangeland decreases by 485 ha and 680 ha, respectively (Figure 31). All of these changes together led to, on average, no alternations in the water quality at the outlet of the basin.

In the EXP land use scenario, the total area of agricultural land remains almost constant (-47 ha) during the simulation period. However, after the end of 30 years of simulation, the area of corn increases the most by 936 ha, yet “other ag land” decreases by a similar amount (604 ha). The latter is managed with the same fertilization regime as corn, thus in terms of nutrient input there is little net change. Changes to the areas of cereals, soybean and vegetables do not influence the water quality. Neither does the forest increase (48 ha) or the urban growth (24 ha).

Table 28. Absolute changes in mean streamflow, mean sediment and mean nutrients for the watershed due to land use scenarios, compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow (m^3/s)	Sediments (kg/ha)	Total P (kg/ha)	NO_3^--N (kg/ha)
HIST	1	0.06	0.03	0.01	0.00
	2	0.09	0.02	0.01	-0.02
	3	0.55	0.35	0.06	-0.08
	4	0.43	0.27	0.02	-0.03
	5	0.02	0.01	0.00	-0.03
	6	0.10	0.05	0.00	-0.02
	7	0.22	0.10	0.00	0.03
	8	0.05	0.02	0.00	0.00
	9	-0.11	-0.05	0.00	-0.05
	10	-0.04	-0.02	0.00	-0.06
	11	0.05	0.02	0.00	-0.04
	12	0.10	0.04	0.01	0.01
EXP	1	0.03	0.02	0.01	0.03
	2	0.05	0.02	0.01	0.01
	3	0.28	0.18	0.05	0.06
	4	0.19	0.13	0.02	0.10
	5	0.03	0.01	0.00	0.05
	6	0.08	0.04	0.00	0.05
	7	0.13	0.05	0.00	0.04
	8	0.01	0.01	0.00	0.00
	9	-0.12	-0.05	0.00	-0.04
	10	0.01	0.00	0.00	0.00
	11	0.02	0.01	0.00	0.01
	12	0.05	0.02	0.01	0.04

Table 29. Relative changes (%) in mean streamflow, mean sediment and mean nutrient loads for the watershed due to land use change scenarios, compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow	Sediments	Total P	NO_3^--N
HIST	1	1	1	22	0
	2	1	0	25	-1
	3	2	3	29	-2
	4	1	2	20	-1
	5	0	0	1	-2
	6	3	3	5	-3
	7	9	9	13	8
	8	2	2	3	0
	9	-2	-2	-1	-4
	10	0	0	4	-2
	11	0	0	7	-1
	12	1	1	19	0
EXP	1	0	0	19	1
	2	1	1	20	1
	3	1	1	25	2
	4	1	1	19	3
	5	0	0	1	4
	6	2	3	4	6
	7	5	5	8	11
	8	0	1	2	1
	9	-2	-2	-1	-3
	10	0	0	4	0
	11	0	0	7	0
	12	0	0	18	1

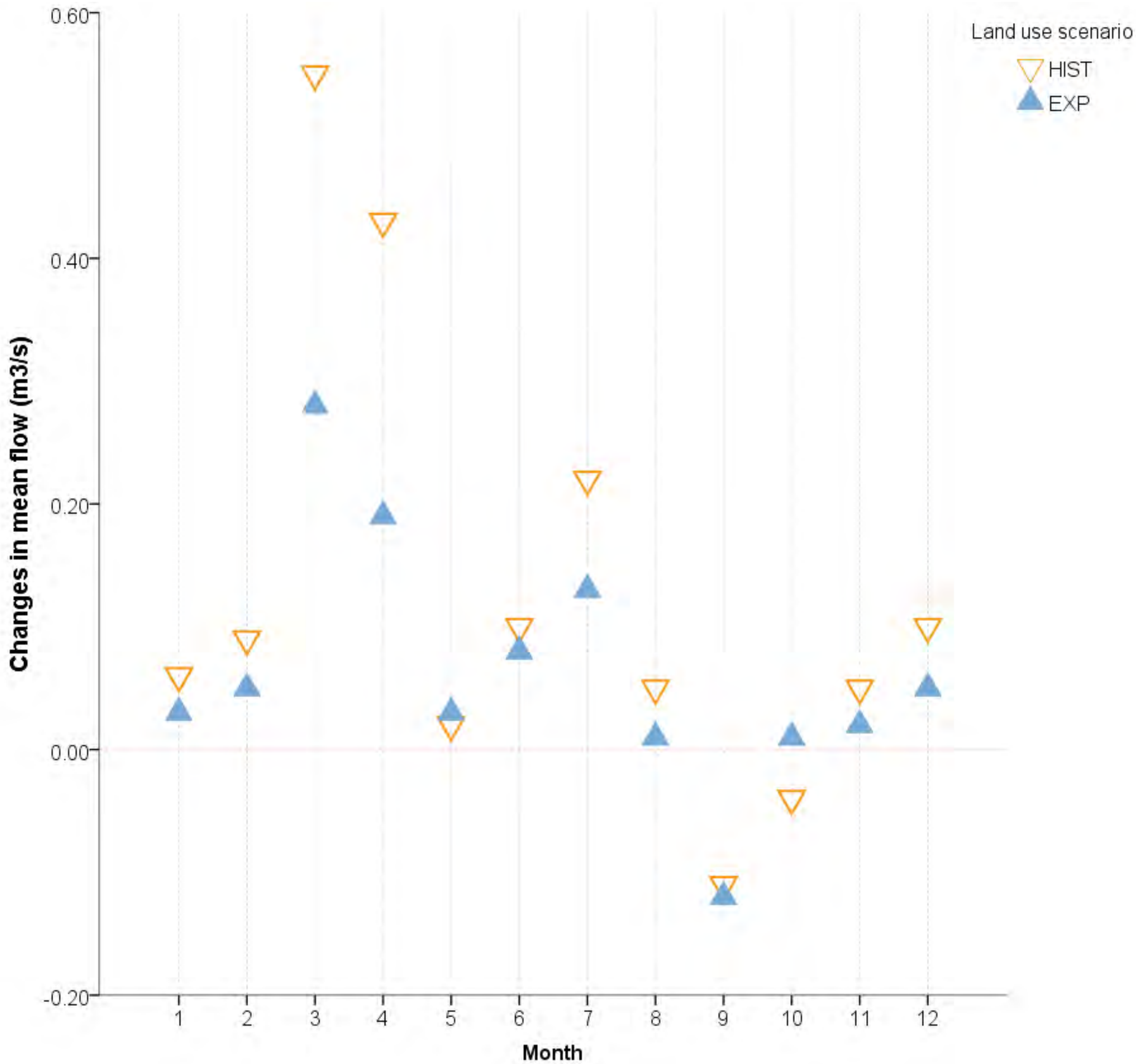


Figure 33. Changes in SWAT simulated mean monthly streamflow (m^3/s) for land use change scenarios with climate of 1971-2000, compared to the reference simulation (red zero line), at the basin outlet.

The land use scenarios (HIST or EXP) did not impact mean streamflow significantly, however some differences were apparent. The mean increases were of greater magnitude than the mean decreases. In most months, a mean increase in flow was simulated. The months of March and April showed the greatest mean increase in flow (0.19 to 0.55 m^3/s). Decreases in mean surface flow were simulated in the months of September for both scenarios (and in October for HIST) by 0.04 to 0.12 m^3/s. The flow increases in both scenarios can be attributed to greater surface runoff due increasing urban areas which provide more impervious surfaces.

The HIST scenario shows overall slightly higher streamflow. After 30 years, this scenario has less forest and rangeland area than EXP, and its total agricultural area increases by 2% in the watershed, whereas in the EXP scenario the area of agricultural land remains constant throughout the simulation period. Agricultural areas have been positively correlated to runoff. For example, in the Chaudière watershed, Quilbé et al. (2008) found a strong positive correlation between the area of agricultural land and the mean annual runoff, which they mainly attributed to the rangeland area being replaced by crop land.

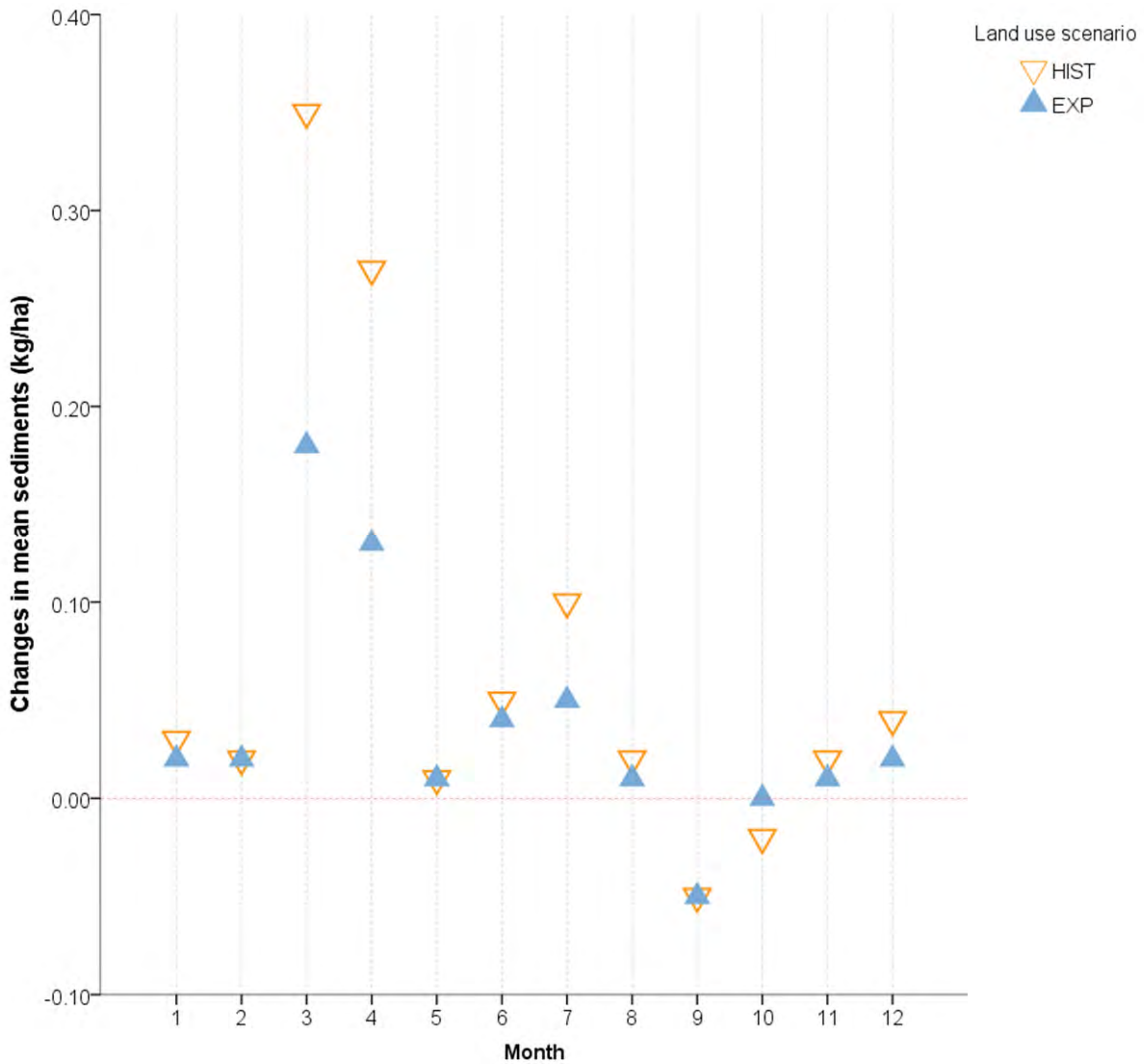


Figure 34. Changes in SWAT simulated mean monthly sediment loads (kg/ha) for land use change scenarios (2041-2070), compared to the reference simulation (red zero line), for the watershed.

The sediments loads are closely linked to streamflow in the land use change scenarios. The regression equation explaining sediment transportation was:

*sediment (kg/ha) = 0.52*flow (m^3/s) – 0.61* (Pearson's R=0.99, p<0.001). Comparing this equation to the regression for the climate simulations, it is evident that the same flow amount will transport more sediments in the climate change scenario. For example, with only climate simulations, a flow of 2 m^3/s will transport 0.73 kg/ha of sediment, yet will transport merely 0.43 kg/ha with the land use scenarios. In SWAT, the surface runoff volume and daily peak flow contribute to sediment transport. The surface runoff also contributes to streamflow. It is possible the regressions point to higher erosivity of surface runoff in a future climate. Further analysis on SWAT outputs would need to be carried out to determine if precipitation is linked to higher surface runoff volumes in the future.

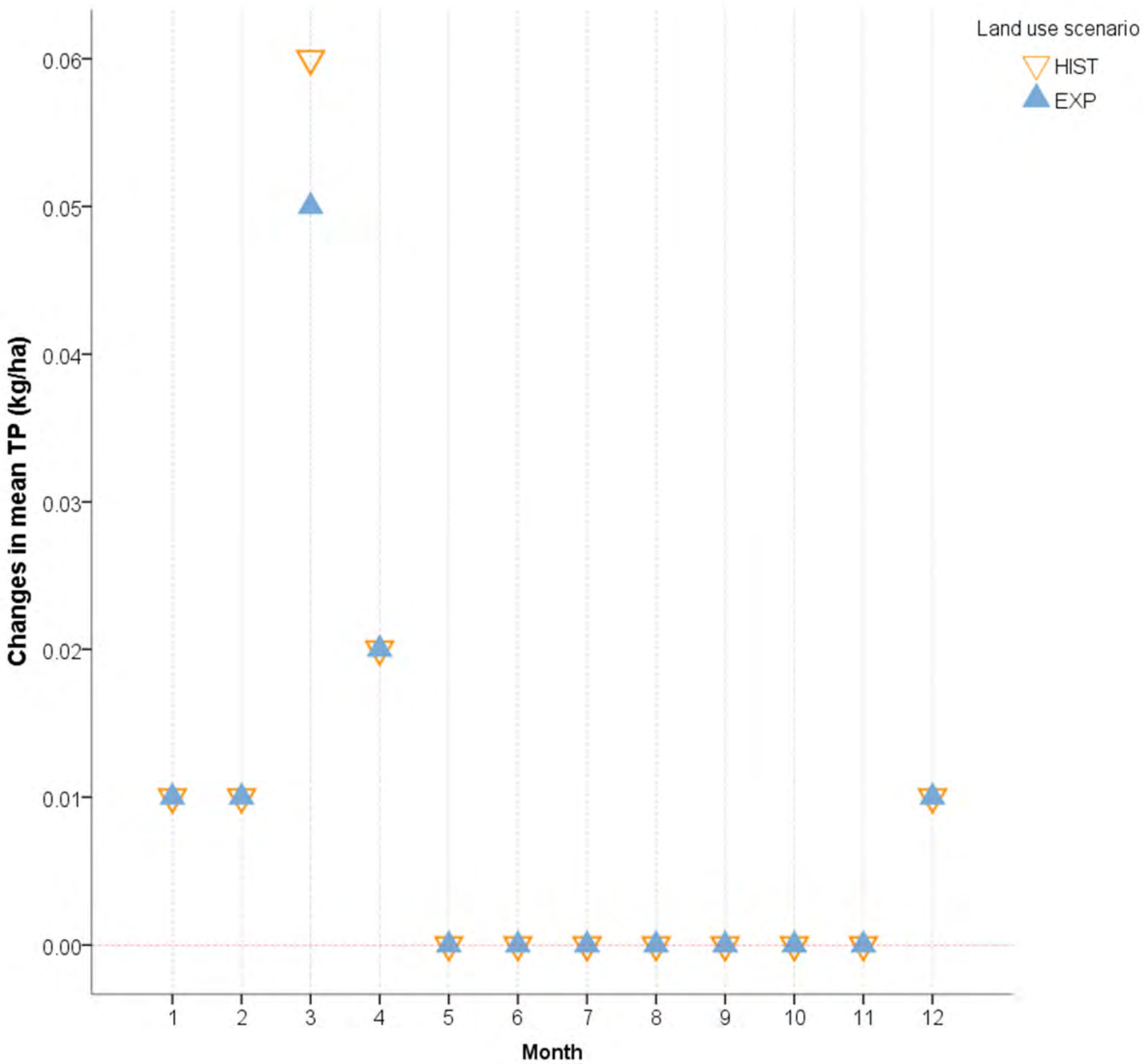


Figure 35. Changes in SWAT simulated mean monthly TP loads (kg/ha) for land use change scenarios (2041-2070), compared to the reference simulation (red zero line), for the watershed.

The mean TP loads change very little due to land use changes. During the months of December to April there are increases in TP loads (of 0.01 to 0.06 kg/ha), with the greatest increase occurring in March. This increase may be due to the decrease in winter wheat (cereal) areas in the HIST and EXP scenarios (-683 ha and -245 ha, respectively), which can act as a catch crop for nutrients in spring when the soil is otherwise bare. The increase in TP loads simulated during March is the same order of magnitude of change as observed with the climate change simulations. Otherwise there are no changes during the year. None of the changes are significant because of the large variation (±0.05 kg/ha each month).

The two land use scenarios also show almost no differences in terms of nutrient transport between each other. The simulated differences that are apparent compared to the reference simulation are due to the different crop configurations in the watershed which entail corresponding changes to the HRU areas, and involve adjusting the amounts of required fertilizer applications in each scenario.

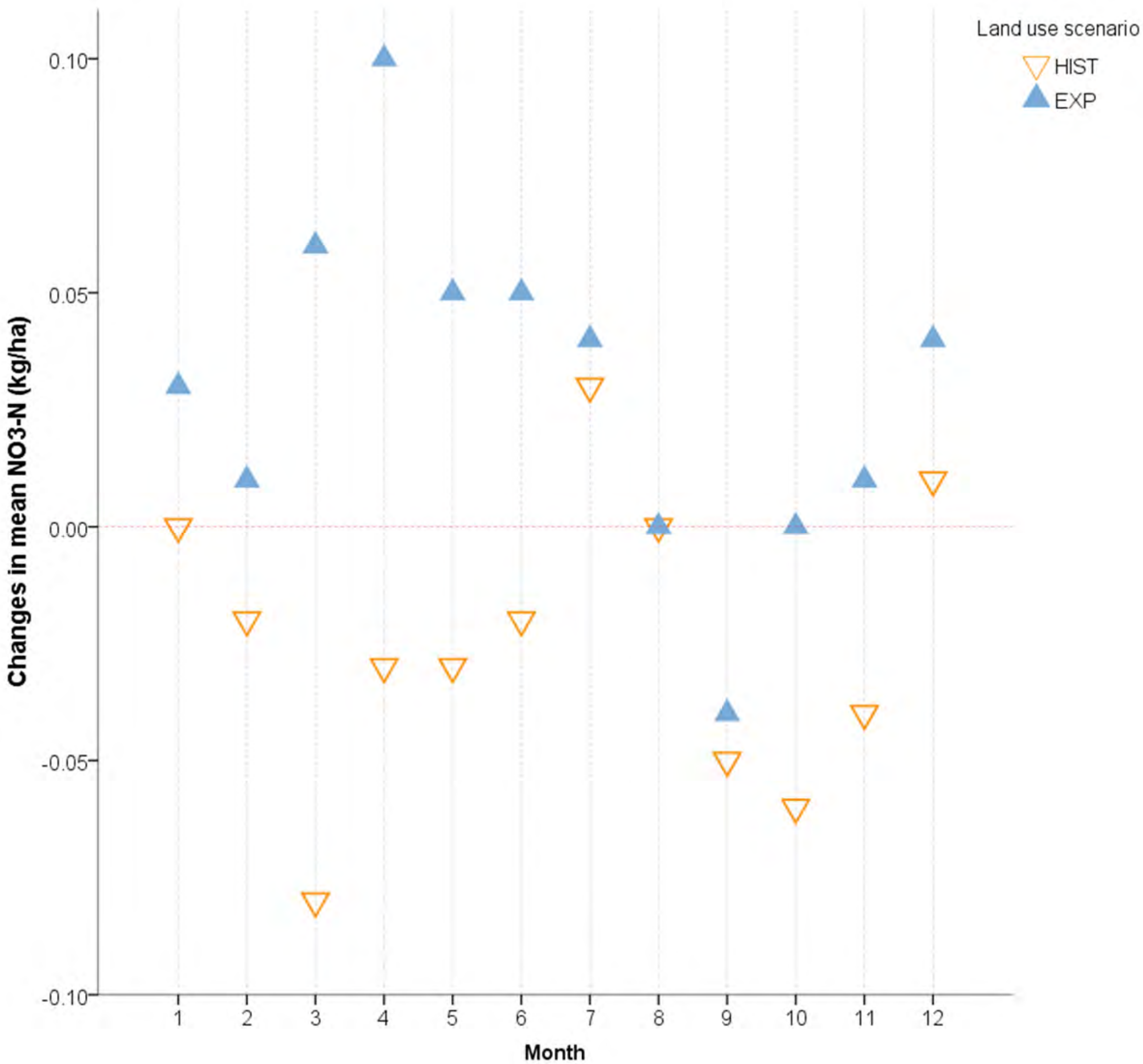


Figure 36. Changes in SWAT simulated mean monthly NO_3^--N loads (kg/ha) for land use change scenarios (2041-2070), compared to the reference simulation (red zero line), for the watershed.

The mean monthly changes in NO_3^--N loads show more variability than TP which may be due to the altering amounts of fertilizer applied each year to the differing crop areas. The EXP scenario has overall higher mean NO_3^--N loads being transported while the HIST shows decreases in mean loads, compared to the reference simulation. None of the changes are significant due to the high variability surrounding the mean values.

Compared to the reference simulation, the largest increase for the EXP takes place in April (up to 0.1 kg/ha) and the largest decreases occur in September (-0.04 kg/ha). These differences are about 10 times less than the changes that took place for the climate change simulations alone.

The HIST scenario overall shows less NO_3^--N loads than the EXP scenario. The largest decrease is in March of 0.08 kg/ha, likely related to the fact that after 30 years, the HIST scenario has a decrease in corn and “other ag land” (of 2892 ha) and an increase soybean area of 4757 ha (which requires no N fertilization), whereas the EXP scenario has an increase in corn and “other ag land” areas and a decrease in soybean area. Corn and “other ag land” are fertilized with 128 kg/ha of N fertilizer (Table 8). Thus, there is more N fertilizer going onto the EXP scenario which may end up in the ground- and surface water. However, once again, none of these differences are statistically significant when compared to the reference simulation.

The two scenarios did not differ significantly from each other in terms of how they impacted surface water quality. The scenarios were too similar to each other and their differences were not great enough from the reference simulation. Both scenarios were configurations of crops that were gradually and slightly altered over 30 years. For example, the percentage of forested area decreased in the HIST land use scenario by 0.8% and in the same scenario, rangeland decreased by 1.1%, corn decreased by 4.1%, soybean increased by 7.5% and the overall area under crop increased from 54.6% in 2011, to 56.5% in 2040. In the EXP scenario, the agricultural land area remained the same, but corn land increased by 1.5%, the “other ag land” decreased by 1%, soybean area increased by 0.1%. Otherwise, there were no drastic shifts in land use; this scenario was more about the spatial distribution of crops.

In summary, the two land use scenarios impacted streamflow and nutrient loads very little; all changes were not statistically significant ($p<0.05$). However, if current land use trends continue (HIST scenario), mean TP loads can increase in the months of December to April, at most by up to 0.06 (±0.05) kg/ha in March, and remain unchanged for most of the rest of the year. The mean monthly NO_3^--N loads are more variable and can increase by 0.03 (± 0.09) in July, and decrease for most of the rest of the year, by up to 0.08 (±0.43) in March.

In the EXP scenario, mean TP loads increased from December to April, by a maximum of 0.05 (±0.05) kg/ha in March, and remain unchanged for most of the rest of the year. The mean NO_3^--N loads can increase during most months of the year (up to 0.1 kg/ha ±0.37 in March), and decrease by 0.36 (±0.31) kg/ha in September.

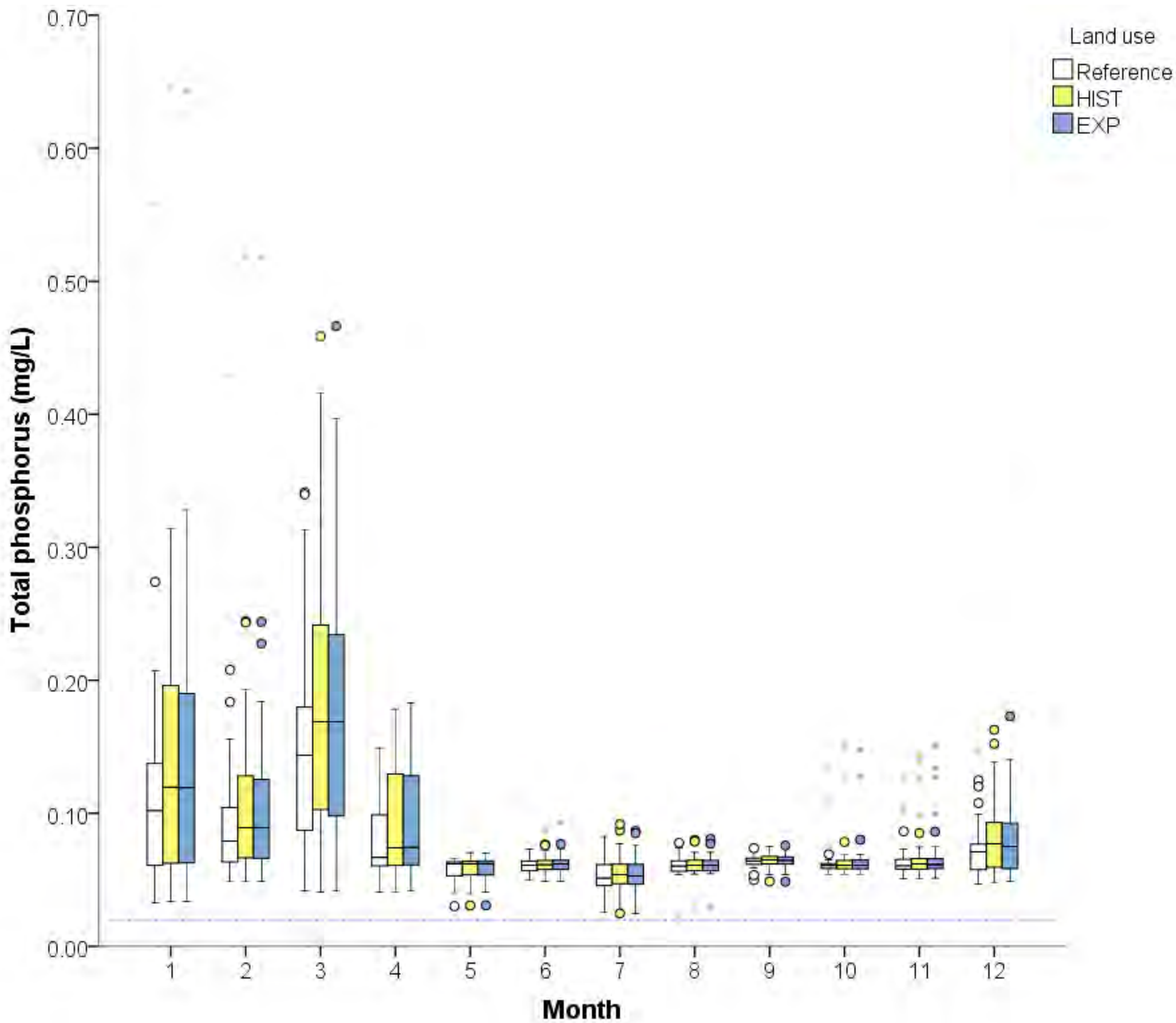


Figure 37. Concentration of SWAT simulated TP (mg/L), at the basin outlet for the land use change scenarios (2041-2070; coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 0.02 mg/L.

Mean monthly streamflow was little impacted by land use changes. The median values were relatively similar (Table 30) and no significant differences were found, partly because of the high standard errors found for the land use change scenarios in most months (which represent the inter annual variability).

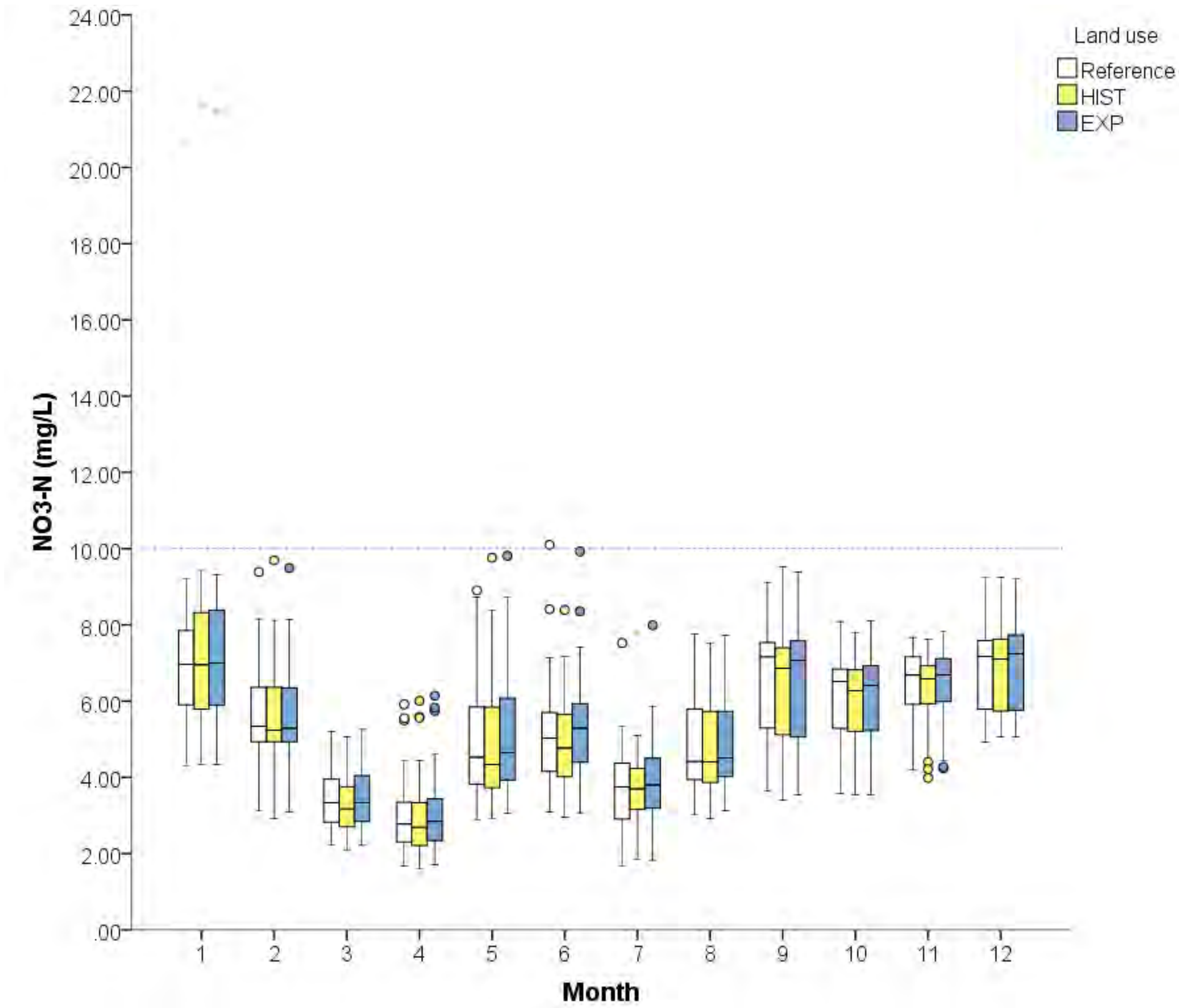


Figure 38. Concentration of SWAT simulated NO_3^--N (mg/L), at the basin outlet for the land use change scenarios (2041-2070; coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 10.0 mg/L.

For both future land use scenarios, the simulated in-stream concentrations of nutrients were similar as for the reference simulation, and neither mean monthly TP nor NO_3^--N concentrations were significantly different ($p<0.05$) than the reference simulation for any of the months.

The water quality criterion for TP was not met by the changes in land use; the mean monthly values were always above 0.02 mg/L. On the other hand, the mean monthly values for water quality criterion of 10 mg/L for NO_3^--N was only exceeded in three cases, all in January; once by each of the land use change scenarios once, and once by the reference simulation.

In summary, due to the conservative changes in the land use scenarios and the high inter-annual variability exhibited, they had little impact on water quality concentrations of TP or NO_3^--N. The median values were similar to the reference simulation and the water quality was not improved or deteriorated to any significant extent.

Table 30. Median nutrient concentrations (mg/L) at the outlet for the reference simulation and the land use change scenarios (1971-2000).

	Month	Total P (mg/L)	NO_3^--N (mg/L)
Reference	1	0.10	6.96
	2	0.08	5.34
	3	0.14	3.33
	4	0.07	2.77
	5	0.06	4.53
	6	0.06	5.03
	7	0.05	3.76
	8	0.06	4.42
	9	0.06	7.16
	10	0.06	6.51
	11	0.06	6.68
	12	0.07	7.14
HIST	1	0.12	6.95
	2	0.09	5.24
	3	0.17	3.18
	4	0.07	2.69
	5	0.06	4.33
	6	0.06	4.77
	7	0.05	3.70
	8	0.06	4.40
	9	0.07	6.86
	10	0.06	6.28
	11	0.06	6.58
	12	0.07	7.18
EXP	1	0.12	7.0
	2	0.09	5.29
	3	0.17	3.33
	4	0.08	2.84
	5	0.06	4.65
	6	0.06	5.29
	7	0.05	3.80
	8	0.06	4.52
	9	0.07	7.06
	10	0.06	6.41
	11	0.06	6.69
	12	0.08	7.24

6.3.2.2. Water quality due to the “extreme” land use scenarios:

The extreme scenarios depict how the nutrient loads and concentrations could be expected to react in SWAT if land use was changed drastically. These were represented by two extreme scenarios: the watershed is covered entirely in forest, except for the urban and water areas; and the entire watershed was planted to corn, again leaving only the urban area and the water area intact.

It should be noted that the extreme scenarios were not ideally represented in the SWAT model since the model was initially set-up for the land use of 1999. The extreme change in land use was altered in SWAT after the model was set-up for this reference simulation. The changes were carried out by modifying the crop types to either forest, or corn, which is not the standard procedure when examining hydrological responses since SWAT was not calibrated for these extreme scenarios and consequently some of the other crop parameters (e.g. evaporation coefficients, groundwater recharge, snowmelt coefficients, etc.) remained in the model although they may not be suited to appropriately portray the extreme scenarios. Nevertheless, these extreme scenarios are useful to determine an approximate range or extent to which the surface water quality can be altered by land use change alone.

After running the two extreme scenarios in SWAT, a calculation of the water balance was carried out to verify if the hydrological budget was being closed. From Table 31, the water balance in the CORN scenario was off by 5.7% which is still considered acceptable for the watershed (we strive for a value under 10%). The CORN water balance error was higher than for the FOREST scenario, which had a water balance error of 1.3% (this was comparable to the reference simulation of 1%), and is considered to be very good (all simulated water balances are provided in Appendix 7).

Table 31. Mean annual water balance for the reference simulation and FOREST and CORN scenarios in SWAT: WB = Precipitation – evapotranspiration - surface runoff – subsurface flow - percolation to deep aquifer.

	Precipitation (mm)	Evapo-transpiration (mm)	Surface runoff (mm)	Subsurface flow (mm)	Percolation to deep aquifer (mm)	Water balance (mm)
Reference	1184	567	29	482	118	12
FOREST	1184	633.4	4	407	125	15
CORN	1184	533.8	74	560	84	67

The changes brought about in mean flow, mean TP and mean NO_3^--N loads are presented, followed by the concentration of TP and NO_3^--N in the surface water.

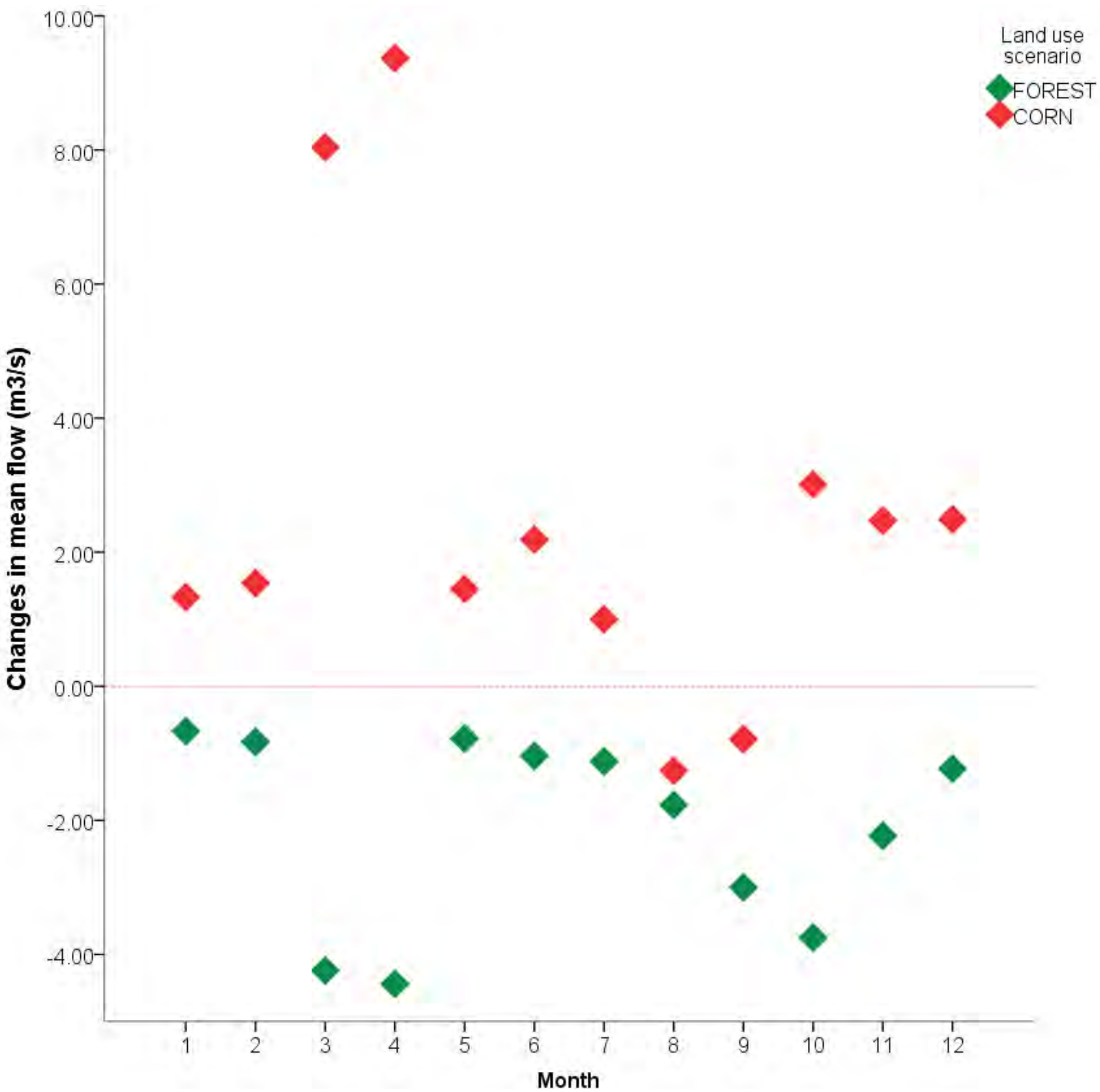


Figure 39. Changes in SWAT simulated mean monthly streamflow (m^3/s) for "extreme" land use change scenarios with climate of 1971-2000, compared to the reference simulation (red zero line), at the basin outlet.

Corn is a crop which has one of the widest row-spacing (75 cm), and also has very shallow roots; both these factors are conducive to surface runoff, rill erosion and low infiltration. Thus, for the CORN scenario, the mean streamflow was higher every month compared to the reference simulation (by up to 9.37 m^3/s in April), except in August and September (-1.26 m^3/s and -0.79 m^3/s, respectively). These months have less baseflow (aquifer recharge) available to sustain the summer low flows (Table 31) because of low groundwater recharge due to higher runoff.

The FOREST scenario always has lower mean streamflow amounts than the CORN and the reference simulation (by up to -4.44 m^3/s compared to the reference simulation in April). Forested land cover has more interception and deeper roots to allow for more infiltration and deeper seepage than corn does. Trees also consume more water than crops, lowering streamflow (Farley et al., 1995).

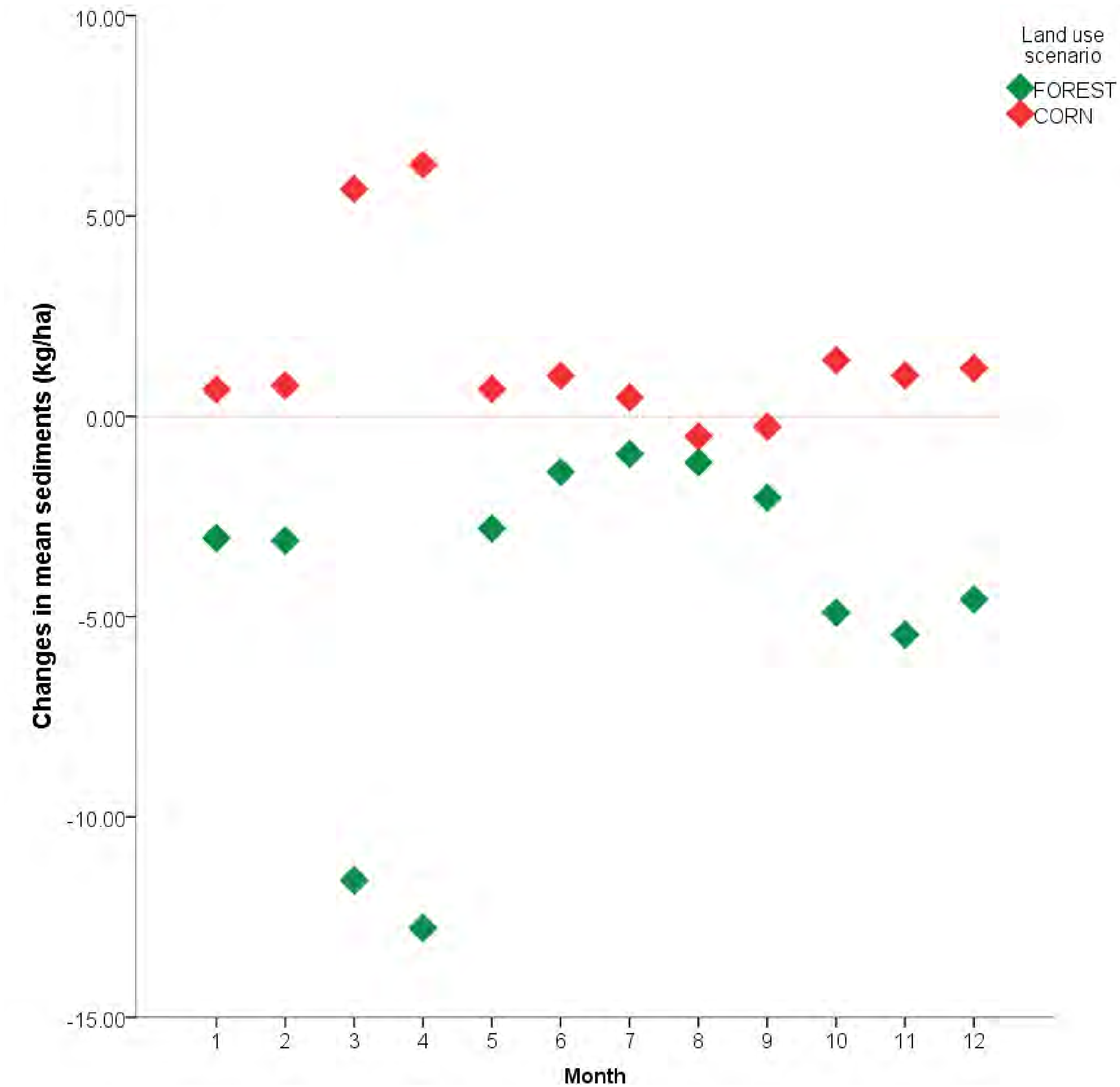


Figure 40. Changes in SWAT simulated mean monthly total sediment loads (kg/ha) for "extreme" land use change scenarios with climate of 1971-2000, compared to the reference simulation (red zero line), at the basin outlet.

The mean sediment loads transported in the CORN scenario are generally higher than in the reference simulation, especially during the spring, of up to 6.28 kg/ha higher in April. During the months of August and September there are somewhat less mean sediment loads than in the reference simulation, which is related to the lower mean streamflows during these months.

As expected, the mean sediments loads in the FOREST scenario are always lower than in the reference simulation and in the CORN scenario. During spring snowmelt, the mean sediment loads decrease the most in FOREST, by up to 12.8 kg/ha less than the reference simulation.

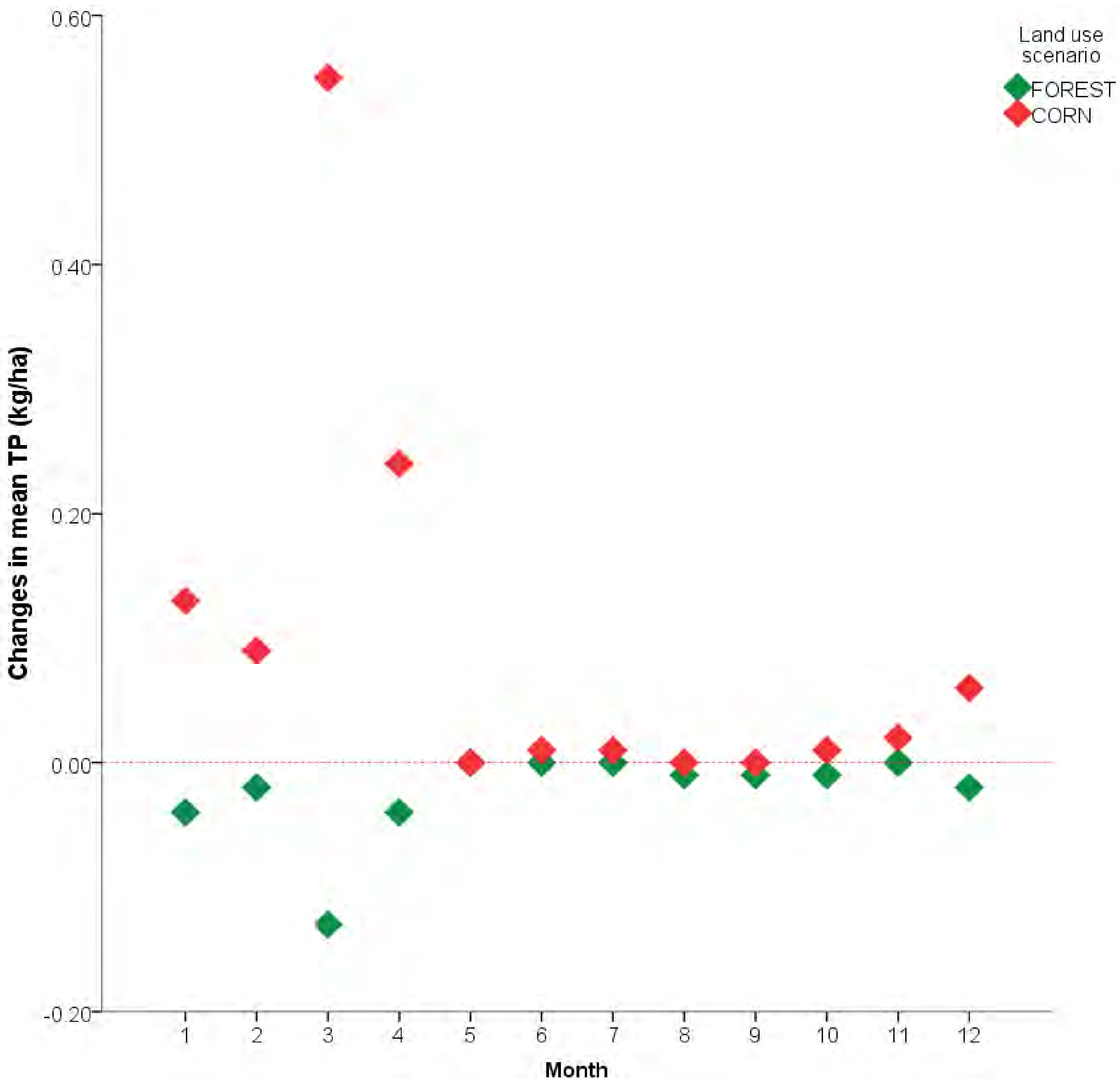


Figure 41. Changes in SWAT simulated mean monthly TP loads (kg/ha) for "extreme" land use change scenarios with climate of 1971-2000, compared to the reference simulation (red zero line), at the basin outlet.

The mean TP loads in the CORN scenario are higher than the reference simulation and FOREST scenario. The greatest mean increase occurs during snowmelt in March, where mean differences are +0.55 kg/ha. As in the other scenarios, few changes occur from May to November.

The FOREST scenario shows lower TP loads than the CORN scenario (except in May when they are similar). Compared to the reference simulation, the largest mean decrease in TP loads occurs during the March snowmelt, which shows a decrease of 0.13 kg/ha.

The difference in TP loads transported between the two scenarios from May to September is minimal, so that any change in land use will not make a significant difference during this period. According to the SWAT model, most of the TP transport reductions with land use change can be achieved during December to April.

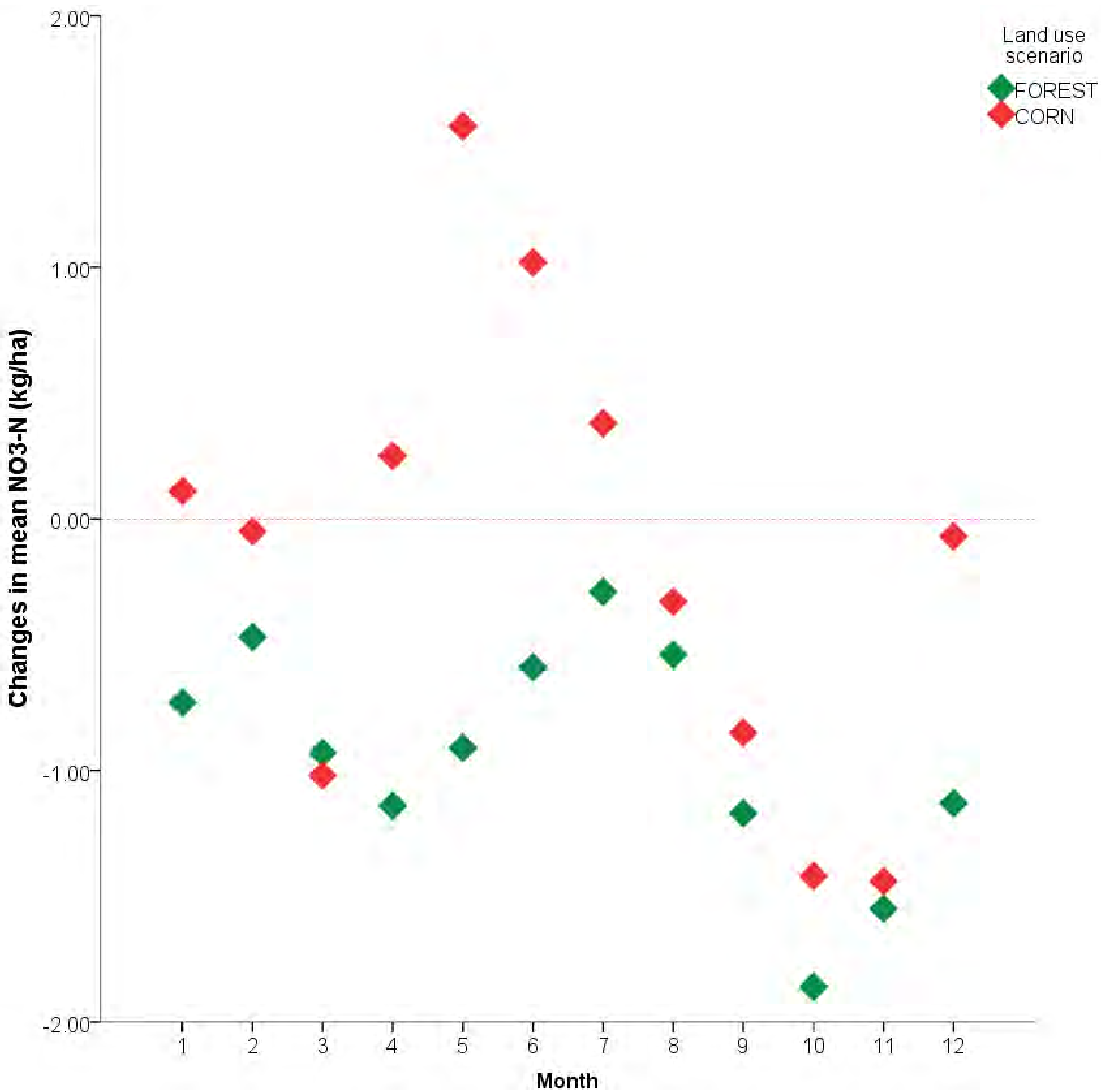


Figure 42. Changes in SWAT simulated mean monthly NO_3^--N loads (kg/ha) for "extreme" land use change scenarios with climate of 1971-2000, compared to the reference simulation (red zero line), at the basin outlet.

The mean monthly NO_3^--N loads were higher in the CORN, than in the FOREST, except for the month of March. However, several (almost half) of the mean monthly NO_3^--N loads in CORN were lower than for the reference simulation. The CORN is fertilized in April each year, and may explain the spike of loads seen in May (mean loads +1.56 kg/ha than the reference). From then, mean NO_3^--N loads decline which is a function of the soil N being depleted by this point (mean loads -1.44 kg/ha) until the next N application, in October, from whereon levels increase until December and remain more or less stable (and comparable to the reference simulation). By March, the soil nitrate levels are again low due to NO_3^--N being constantly leached and not being replenished (comparable to the FOREST scenario; of -1.02 kg/ha than the reference simulation).

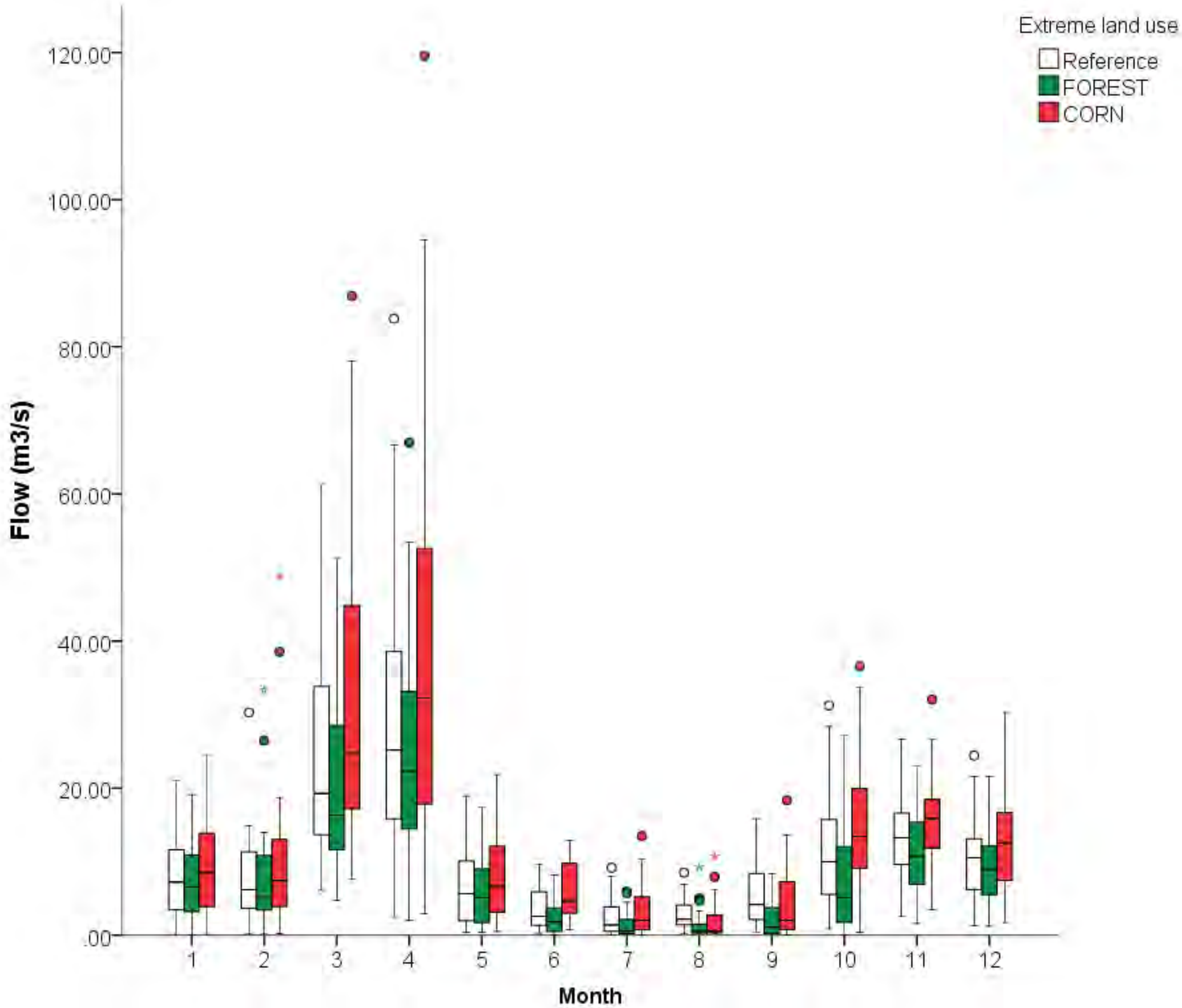


Figure 43. Simulated streamflow (m^3/s) at the basin outlet for the "extreme" land use change scenarios (colored boxes), compared to the reference simulation (white boxes).

The months of July, August and September in the FOREST have significantly lower mean flows than the reference simulation. Bosch and Hewlett (1982) found a tendency for water yield to decrease when forest vegetation was planted (up to five years after being planted), and research since then has well-established that afforestation decreases water yield (e.g. Farley et al., 2005).

The CORN scenario has significantly higher mean flows during March, April, June, July, September, October, November and December when compared to the FOREST scenario.

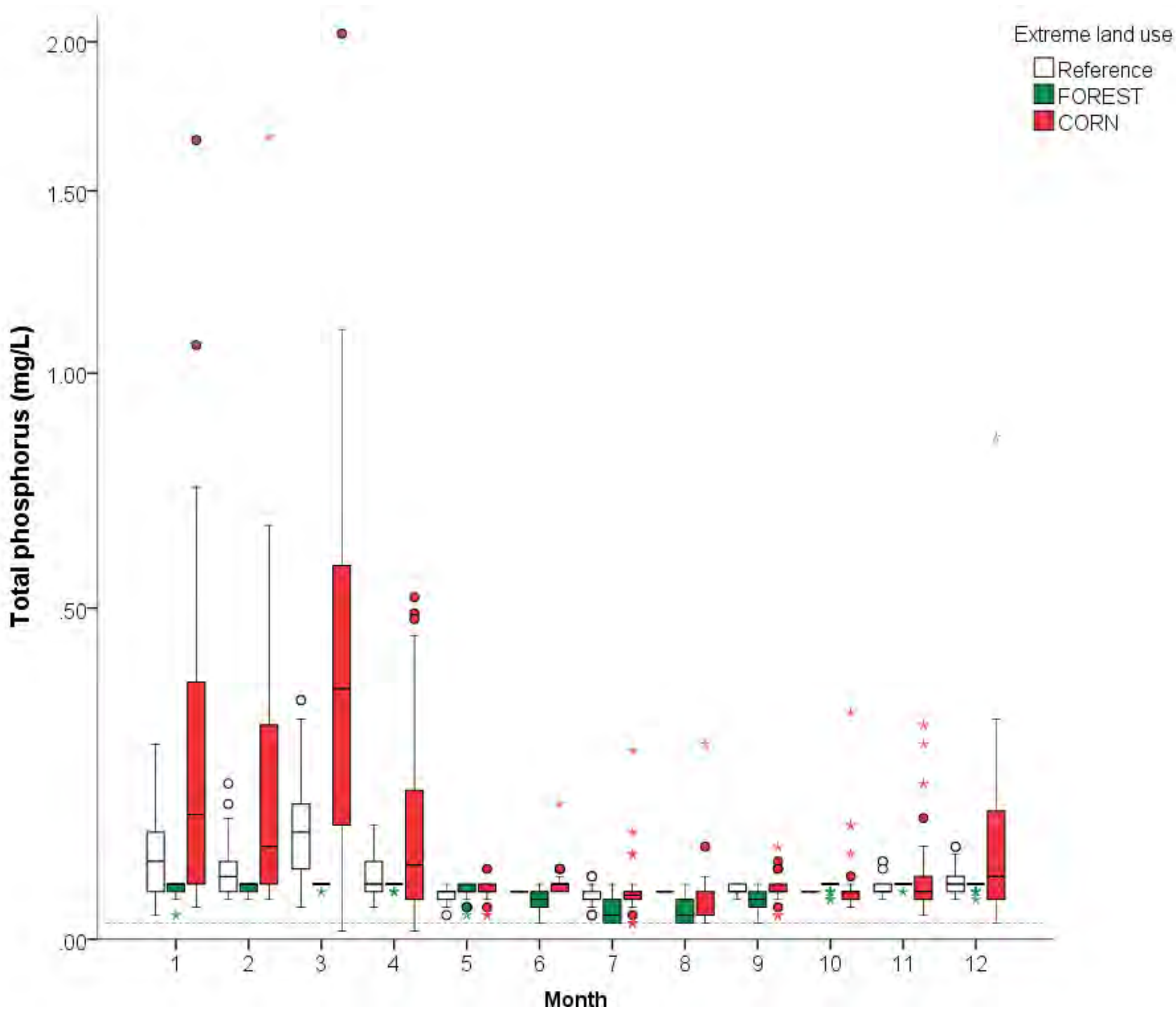


Figure 44. Concentration of simulated TP (mg/L, exponential scale), at the basin outlet for the "extreme" land use change scenarios (coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 0.02 mg/L.

Compared to the reference simulation, the CORN scenario has high variability and significantly higher mean TP concentrations in January to April when the soil is bare and prone to surface runoff, and in June to July after fertilizer application, when the corn is just starting to grow.

The FOREST scenario has low variability and significantly lower mean TP concentrations than the reference simulation in most months, except for the months of April, May, October, November and December. The mean monthly FOREST scenario values were able to attain the water quality criterion of TP concentrations of 0.02 mg/L in 8 months out of the 30 years. This result can be improved if the model was calibrated for a forest scenario; we feel this is likely influenced by the limitation of the SWAT model set-up. For example, the parameter GWSOLP dictates the concentration of P in the groundwater and was not changed from the agricultural land inflows.

The mean monthly values for CORN attained TP 0.02 mg/L 14 times in 30 years. Corn is a nutrient intensive crop and will deplete the soil nutrients if insufficient N amounts are applied.

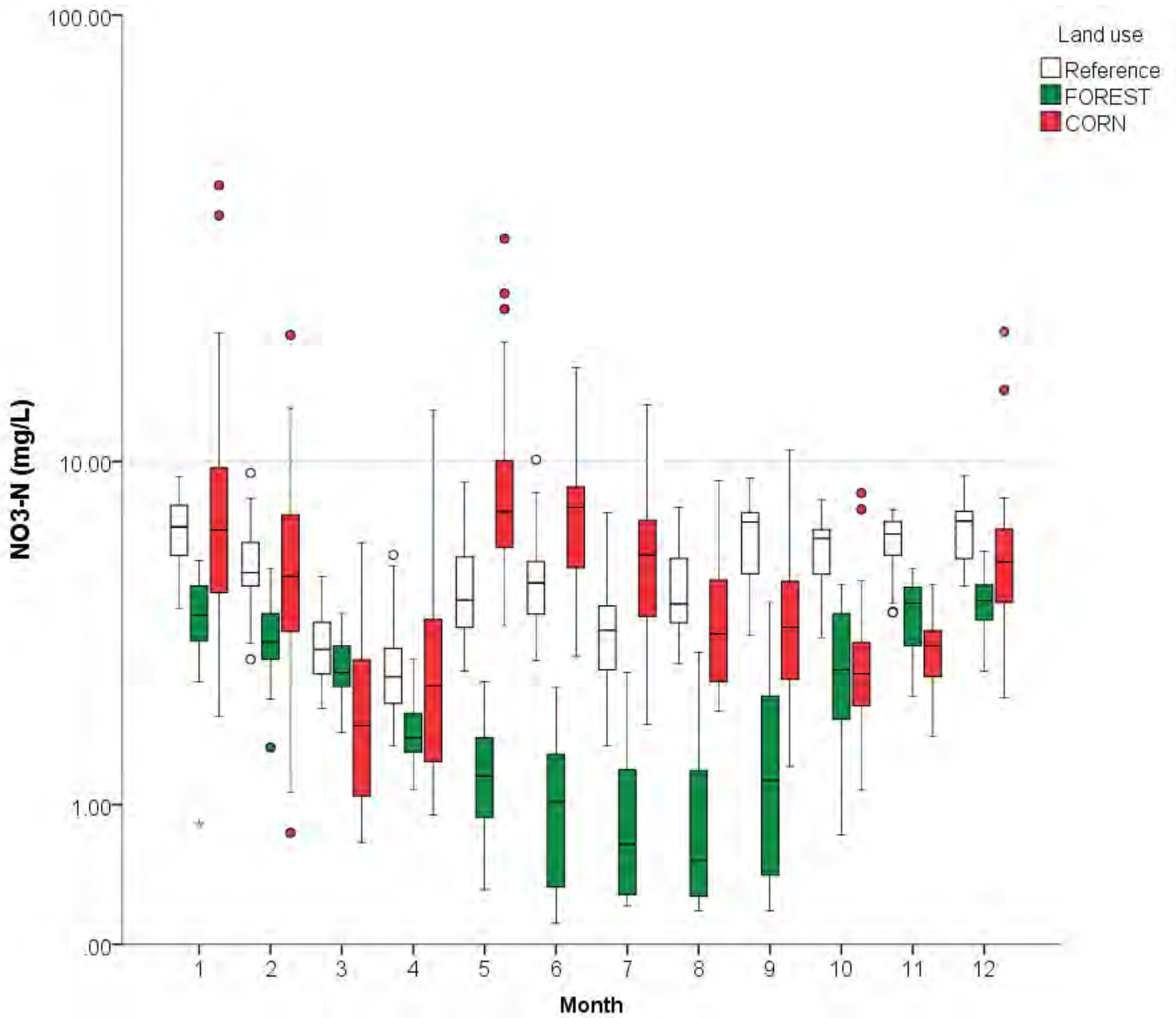


Figure 45. Concentration of simulated NO_3^--N (mg/L, exponential scale), at the basin outlet for the “extreme” land use change scenarios (coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 10.0 mg/L.

The FOREST scenario significantly improved the mean concentration of NO_3^--N in every month and never exceeded 10 mg/L.

For CORN, the mean concentration of NO_3^--N exceeds the water quality criterion of 10 mg/L often. The area of maize cropland has been strongly correlated to nitrogen and phosphorus amounts in surrounding water bodies (Donner, 2003). Overall, CORN negatively affected water quality while FOREST improved it. The mean concentrations of TP and NO_3^--N were significantly different between FOREST and CORN, (except for mean TP concentrations in May, August, October and November. And mean NO_3^--N concentrations in October).

It should be kept in the mind that the reference simulation may have conditions in which too much N and P fertilizer is being applied. Thus, the reference simulation can have improvements that reduce its non-point source pollution. We have graphically presented the breadth of the nutrient simulations that can be attained by the simulations using our SWAT model set-up.

6.3.3. Water quality resulting from both climate change and land use change impacts

To determine the combined impacts of both climate change and land use change on the future surface water quality in the Pike River, four simulations were carried out with SWAT consisting of a combination of two climate change simulations and two land use change scenarios.

All three climate simulations, ACU, AGR and AHK, impacted water quantity as well as water quality. The climate simulations ACU and AGR had rather similar impacts on nutrients; however AGR tended to simulate the lowest changes in streamflow and nutrients. On the other hand, AHK simulated the most opposing results (i.e. it set the upper boundaries of change) in sediment and nutrient transport, especially in the winter and spring months.

Two climate simulations had to be chosen to combine with the land use scenarios. In order to narrow down the choices, we looked for the greatest range of possibilities covered by the outcomes. Hence, after consultation with the stakeholders and Ouranos, it was agreed that the AGR and AHK climate simulations should be retained for further analysis because they provided the lower and upper limits, respectively, of change from the available climate simulations. These two climate simulations were combined in SWAT, in conjunction with the two “realistic” land use change scenarios, respectively.

Table 32. Combination of climate change simulations and land use change scenarios modelled.

	Climate change simulations:	
	AGR	AHK
Land use change scenario:		
Historical Trends Continue	AGR_HIST	AHK_HIST
Expert Guided	AGR_EXP	AHK_EXP

For each simulation in the matrix (Table 32), the mean annual streamflow, sediment load, TP and NO_3^--N loads were calculated. The inter-annual variability was quite high (Table 33), especially for the nutrients. Compared to the reference simulation, the mean annual streamflow was approximately 1 m^3/s higher. The mean sediment, TP and NO_3^--N loads were also higher than the reference simulation, yet none of the mean annual nutrient values were significantly different than the reference simulation. The mean annual differences between the combined scenarios and the reference simulation are presented in Table 34.

Table 33. Mean annual simulated streamflow, sediment, TP and NO_3^--N loads (with standard deviations) at outlet 23 for the reference simulation (1971-2000) and the combined climate and land use change scenarios (2041-2070).

	Flow (m^3/s)	Sediments Mg/yr	TP Mg/yr	NO_3^--N Mg/yr
Reference	10.6 ±2.1	3740.8 ±885.3	35.5 ±13.2	1530.4 ±289.5
AGR_EXP	11.7 ±1.9	4020.8 ±649.3	43.9 ±15.0	1627.3 ±281.5
AGR_HIST	11.8 ±1.9	4042.1 ±656.1	44.3 ±15.0	1589.8 ±268.6
AHK_EXP	11.5 ±2.2	3908.6 ±817.3	41.7 ±19.8	1681.8 ±286.0
AHK_HIST	11.6 ±2.2	3927.8 ±823.2	42.1 ±19.6	1639.7 ±272.2

Table 34. Annual mean changes (with standard errors) in the transportation of sediments, TP and NO_3^--N at outlet 23 due to the combined effects of climate and land use change (2041-2070).

	Sediments Mg/yr	TP Mg/yr	NO_3^--N Mg/yr
AGR_EXP	279.9 ±200.4	8.4 ±3.6	96.9 ±73.7
AGR_HIST	301.3 ±201.2	8.8 ±3.7	59.4 ±72.1
AHK_EXP	167.7 ±220.0	6.3 ±4.3	151.4 ±74.3
AHK_HIST	186.9 ±220.7	6.6 ±4.3	109.4 ±72.6

The analysis then focused on mean monthly values of model outputs, at the monthly time step significant differences from the reference simulation were found (Tables 35-36).

Table 35. Absolute changes in mean streamflow, mean sediment and mean nutrients for the watershed due to climate and land use change scenarios (2041-2070) compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow (m3/s)	Sediments (kg/ha)	Total P (kg/ha)	NO_3^--N (kg/ha)
AGR_EXP	1	8.07	3.82	0.07	1.32
	2	6.21	2.72	0.07	0.73
	3	-0.38	-0.86	0.01	-0.61
	4	-10.49	-5.85	-0.06	-1.01
	5	0.44	0.19	0.00	0.15
	6	-1.20	-0.54	0.00	-0.16
	7	-1.19	-0.53	-0.01	-0.16
	8	0.00	0.05	0.00	0.10
	9	1.71	0.81	0.01	0.17
	10	0.05	0.18	0.00	-0.28
	11	1.95	0.73	0.01	-0.04
	12	7.85	3.72	0.04	1.32
AGR_HIST	1	8.18	3.89	0.07	1.26
	2	6.31	2.74	0.07	0.67
	3	-0.14	-0.72	0.01	-0.72
	4	-10.39	-5.81	-0.06	-1.07
	5	0.46	0.19	0.00	0.07
	6	-1.16	-0.53	0.00	-0.19
	7	-1.16	-0.52	-0.01	-0.16
	8	0.02	0.05	0.00	0.09
	9	1.71	0.81	0.01	0.13
	10	0.01	0.15	0.00	-0.33
	11	2.01	0.76	0.01	-0.07
	12	7.95	3.76	0.04	1.28
AHK_EXP	1	3.66	1.93	0.05	0.57
	2	9.40	4.18	0.09	1.14
	3	-5.01	-3.32	-0.06	-0.99
	4	-14.89	-7.78	-0.07	-1.25
	5	1.10	0.48	0.01	0.19
	6	2.02	0.89	0.01	0.48
	7	-0.40	-0.27	0.00	0.09
	8	1.08	0.54	0.00	0.39
	9	2.98	1.46	0.02	0.54
	10	-1.44	-0.72	0.00	-0.60
	11	5.30	2.20	0.03	0.76
	12	6.54	3.06	0.03	1.07
AHK_HIST	1	3.73	1.96	0.05	0.52
	2	9.52	4.23	0.09	1.06
	3	-4.81	-3.25	-0.06	-1.09
	4	-14.84	-7.77	-0.07	-1.30
	5	1.10	0.49	0.01	0.09
	6	2.08	0.92	0.01	0.41
	7	-0.35	-0.24	0.00	0.08
	8	1.10	0.55	0.00	0.37
	9	2.97	1.45	0.02	0.49
	10	-1.49	-0.74	0.00	-0.65
	11	5.36	2.24	0.03	0.72
	12	6.62	3.10	0.03	1.03

Table 36. Relative changes (%) in mean streamflow, mean sediment and mean nutrient loads for the watershed due to climate and land use change scenarios (2041-2070), compared with the reference simulation (1971-2000). Green boxes denote a statistically significant change ($p<0.05$).

	Month	Flow	Sediments	Total P	NO_3^--N
AGR_EXP	1	103	111	121	64
	2	74	79	162	46
	3	-1	-7	3	-17
	4	-36	-41	-57	-34
	5	6	6	10	12
	6	-32	-36	-28	-20
	7	-47	-53	-51	-42
	8	0	4	4	15
	9	33	38	46	12
	10	0	3	10	-9
	11	15	12	22	-1
	12	73	74	90	45
AGR_HIST	1	104	113	125	61
	2	76	80	162	43
	3	-1	-6	5	-21
	4	-36	-41	-56	-36
	5	7	6	10	5
	6	-31	-35	-27	-25
	7	-46	-51	-50	-42
	8	1	4	4	13
	9	33	38	44	9
	10	0	3	8	-11
	11	15	13	23	-2
	12	74	75	89	43
AHK_EXP	1	47	56	86	28
	2	113	121	211	73
	3	-20	-26	-34	-28
	4	-51	-55	-64	-42
	5	16	16	37	14
	6	54	59	122	62
	7	-16	-26	-20	24
	8	35	44	41	60
	9	57	68	170	38
	10	-13	-14	0	-19
	11	40	37	72	22
	12	61	61	63	36
AHK_HIST	1	48	57	85	26
	2	114	123	218	67
	3	-19	-25	-32	-31
	4	-51	-55	-64	-43
	5	16	16	37	7
	6	56	61	132	53
	7	-14	-24	-18	21
	8	35	45	41	57
	9	57	68	163	34
	10	-13	-14	1	-21
	11	41	38	73	21
	12	62	62	64	35

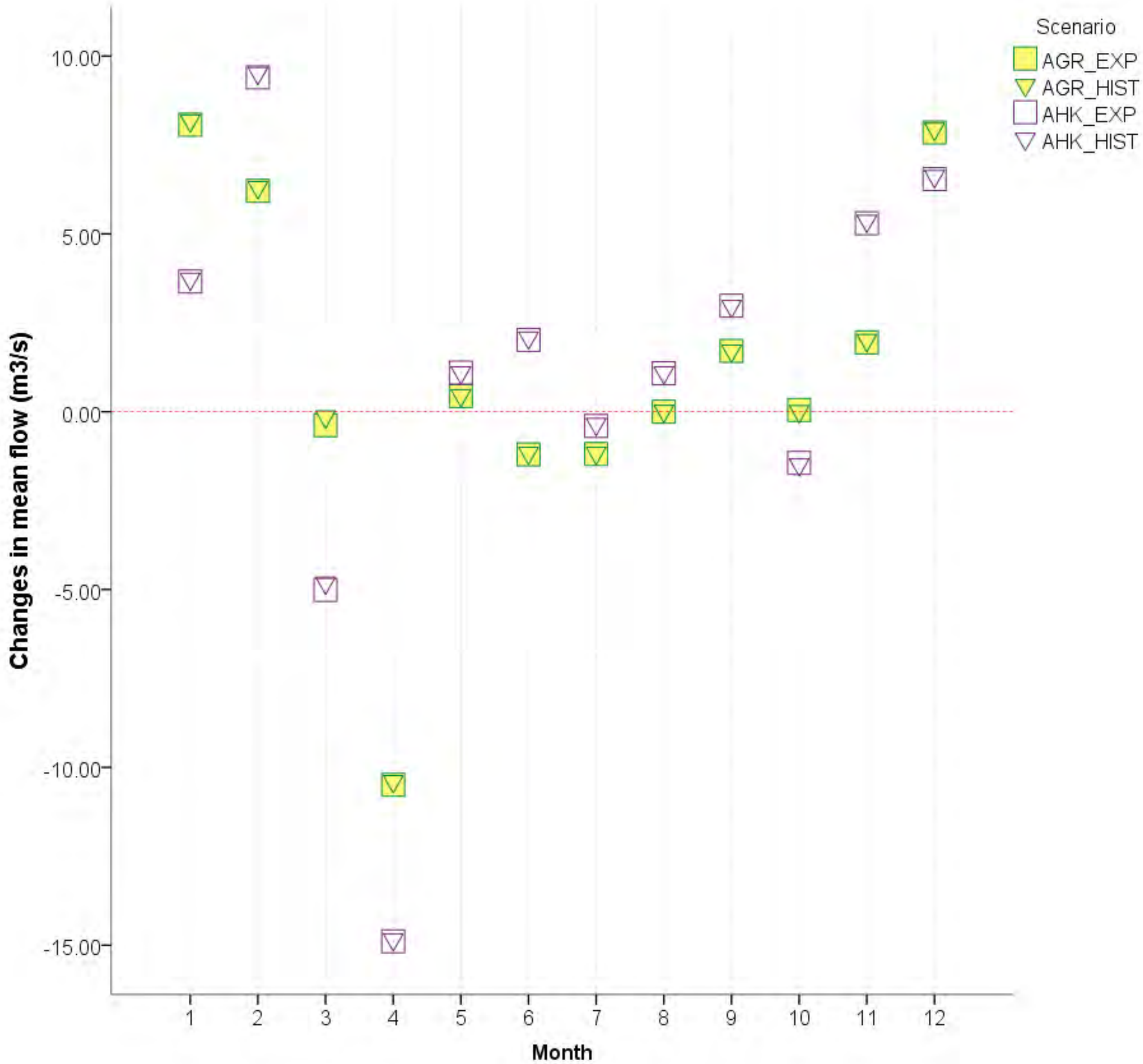


Figure 46. Changes in SWAT simulated mean monthly streamflow (m^3/s) for the climate change simulations combined with land use change scenarios, representing the period 2041-2070, compared to the reference simulation (red zero line), at the basin outlet.

The changes in mean streamflow were mostly increased in the combined scenarios of change, compared to the reference simulation. The greatest increase took place in February of 9.5 m^3/s. During March and April however there were mean decreases (of -15 m^3/s in April) due to the shift in earlier snowmelt. The climate change scenarios were driving the mean streamflow changes. The two land use scenarios produced very similar results with each of the climate simulations.

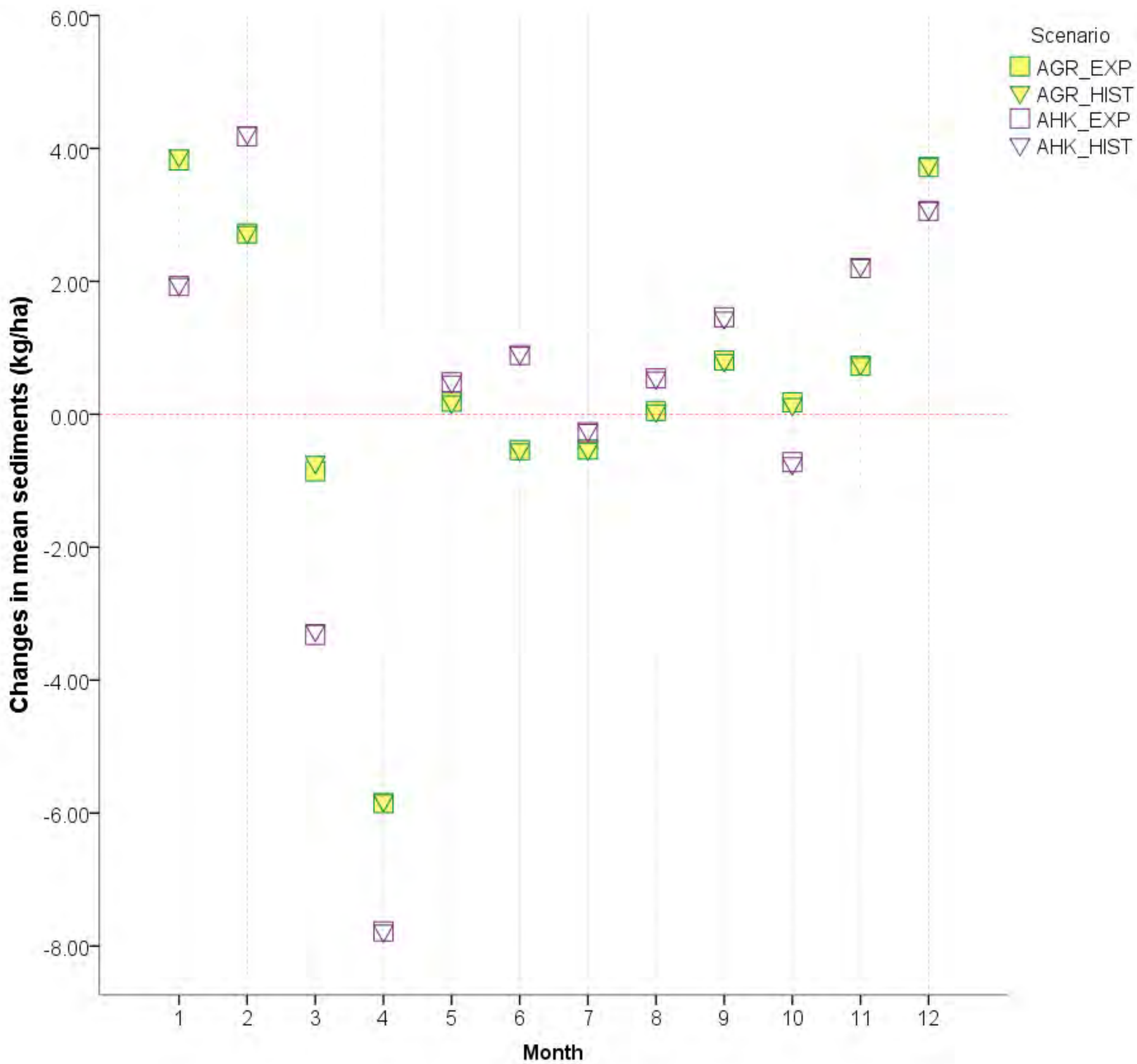


Figure 47. Changes in SWAT simulated mean monthly sediments (kg/ha) for the climate change simulations combined with land use change scenarios, representing the period 2041-2070, compared to the reference simulation (red zero line), for the watershed.

The change in mean monthly sediment loads followed the same pattern as for streamflow; February had the greatest mean increase of up to 4.23 kg/ha, and April the most mean decrease of almost 8 kg/ha. Once again, the streamflow was significantly correlated to sediment transport (Pearson's R = 0.99, p <0.001) and was explained by the following regression equation:

*sediment (kg/ha) = 0.47*flow* (m^3/s) *– 0.19*

which illustrates that with the same flow volume, more sediment is transported in the combined scenarios than with climate change simulations alone, or with land use change scenarios alone. For example, given a flow of 2 m^3/s, 0.75 kg/ha of sediment would be transported due to a combination of climate change and land use change, compared to 0.73 kg/ha and 0.43 kg/ha, with climate change alone and land use change alone, respectively.

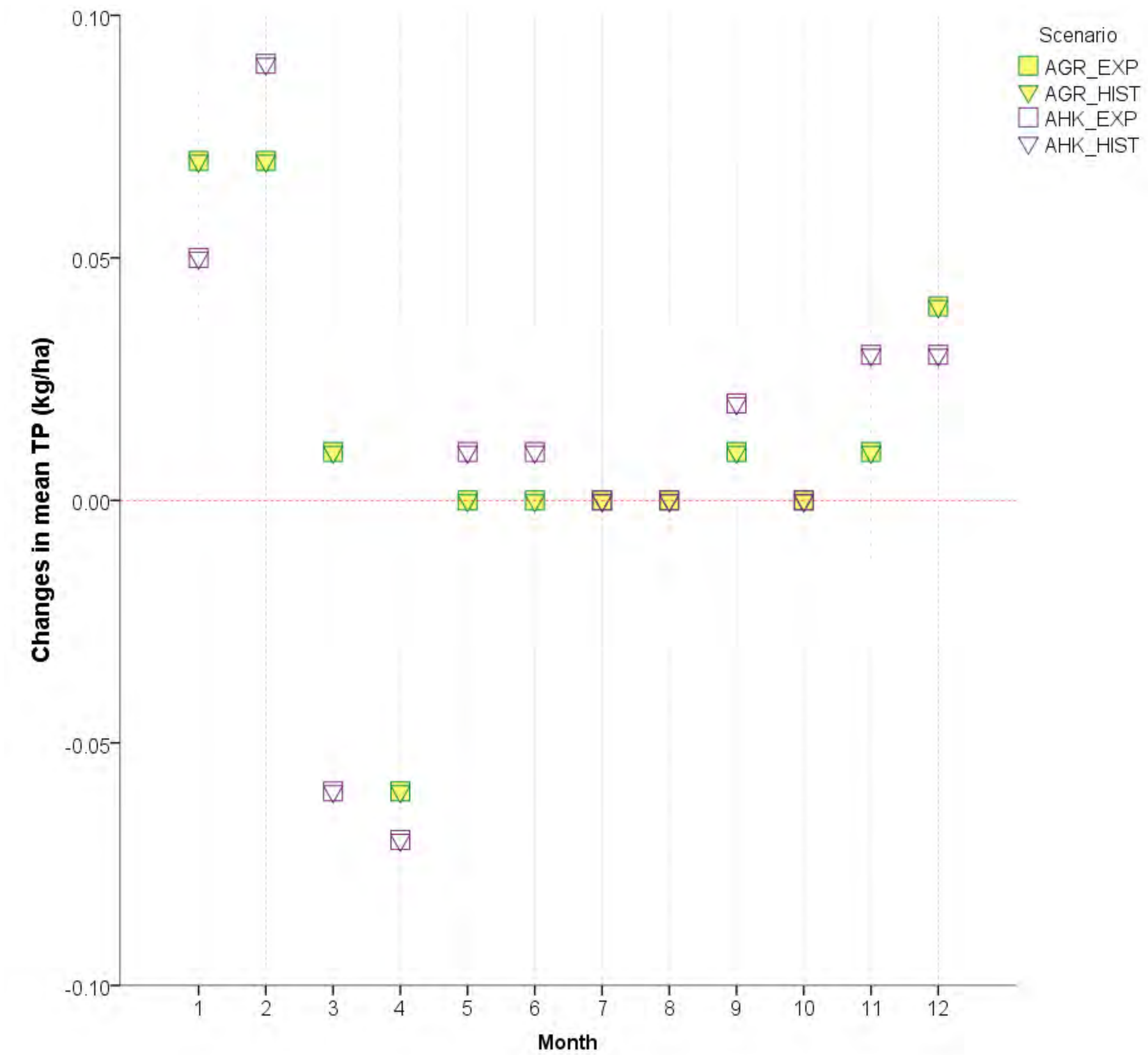


Figure 48. Changes in SWAT simulated mean monthly TP (kg/ha) for the climate change simulations combined with land use change scenarios, representing the period 2041-2070, compared to the reference simulation (red zero line), for the watershed.

The changes to mean TP loads were again mainly driven by the climate change simulations. However the months with significant mean changes were not necessarily the same as when climate change alone was simulated (see Figure 35). For example the mean TP load for AGR_EXP was significantly higher (0.03 kg/ha) than the reference simulation in December, whereas the mean TP load differences in the AGR simulation alone, and in the EXP simulation alone, were not significant in December.

In three of the months (July, August and October) there was no difference in any of the future scenarios, compared with the reference simulation. This was similar to what was found with the climate simulations alone.

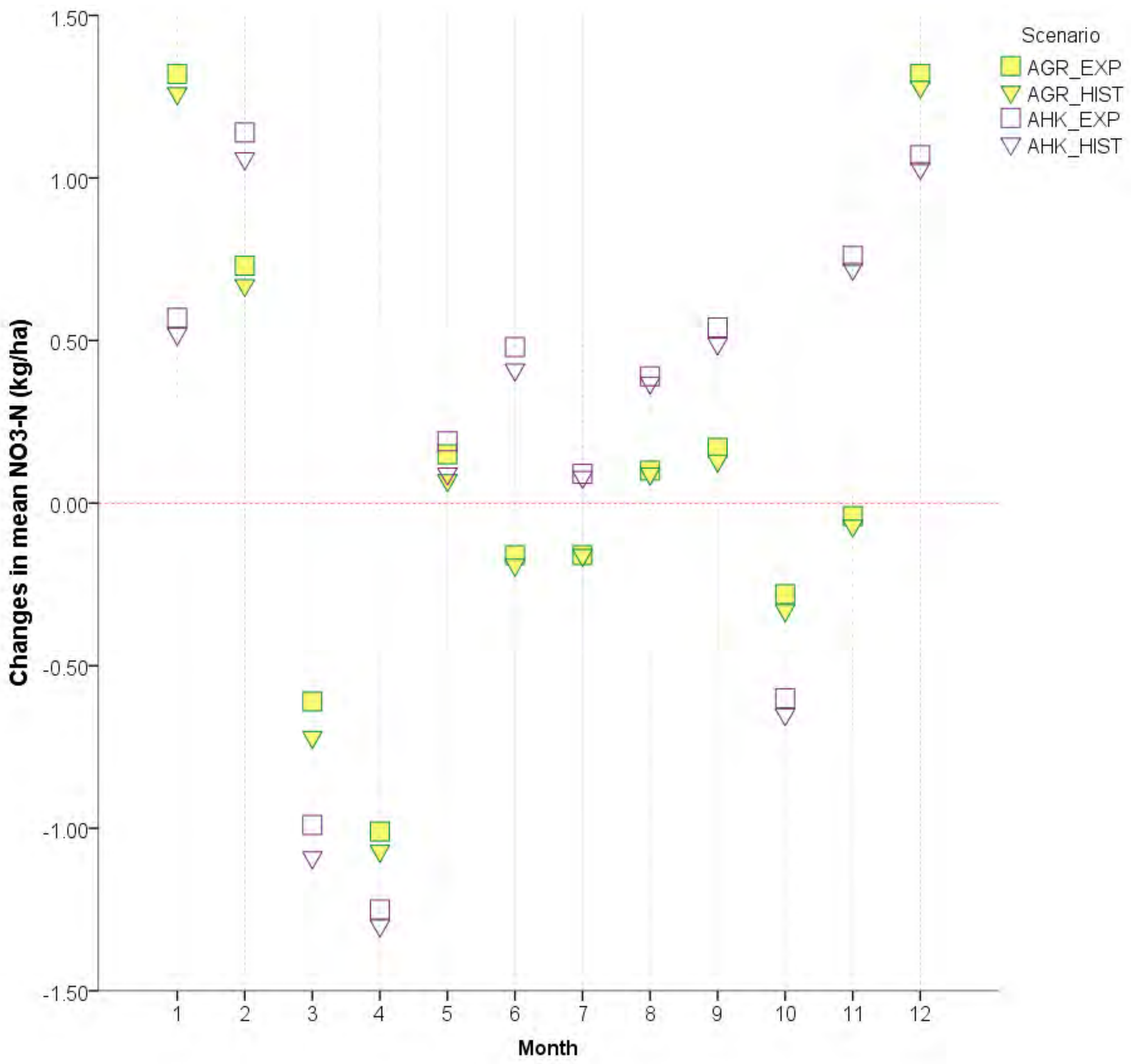


Figure 49. Changes in SWAT simulated mean monthly NO_3^--N (kg/ha) for the climate change simulations combined with land use change scenarios, representing the period 2041-2070, compared to the reference simulation (red zero line), for the watershed.

The land use scenarios in combination with climate change simulations have an influence on the mean monthly NO_3^--N loads. Overall, the mean loads for the EXP scenario combined with climate change are mostly higher than the HIST scenario combined with climate change. As was also observed in the simulations with the land use change scenarios alone; the EXP had higher mean changes that the HIST scenario (Figure 36).

The mean monthly changes in the NO_3^--N loads followed a similar pattern as the climate change simulations alone, yet there were differences. For example, the mean load for AHK_EXP had a significantly higher mean change (0.48 kg/ha) in June, which was not previously the case with only the AHK or with the EXP alone; which had lower, insignificant, changes (0.36 kg/ha and

0.05 kg/ha, respectively). Overall, the AHK_EXP scenario has the highest increases in mean NO_3^--N loads.

In the simulated combined impacts of the climate with land use change scenarios, we examined two months where significant changes were noticed. The outcomes on mean sediments, TP and NO_3^--N loads demonstrate that there is not a simple additive effect of the two types of changes; rather there is either a greater, or a lesser combined effect for each month (Table 37).

Table 37. Example of absolute changes in streamflow, sediment, TP, and NO_3^--N for the climate change scenario (AHK), the land use change scenario (EXP), and the combined effect scenario (AHK_EXP), for the months of April and December, with respect to the same months in the reference simulation (1971-2000).

	Mean monthly changes for April				Mean monthly changes for December			
Scenario	Flow (m^3/s)	Sediment (kg/ha)	TP (kg/ha)	NO_3^- N (kg/ha)	Flow (m^3/s)	Sediment (kg/ha)	TP (kg/ha)	NO_3^- N (kg/ha)
AHK	-14.93	-7.92	-0.07	-1.23	6.53	2.90	0.02	1.41
EXP	0.19	0.13	0.02	0.10	0.05	0.02	0.01	0.04
AHK_EXP	-14.89	-7.78	-0.07	-1.25	6.54	3.06	0.03	1.07

In summary, the combination of climate and land use change scenarios was mostly driven by the climate change. At the monthly time step, the land use change scenarios (EXP and HIST) combined with climate change simulations, have comparable simulated impacts regarding the changes to mean streamflow, mean sediment and mean TP loads as their climate change scenario (AGR and AHK) alone. There was no significant difference between AGR_EXP and AGR_HIST scenarios, or between AHK_EXP with AHK_HIST using independent t-tests ($p<0.05$).

Given a combination of climate and land use change, compared to the reference simulation, there were significant differences. The mean monthly streamflow differences simulated were greatest in February, by up to 9.5 (± 2.2), m^3/s and decreases were greatest in April by almost 15 (± 3.7) m^3/s. Sediment differences were also greatest in February, up to 4.2 (± 0.98) kg/ha and least in April (-7.8 (± 2.0) kg/ha). Mean TP loads increased by up to 0.09 (± 0.02) kg/ha in February, and decreased the most in April by 0.07 (± 0.02) kg/ha. The mean loads of NO_3^--N increased the most in the winter months (DJF) by up to 1.32 (± 0.33) kg/ha, and decreased the most in April by 1.3 (± 0.28) kg/ha.

The combined climate and land use change impacts were less than adding both mean changes to each other during some months, and greater during other months. Thus, the magnitude and even the direction of the combined change were not predictable as a simple sum of both impacts.

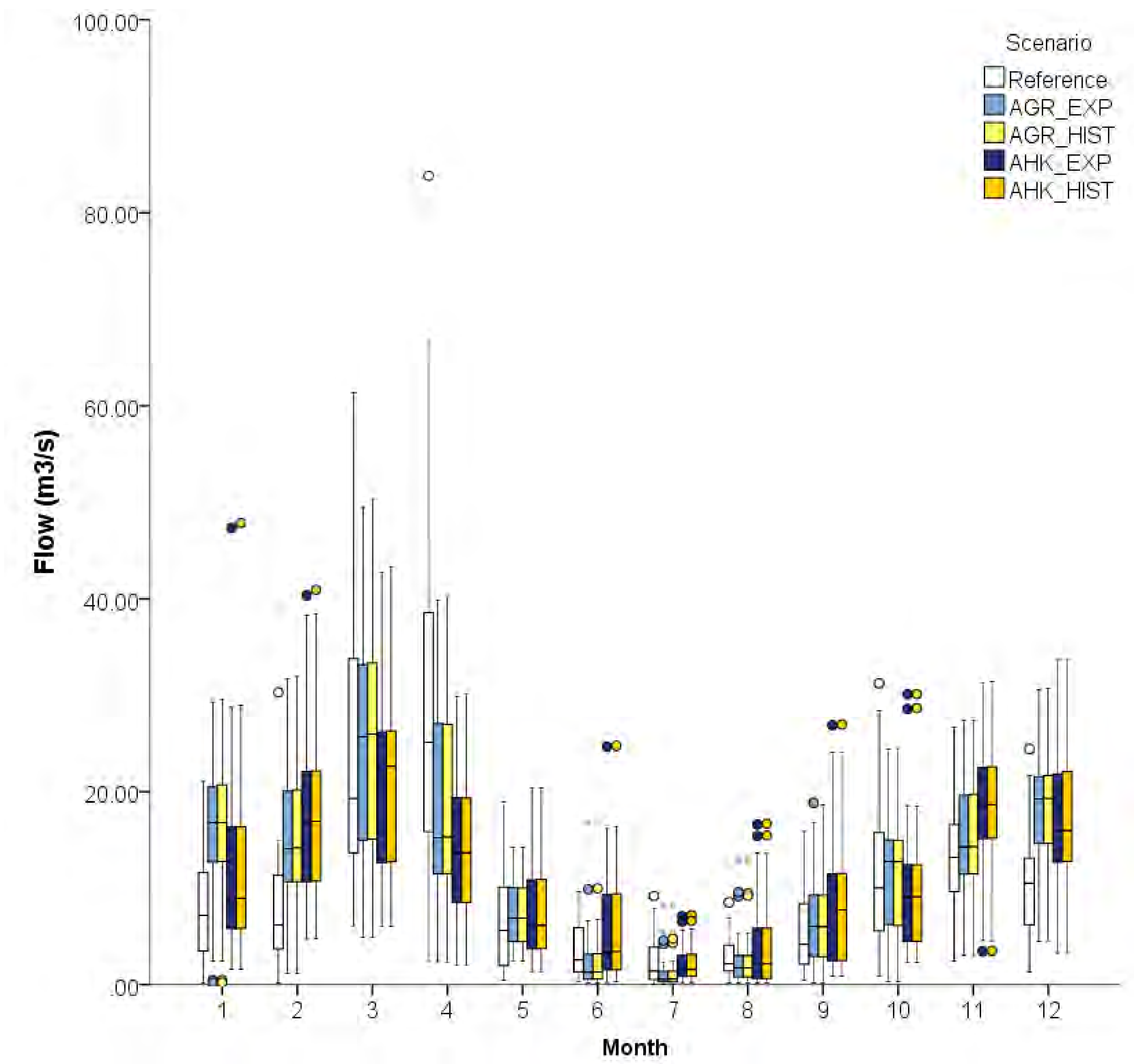


Figure 50. SWAT simulated streamflow (m^3/s) at the basin outlet for the climate change simulations combined with land use change scenarios, representing the period 2041-2070 (colored boxes), compared to the reference simulation (white boxes).

The mean monthly streamflow is driven by the climate change simulations, and follows the same magnitude of change and pattern as seen in Figure 28.

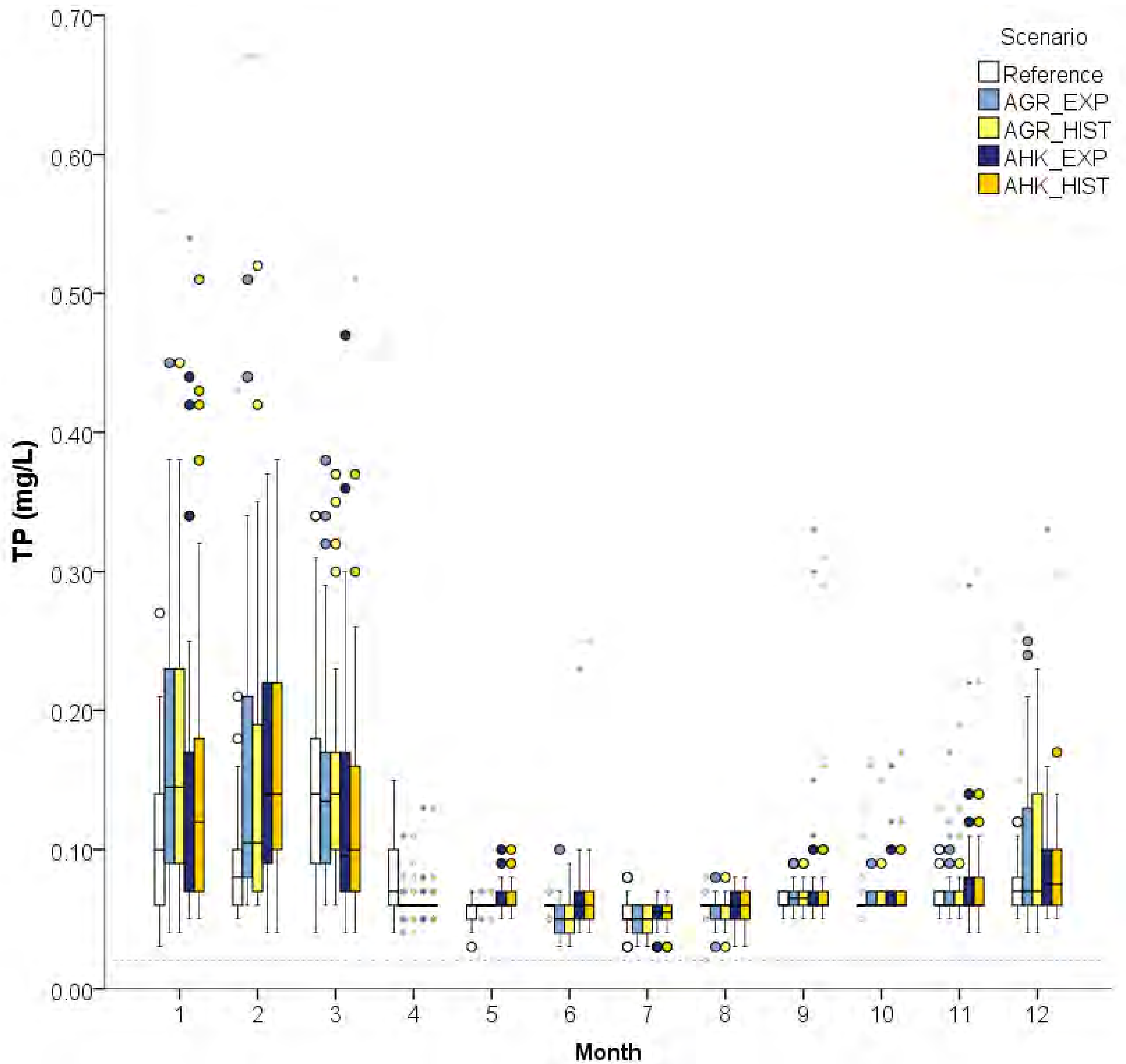


Figure 51. Concentration of SWAT simulated TP (mg/L), at the basin outlet for the climate change simulations combined with land use change scenarios, representing the period 2041-2070 (coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 0.02 mg/L.

During the months of January and February, the mean monthly median values were higher for the scenarios than in the reference simulation. In March, April, and June they were lower. For the remainder of the year they were very similar to the reference simulation. In none of the scenarios were the mean monthly values for the water quality criterion of 0.02 mg/L met. This is in contrast to the climate change simulations only, when it was met twice (2 out of 1080 months, see Figure 29), the land use change scenarios did not meet the criterion ever.

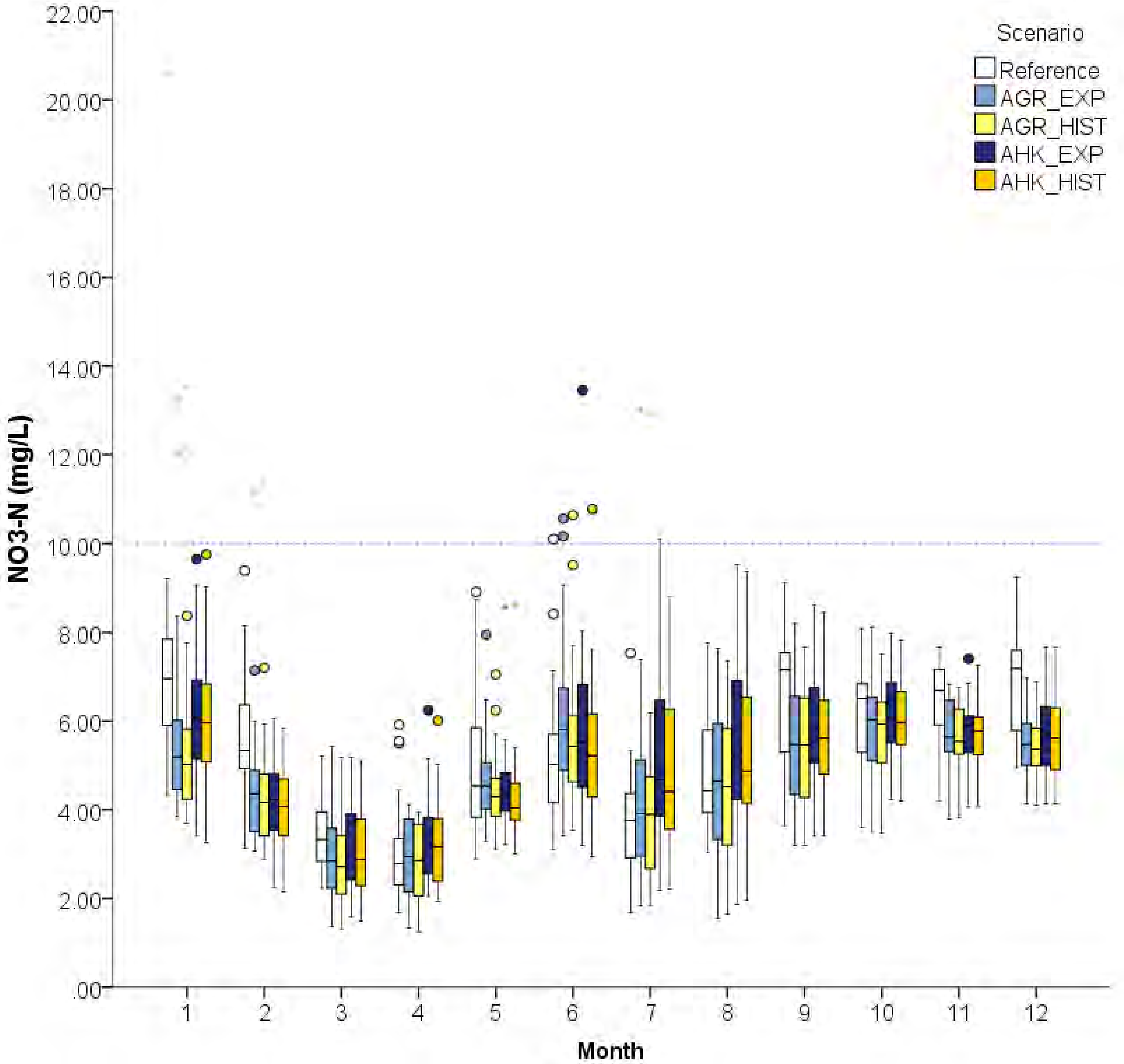


Figure 52. Concentration of SWAT simulated NO_3^--N (mg/L), at the basin outlet for the climate change simulations combined with land use change scenarios, representing the period 2041-2070 (coloured boxes), compared to the reference simulation (white boxes). The dotted line is the water criterion of 10.0 mg/L.

The mean monthly NO_3^--N concentrations from September to March, and in May were lower than for the reference simulation. For the remaining months they were higher than the reference. Overall, there was more variability in the future scenarios than in the reference simulation.

The mean monthly value exceeded the water quality criterion of 10 mg/L in 14 months in 30 years (for the climate change simulations only, this was exceeded 8 times, and for the land use changes scenarios only it was exceeded 3 times).

Table 38. Median nutrient concentrations (mg/L) at the outlet for the reference simulation and for the combined climate and land use change scenarios (2041-2070).

	Month	Total P (mg/L)	NO_3^--N (mg/L)
Reference	1	0.10	6.96
	2	0.08	5.34
	3	0.14	3.33
	4	0.07	2.77
	5	0.06	4.53
	6	0.06	5.03
	7	0.05	3.76
	8	0.06	4.42
	9	0.06	7.16
	10	0.06	6.51
	11	0.06	6.68
	12	0.07	7.14
AGR_EXP	1	0.15	5.19
	2	0.11	4.36
	3	0.14	2.84
	4	0.06	2.94
	5	0.06	4.53
	6	0.05	5.81
	7	0.05	3.92
	8	0.06	4.64
	9	0.07	5.48
	10	0.06	6.04
	11	0.06	5.64
	12	0.07	5.48
AGR_HIST	1	0.15	5.03
	2	0.11	4.18
	3	0.14	2.71
	4	0.06	2.86
	5	0.06	4.30
	6	0.05	5.43
	7	0.05	3.90
	8	0.06	4.52
	9	0.07	5.46
	10	0.06	5.93
	11	0.06	5.54
	12	0.07	5.37

AHK_EXP	1	0.12	6.06
	2	0.14	4.23
	3	0.10	2.98
	4	0.06	3.24
	5	0.06	4.34
	6	0.06	5.51
	7	0.06	4.67
	8	0.06	5.21
	9	0.06	5.83
	10	0.06	6.06
	11	0.06	5.90
	12	0.08	5.74
AHK_HIST	1	0.12	5.97
	2	0.14	4.08
	3	0.10	2.87
	4	0.06	3.16
	5	0.06	4.05
	6	0.06	5.22
	7	0.06	4.41
	8	0.06	4.87
	9	0.06	5.62
	10	0.06	5.98
	11	0.06	5.78
	12	0.07	7.18

In summary, the future scenarios of combined climate and land use change simulated median TP concentrations to be higher during the months of January and February, and they were only lower during the month of April. The water quality criterion of 0.02 mg/L was never met by any of the four scenarios.

The median NO_3^--N concentrations were lower than the reference simulation during most months in the year (8 months out of 12) but the NO_3^--N concentrations had more monthly variability than the reference simulation, so that the mean water quality criterion of 10 mg/L was exceeded in 14 months out of the 30 years.

6.3.4. Water quality as a result of implementing best management practices

For the next step; the testing of adaptation strategies, one out of the four combined scenarios had to be retained for future examination with the adaptation strategies. The partners and stakeholders in the project were consulted. There was a consensus to keep the climate scenario AHK to be run in combination with the land use scenario EXP.

We came to this decision because our analysis showed that the AHK climate scenario resulted in the greatest sediment and nutrient load exportations, therefore the AHK climate scenario demonstrated the greatest changes compared to the reference simulation in terms of nutrient transport, so this would represent the "worst case scenario" from our simulations, which was desirable. The land use simulation EXP was retained because it was developed using expertise from producers, stakeholders and researchers and it included the results from the questionnaires. Therefore, this scenario evoked greater confidence than HIST, in which historic trends were extrapolated. Finally, by examining the AHK_EXP scenario simulation results at the monthly step, they confirmed the greatest nutrient increases, especially for nitrate, and again strengthened the argument that this was a "worse" scenario for impacting water quality, than the other three.

Thus, all of the adaptation strategies in this section were executed in combination with the AHK_EXP scenario. These are then compared to the AHK_EXP scenario without adaptation strategies. This was done to determine the effectiveness of the adaptation strategies to mitigate the impacts of the simulated climate and land use change in the basin.

The improvements in TP loads were significant for all of the adaptation scenarios. Compared to the AHK_EXP scenario, the STRAT reduced mean annual TP loads at the outlet by 32%; the FEASB by 26% and the OPTIM by 47% (Note: compared to the reference simulation, the OPTIM scenario reduced TP amounts by 38% instead of the targeted 41%). The mean annual sediment loads were only significantly reduced in the OPTIM scenario, by 62% (Table 39).

Table 39. Mean annual simulated streamflow, sediments, TP and NO_3^--N loads (with standard deviations) at outlet 23, for the AHK_EXP scenario alone, and with the three adaptation strategies (2041-2070).

	Flow (m^3/s)	Sediments (Mg/yr)	TP (Mg/yr)	NO_3^--N (Mg/yr)
AHK_EXP	11.5 ±2.2	3908.6 ±817.3	41.7 ±19.8	1681.8 ±286.0
STRAT	12.0 ±2.3	3569.8 ±957.8	28.4 ±10.3	1567.8 ±276.2
FEASB	11.5 ±2.2	3778.8 ±874.9	30.8 ±11.8	1628.5 ±279.0
OPTIM	11.3 ±2.3	1486.7 ±860.5	22.1 ±6.4	1646.1 ±326.4

Table 40. Annual mean changes (with standard errors) to sediments, TP and NO_3^--N loads at outlet 23 due to the effects of adaptation strategies (compared to the AHK_EXP scenario without adaptation) from 2041-2070. Green boxes denote a statistically significant change ($p<0.05$).

	Sediments (Mg/yr)	TP (Mg/yr)	NO_3^--N (Mg/yr)
STRAT	- 338.8 ±229.9	- 13.5 ±4.1	- 114.0±72.6
FEASB	- 129.8 ±218.6	- 11.0 ±4.2	- 52.3 ±72.9
OPTIM	- 2421.9 ±216.7	- 19.7 ±3.8	- 35.7 ±79.2

Table 41. Values of absolute changes in mean streamflow, mean sediment and mean nutrient loads (2041-2070) at outlet 23, for AHK_EXP with adaptation strategies STRAT, FEASB and OPTIM, all compared to AHK_EXP without adaptation strategies. Green boxes denote a statistically significant change ($p<0.05$).

Scenario	Month	Flow (m3/s)	Sediments (kg/ha)	Total P (kg/ha)	NO_3^--N (kg/ha)
STRAT	1	0.33	-0.51	-0.05	-0.16
	2	0.35	-0.42	-0.06	-0.27
	3	0.63	-0.56	-0.05	-0.36
	4	0.83	-0.49	0	-0.24
	5	0.72	-0.10	0	-0.17
	6	0.37	-0.17	0	-0.13
	7	0.30	0.03	0	-0.01
	8	0.18	-0.17	0	0.01
	9	0.66	-0.08	-0.01	-0.03
	10	0.56	-0.45	0	-0.05
	11	0.57	-0.97	-0.01	-0.15
	12	0.45	-1.47	-0.02	-0.23
FEASB	1	0.08	-0.18	-0.04	0
	2	0.06	-0.10	-0.05	-0.01
	3	0.10	-0.17	-0.04	-0.07
	4	0.07	-0.26	0	-0.09
	5	0.06	-0.08	0	-0.05
	6	0.16	-0.06	0	0.12
	7	-0.38	-0.15	0	-0.02
	8	-0.17	-0.08	0	-0.19
	9	0.17	-0.03	-0.01	-0.23
	10	0.06	-0.25	0	-0.16
	11	0.04	-0.27	-0.01	-0.11
	12	0	-0.42	-0.02	-0.02
OPTIM	1	0.32	-2.73	-0.07	0.22
	2	0.28	-3.56	-0.08	0.17
	3	0.55	-5.57	-0.08	0.03
	4	0.56	-4.25	-0.01	-0.06
	5	0.20	-2.41	0	-0.19
	6	-0.24	-1.35	-0.01	-0.16
	7	-0.17	-0.48	0	-0.04
	8	-0.42	-1.19	0	-0.10
	9	-0.90	-2.20	-0.01	-0.16
	10	-1.06	-2.87	-0.01	-0.24
	11	-0.62	-5.82	-0.02	-0.11
	12	-0.21	-5.90	-0.03	0.09

Table 42. Relative changes (%) in mean streamflow, mean sediment and mean nutrient loads (2041-2070) at outlet 23, for AHK_EXP with adaptation strategies STRAT, FEASB and OPTIM, all compared with AHK_EXP without adaptation strategies. Green boxes denote a statistically significant change ($p<0.05$).

Scenario	Month	Flow	Sediments	Total P	NO_3^--N
STRAT	1	3	-9	-46	-6
	2	2	-6	-44	-10
	3	3	-6	-40	-14
	4	6	-8	-13	-14
	5	9	-3	-9	-12
	6	6	-7	-14	-11
	7	13	4	11	-3
	8	4	-9	-1	1
	9	8	-2	-20	-1
	10	6	-10	-14	-2
	11	3	-12	-22	-3
	12	3	-18	-31	-6
FEASB	1	1	-3	-40	0
	2	0	-1	-38	0
	3	0	-2	-34	-3
	4	0	-4	-9	-5
	5	1	-2	-6	-3
	6	3	-2	-7	10
	7	-17	-21	-21	-5
	8	-4	-5	-1	-18
	9	2	-1	-14	-12
	10	1	-5	-8	-6
	11	0	-3	-16	-3
	12	0	-5	-23	0
OPTIM	1	3	-51	-67	8
	2	2	-47	-64	6
	3	3	-58	-60	1
	4	4	-67	-14	-4
	5	2	-68	-10	-13
	6	-4	-56	-30	-13
	7	-8	-65	-5	-9
	8	-10	-68	-11	-10
	9	-11	-61	-34	-8
	10	-11	-63	-26	-10
	11	-3	-71	-30	-2
	12	-1	-73	-40	2

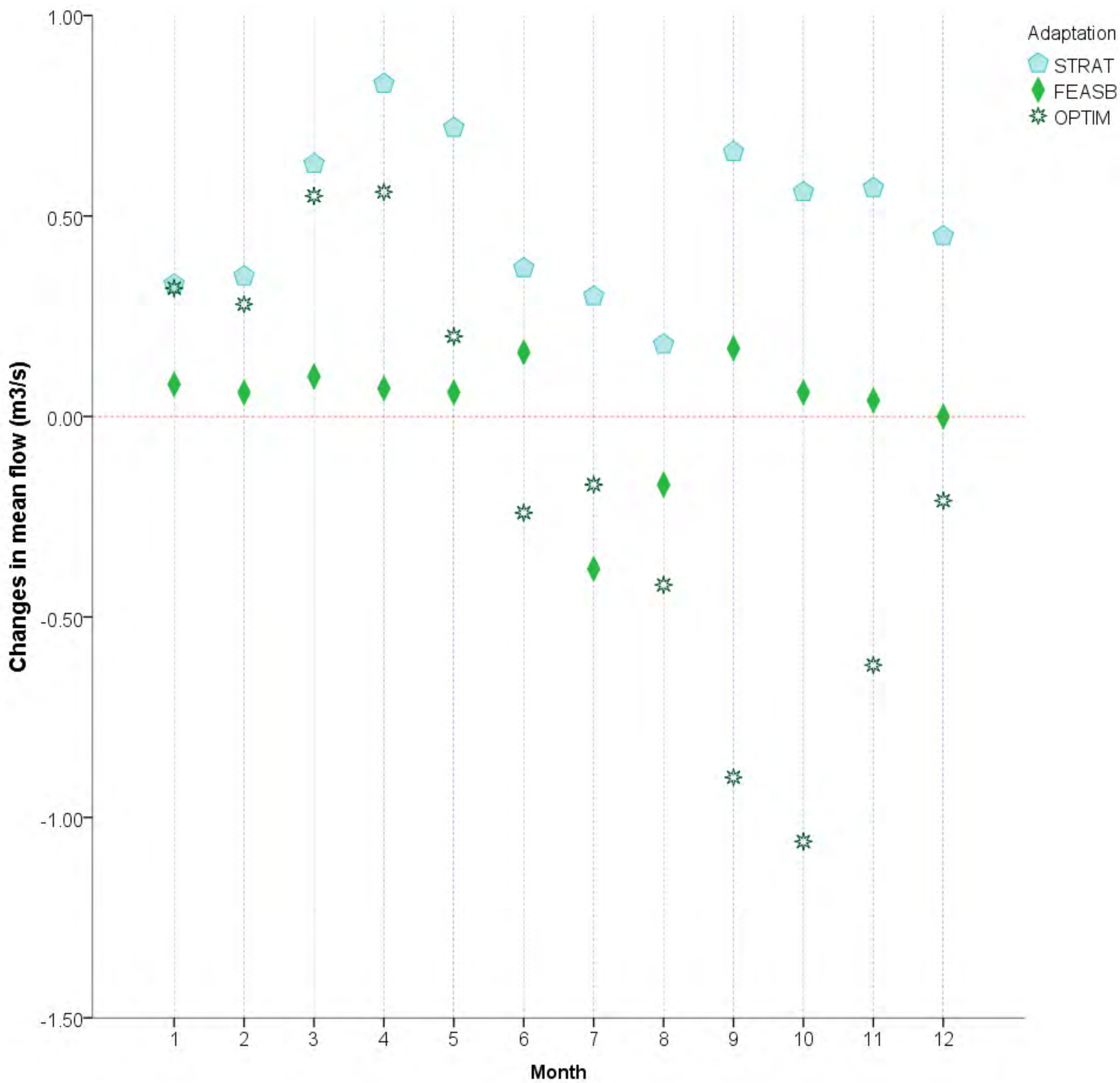


Figure 53. Changes in SWAT simulated mean monthly streamflow (m^3/s) for the adaptation strategies carried out on the climate and land use change scenario AHK_EXP, compared to the AHK_EXP scenario without adaptation strategies (red zero line), at the basin outlet.

The streamflow did not change significantly due to the adaptation strategies being implemented in the watershed. The small fluctuations (±1 m^3/s) observed are within the range of natural variability. It is still interesting to note that there are some impacts on streamflow due to the adaptation strategies that may wish to be considered. In particular the OPTIM scenario reduces the flow from June to December which could have a negative effect on the overall in-stream conditions as June to September are already low flow months.

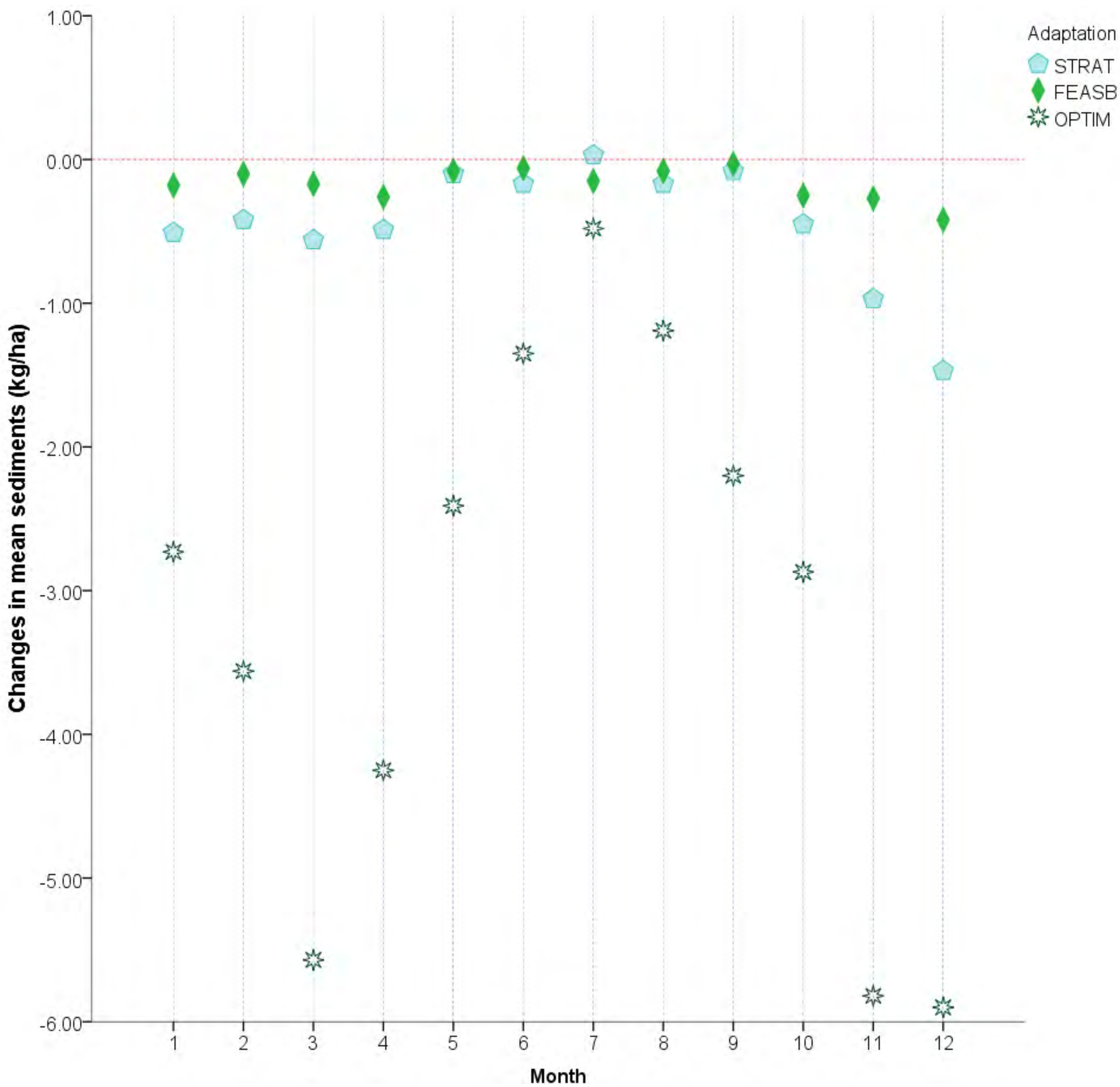


Figure 54. Changes in SWAT simulated mean monthly sediments (kg/ha) for the adaptation strategies with the climate and land use change scenario AHK_EXP, compared to the AHK_EXP scenario without adaptation strategies (red zero line), at the basin outlet.

All of the adaptation scenarios were effective at decreasing the mean monthly sediment loads, compared to the AHK_EXP scenario without adaptations. Examining the data from all 3 adaptations, showed the linear correlation between streamflow and sediment transport to be significant (Pearson's $R = 0.88$, $p<0.001$), and was explained by the regression equation: *sediment (kg/ha) = 0.37*flow* (m^3/s) *- 0.38*.

Yet, only the OPTIM was effective at significantly decreasing the mean monthly transport of sediments. This is reflected in the annual sediment decrease (Table 40), which causes a total of 2421.9 ±216.7 Mg less sediments at the outlet. The transport of mean monthly sediments was also significantly reduced in all months, except for January. The most decrease took place in the winter months, by up to 70%.

The STRAT and FEASB adaptation scenarios had no significant differences in monthly sediment loads compared to the AHK_EXP scenario. The relative reductions were also much smaller each month (at most - 21% in FEASB) than for the OPTIM and stayed within the range of natural variability.

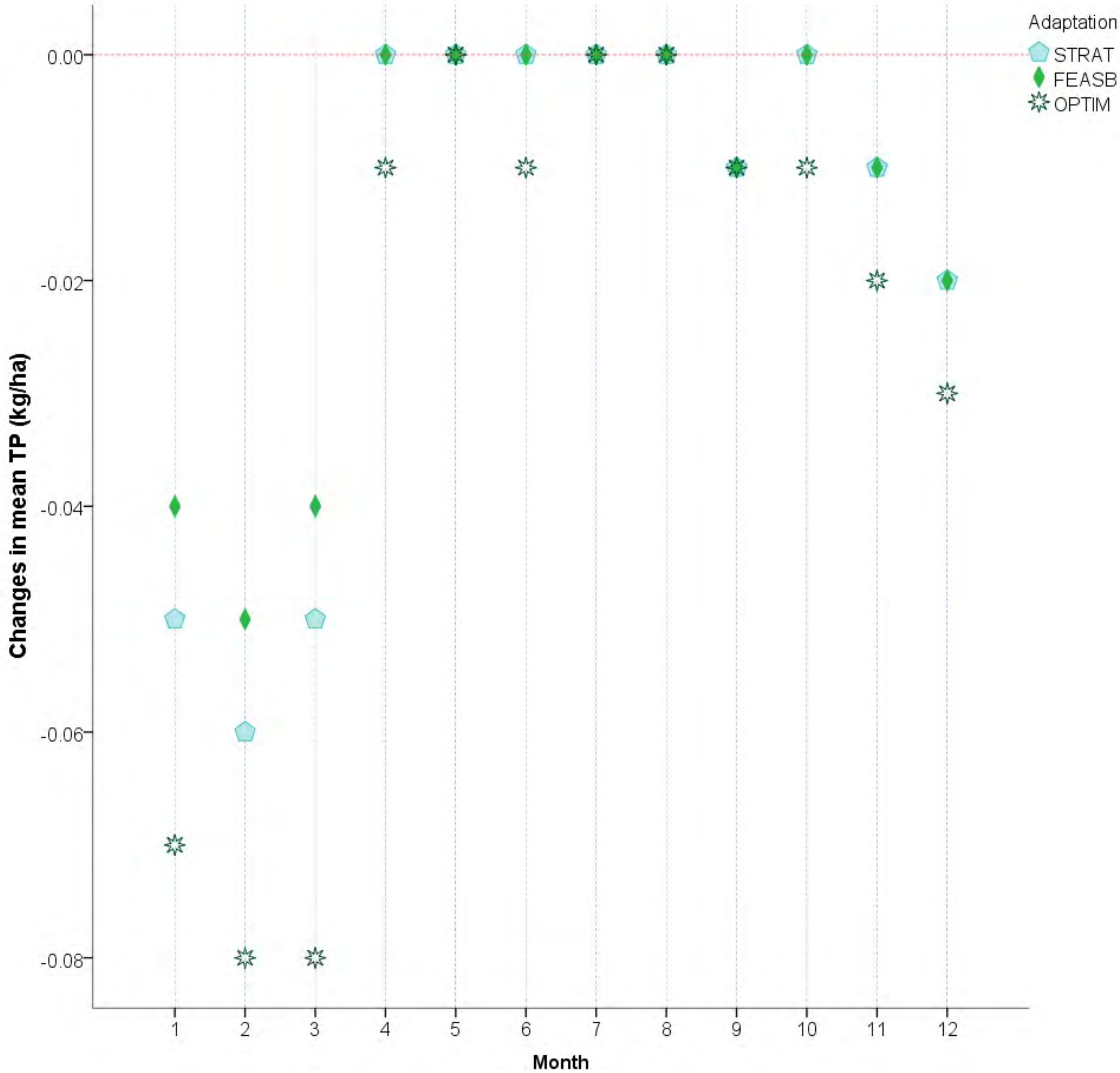


Figure 55. Changes in SWAT simulated mean monthly TP (kg/ha) for the adaptation strategies with the climate and land use change scenario AHK_EXP, compared to the AHK_EXP scenario without adaptation strategies (red zero line), at the basin outlet.

Overall, the mean monthly TP loads were reduced by all of the three adaptation scenarios, compared to the AHK_EXP scenario. The greatest reductions occurred from January to March.

The greatest and most significant reductions were achieved with OPTIM, in which TP loads were significantly reduced in 3 months of the year (February, March and December) by up to 0.08 kg/ha. The STRAT scenario was also effective at significantly reducing mean TP loads in

February and March by up to 0.06 kg/ha. Both of these scenarios targeted the 10% of cropland (1795 ha) that was most prone to phosphorus transportation. The results reflect the efficiency of focusing on “hot spots” also under climate change conditions with greater precipitation. The reductions in mean TP loads are encouraging, as two of the adaptation scenarios were able to significantly reduce TP transport during the months when snowmelt and high runoff amounts contribute to the most non-point source pollution.

In the OPTIM scenario, the amount of particulate P was reduced the most to 0.07 kg/ha, and the soluble P was also reduced to 0.33 kg/ha (Appendix 9), this was surprising as manure has a high amount of soluble P. But due to the combination of best management strategies, the soluble P was retained in the soil and was not transported to the water ways.

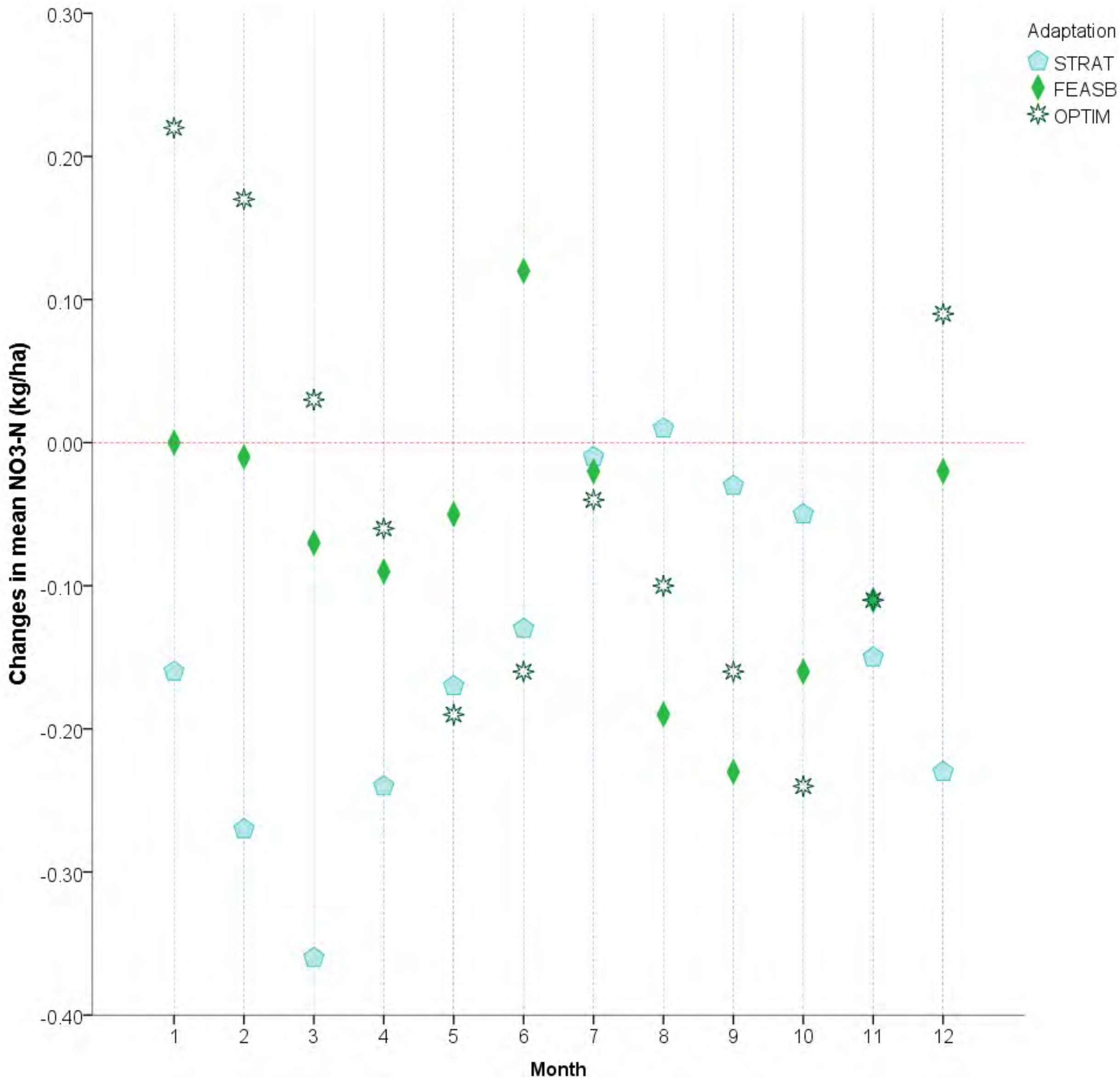


Figure 56. Changes in SWAT simulated mean monthly NO_3^--N (kg/ha) for the adaptation strategies with the climate and land use change scenario AHK_EXP, compared to the AHK_EXP scenario without adaptation strategies (red zero line), at the basin outlet.

Again, the mean monthly NO_3^--N loads show more variability in the direction of change with the different scenarios, than the mean TP values. The FEASB scenario reduced the transport of NO_3^--N consistently each month (up to -0.23 kg/ha in November), and the STRAT reduced the mean NO_3^--N loads in all months except for August by up to -0.36 kg/ha in March. The OPTIM scenario increased the mean NO_3^--N loads in December to March (up to 0.22 kg/ha), but otherwise decreases were simulated (up to -0.24 kg/ha). However, the NO_3^--N loads were not significantly reduced, or increased, in any month by any of the adaptation scenarios.

The increased mean NO_3^--N loads in the OPTIM scenario are explained by the swine manure (N-P-K = 03-03-0) that was applied. The application rates were calculated to meet the phosphorus requirements of the crops, disregarding the quantity of nitrogen that was being supplied. This led to an over application of N for the crop in most cases. However, this is often a compromise of using manure as the only source of fertilization.

Overall, the OPTIM scenario was the most effective at significantly reducing sediment and TP loads. Annually, the OPTIM reduced mean sediment loads by 2421.9 (±216.7) Mg compared to AHK_EXP, and mean annual TP loads were reduced by 19.7 (±3.8) Mg. The STRAT was effective at significantly reducing the mean annual TP loads by 13.5 (±4.1) Mg, and the FEASB significantly reduced mean annual TP by 11.0 (±4.2) Mg, compared to the AHK_EXP scenario.

At the monthly time step, the OPTIM scenario was able to significantly reduce the sediment loads compared to the AHK_EXP scenario during all months except for January; decreases ranged from -0.48 (±0.16) kg/ha in July to -5.90 (±0.66) kg/ha in December. The mean monthly TP loads were significantly reduced by the OPTIM and STRAT scenarios. The OPTIM reduced mean TP loads in February, March and December by up to 0.08 (±0.02) kg/ha. The STRAT reduced mean TP loads in February and March by 0.06 (±0.02) kg/ha.

None of the scenarios improved (or deteriorated) the mean NO_3^--N loads compared to the AHK_EXP scenario.

In summary, The STRAT and the OPTIM managed to reduce TP loads during the critical months of February and March. The FEASB scenario showed only limited mean monthly reductions in sediment and nutrient transport and thus proved inefficient in adequately mitigating climate and land use change effects in the future.

To identify if the adaptation strategies were successful in mitigating the impacts of climate and land use change, an examination of the mean monthly nutrient concentrations at the outlet of the basin was carried out, and were also compared to the reference simulation.

Table 43. Median nutrient concentrations (mg/L) at the outlet for the AHK_EXP scenario and for the adaptation scenarios (2041-2070).

	Month	Total P (mg/L)	NO_3^--N (mg/L)
AHK_EXP	1	0.12	6.06
	2	0.14	4.23
	3	0.10	2.98
	4	0.06	3.24
	5	0.06	4.34
	6	0.06	5.51
	7	0.06	4.67
	8	0.06	5.21
	9	0.06	5.83
	10	0.06	6.06
	11	0.06	5.90
	12	0.08	5.74
STRAT	1	0.07	5.50
	2	0.08	3.76
	3	0.06	2.40
	4	0.05	2.68
	5	0.06	3.49
	6	0.06	4.32
	7	0.05	3.71
	8	0.06	4.82
	9	0.06	5.09
	10	0.06	5.60
	11	0.06	5.60
	12	0.06	5.61
FEASB	1	0.08	6.04
	2	0.10	4.20
	3	0.07	3.00
	4	0.06	3.04
	5	0.06	4.18
	6	0.06	5.73
	7	0.05	5.16
	8	0.06	4.89
	9	0.06	5.11
	10	0.06	5.62
	11	0.06	5.61
	12	0.06	5.82
OPTIM	1	0.06	6.47
	2	0.06	4.38
	3	0.06	2.96
	4	0.06	2.92
	5	0.06	3.88
	6	0.06	4.65
	7	0.05	3.99
	8	0.06	4.89
	9	0.06	5.81
	10	0.06	6.14
	11	0.06	5.96
	12	0.06	5.92

18

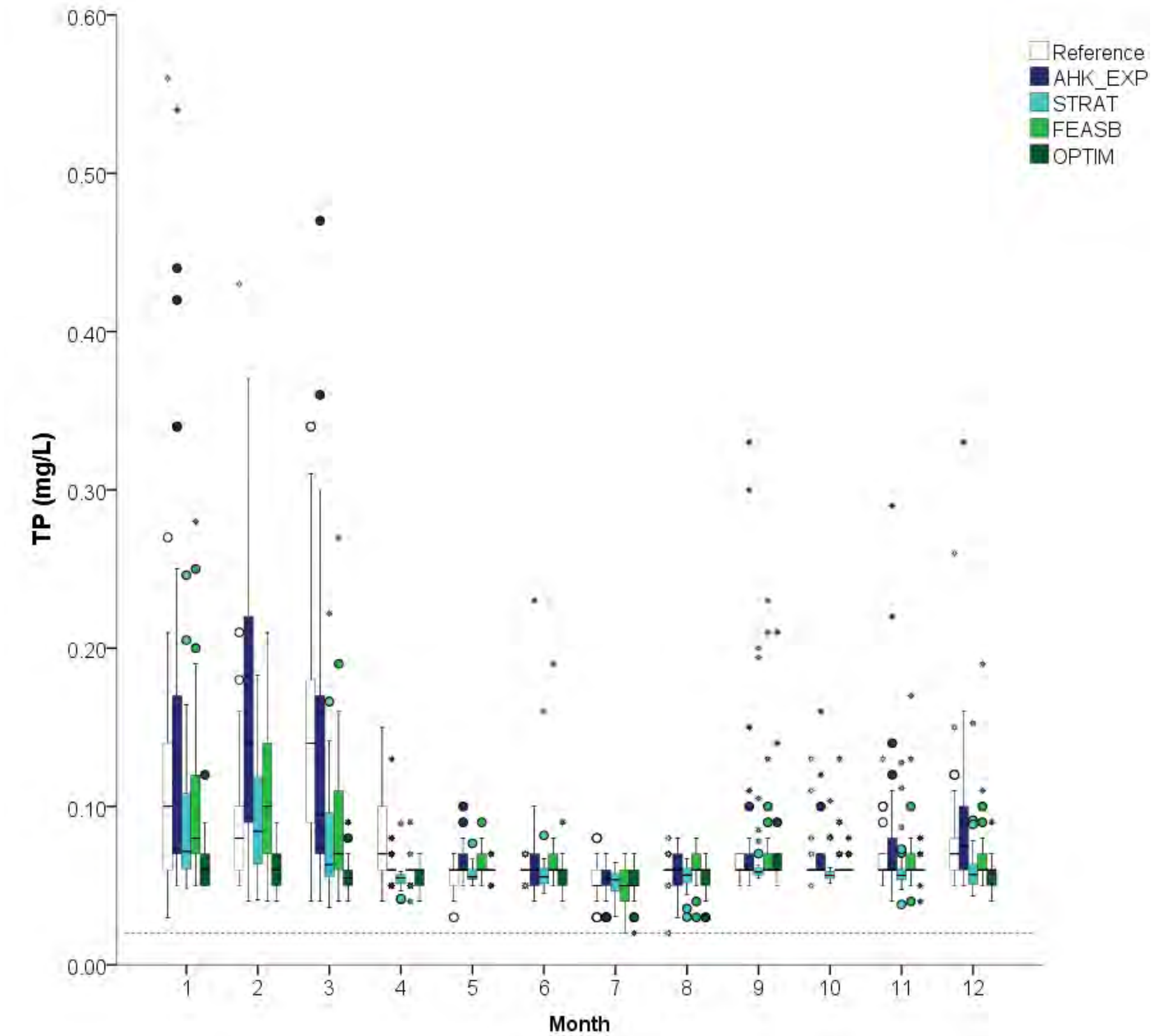


Figure 57. Simulated mean monthly TP (mg/L) at the basin outlet for the reference simulation (white boxes), climate and land use change AHK_EXP scenario (dark blue boxes), and the AHK_EXP with adaptation scenarios (green boxes). The dotted line is the water criterion of 0.02 mg/L.

Compared to the AHK_EXP scenario, the STRAT scenario significantly reduced mean TP concentrations from November to May; the FEASB significantly reduced them from January to March, as well as in July; and the OPTIM scenario reduced mean TP concentrations from June to October.

Although for the most part, the monthly median TP concentrations were lower than the AHK_EXP (Table 43), the mean monthly water quality criterion of 0.02 mg/L was only reached in 2 months in the 30 years of simulation (both times by the OPTIM scenario, in July). Despite the significant reductions in the mean TP concentrations the water quality criterion was still not consistently attained after implementing the adaptation scenarios. However, the adaptation strategies managed to reduce the monthly median concentrations of TP to levels lower or similar than those during the reference simulation.

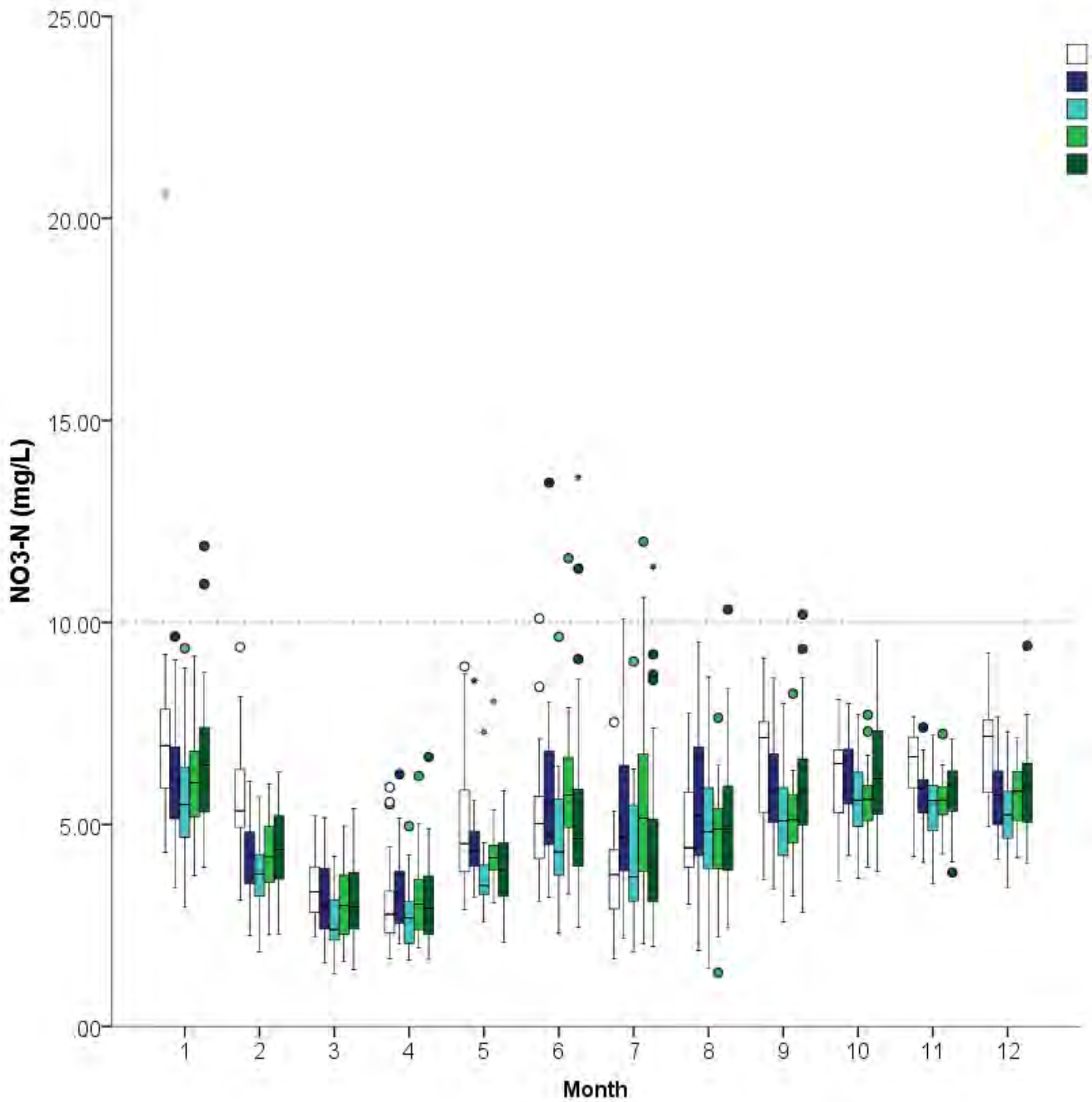


Figure 58. Simulated NO_3^--N (mg/L) at the basin outlet for the reference simulation (white boxes), climate and land use change AHK_EXP scenario (dark blue boxes), and the AHK_EXP with adaptation scenarios (green boxes). The dotted line is the water criterion of 10.0 mg/L.

The adaptation scenarios are effective, for the most part, at reducing the monthly median concentrations of NO_3^--N at the outlet compared to the AHK-EXP scenario. The STRAT scenario significantly reduced mean NO_3^--N concentrations from March to June; the FEASB only in August; and the OPTIM only in May.

Despite the high variability in some months, the median NO_3^--N concentrations in the STRAT and FEASB scenarios were almost always reduced (except for the FEASB scenario in June and July). The decrease was likely the result of the cover crops being planted after the fall harvest of corn and cereals. However, with FEASB, in June and July just before the planting of cover crops the median NO_3^--N was higher than in the AHK_EXP scenario and in the reference simulation which may be attributed to the fertilization of the switchgrass in the FEASB after harvest in May. Overall, the monthly median NO_3^--N concentrations exceeded the critical threshold 10 times, mostly in the OPTIM scenario.

In OPTIM, the extreme values of NO_3^--N are greater than for the other scenarios, which is a function of only swine manure being applied to the crops in this scenario. The ratio of the N:P in the manure applied in this scenario was almost 1:3. As the P values were used to calculate the required fertilizer amounts for each crop, N was over-applied. Hence, there is relatively more nitrogen in the basin with the OPTIM scenario.

In summary, the adaptation scenarios were able to decrease the median TP concentrations at the outlet of the basin to lower levels than the AHK_EXP scenario, and even to restore concentrations to lower or similar levels to the reference simulation (especially in February) before climate and land use change. Yet the 0.02 mg/L criterion was not achieved by the STRAT or FEASB scenarios, and only rarely (twice) by the OPTIM scenario.

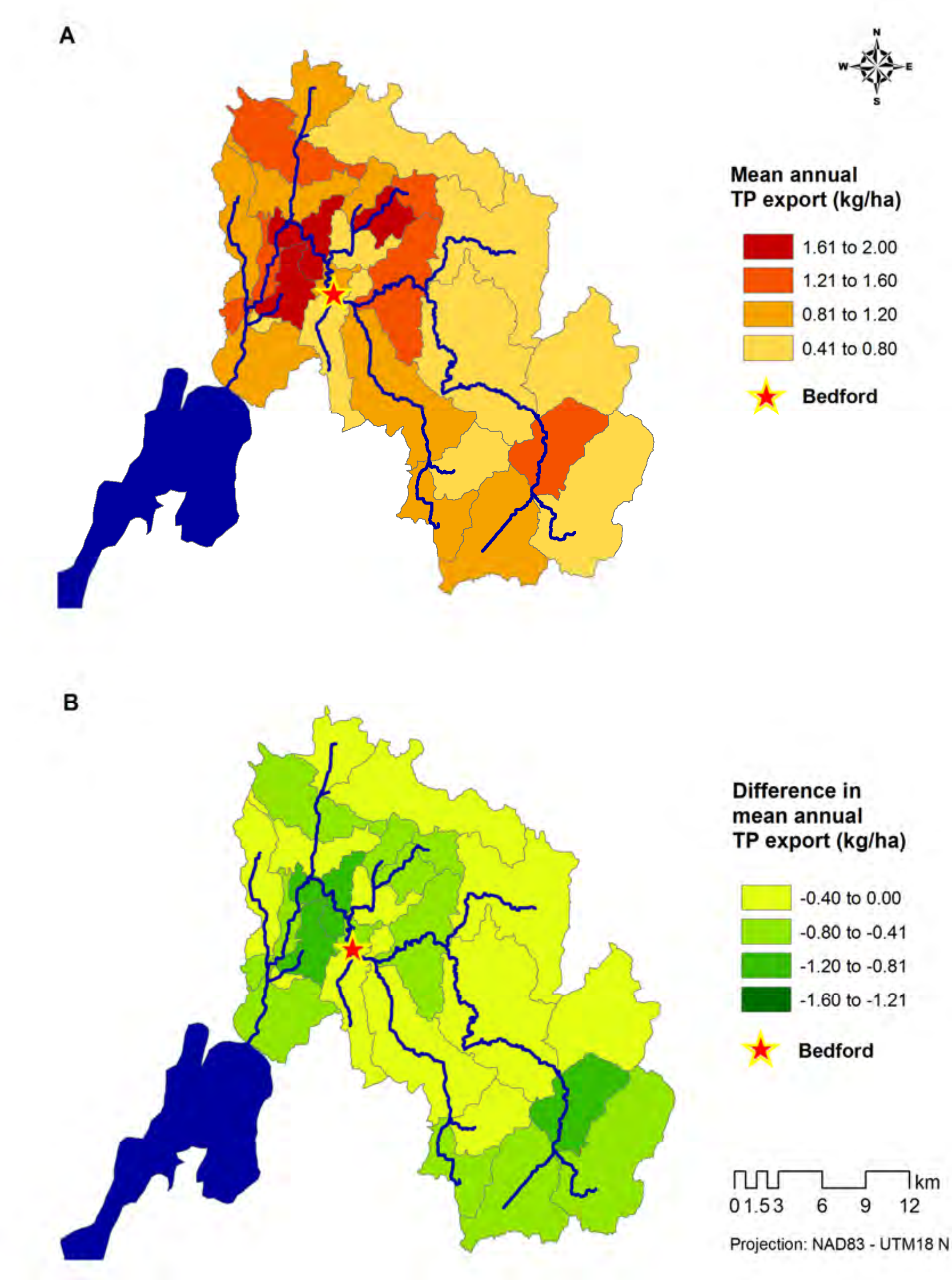
Compared to the AHK_EXP scenario, the median NO_3^--N concentrations at the outlet of the basin were consistently lower in the STRAT scenario. As well, they were lower during all but four months for the FEASB, and six months for the OPTIM scenarios. The water quality criterion of 10.0 mg/L was respected by the STRAT scenario, but was exceeded 3 times in the FEASB and 7 times in the OPTIM scenario during the 30 years of simulation. The median concentrations for all adaptation scenarios were lower than the reference simulation, except in April, June, July and August they were similar to the reference values.

To determine the spatial reduction of TP and NO_3^--N loads from the sub-basins by each of the adaptations, the changes brought about by the management practices were depicted in the watershed using ArcGIS (Figure 59). Figure A represents the AHK_EXP scenario without adaptation strategies. It is evident that the most TP (1.21 to 2.00 kg/ha) is exported around the Bedford area and on the agriculturally most intensive lands to the west of Bedford. There is a sub-basin in the east, straddling the Québec-Vermont border that is mainly forested but with patches of grain corn, orchards and hay, which is also prone to TP transport because it has some of the steepest slopes in the basin (average slope of 5%).

Figure B depicts reductions in TP due to the STRAT scenario through changes in management practices. The greatest reductions (0.81 to 1.20 kg/ha) were achieved in the agriculturally most intensive sub-basin near Bedford, and in the sub-basin with steep slopes in the forested area. Both sub-basins transported the most TP in AHK_EXP. Thus, the STRAT scenario effectively targeted the critical sub-basins with high TP transport, and did not affect sub-basins with relatively low TP loads. This scenario also had an additional TP reduction mechanism implemented at the basin outlet, to mimic runoff control structures, which is not observable in Figure B.

The FEASB scenario (Figure C) showed strong reductions in TP loads (0.81 to 1.20 kg/ha) in the critical sub-basin around Bedford. Smaller reductions (0.41 to 0.80 kg/ha) were evident in 5 other sub-basins with high TP loads in the AHK_EXP scenario, however not all of the critical sub-basins were targeted.

The OPTIM scenario (Figure D) achieved the largest of all modeled TP reductions (1.21 to 1.60 kg/ha) from the sub-basin of the town of Bedford. It also achieved reductions in TP from a much larger area in the whole watershed, due to its all-encompassing approach. The OPTIM scenario did not have a targeted approach, but rather implemented all best management practices holistically over the watershed. It had the most impact on reducing the overall TP loads in the watershed.



C

D

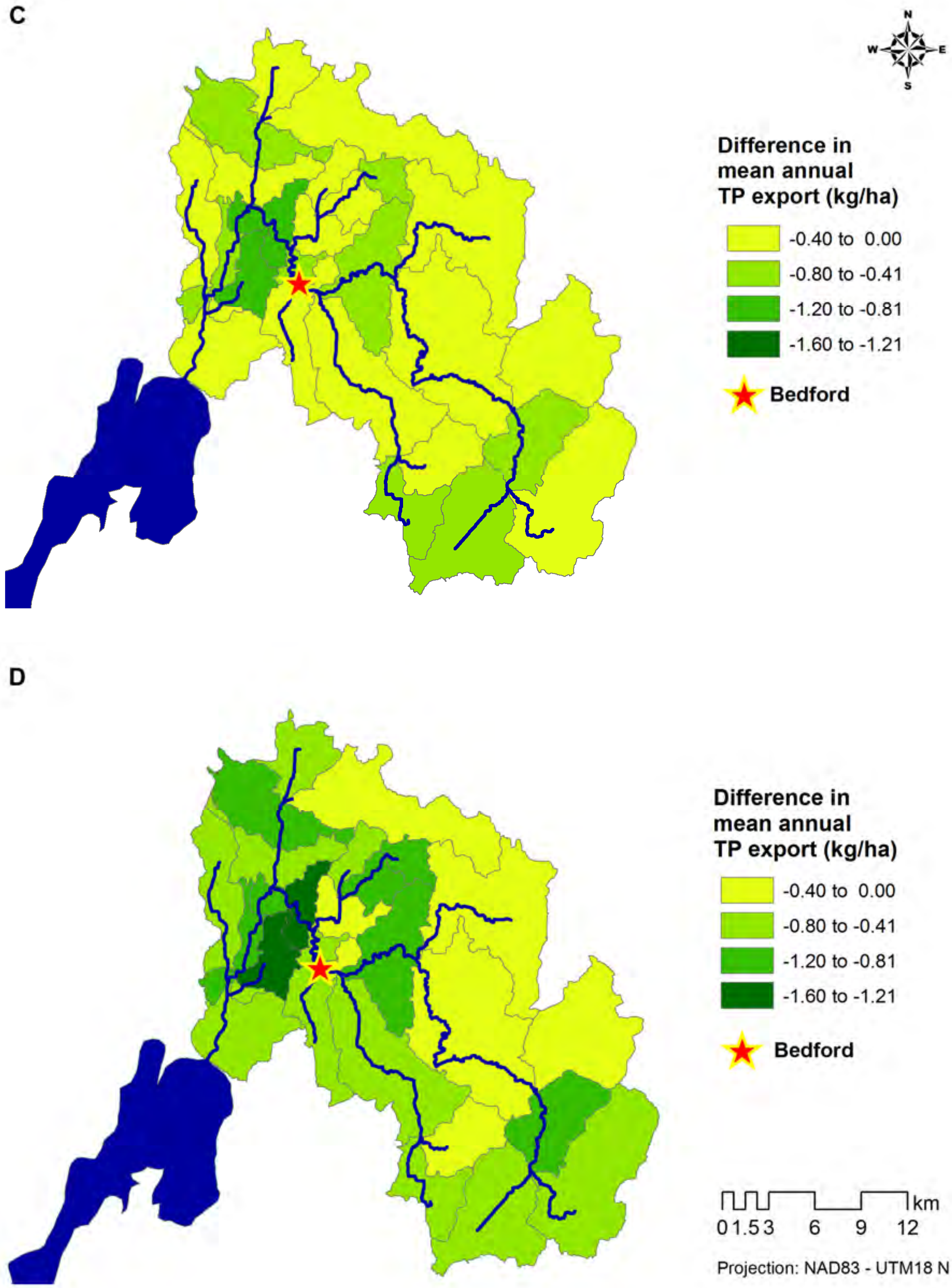


Figure 59. A) Mean annual TP export from the AHK_EXP scenario. Reduction in TP loads due to adaptation strategies based on B) STRAT scenario; C) FEASB scenario; D) OPTIM scenario.

7. Discussion

For the most part, the future climate simulations chosen in this study for the Pike River project, showed increases in precipitation for every month, yet some simulations projected slight decreases during the months from June to October and also from January to February. Yearly, an average of 66.4 mm in the ACU, 98.4 mm in the AGR, and 101.9 mm in AHK simulation were added to the basin. As a consequence, streamflow was simulated to be overall higher as well, especially during November to February. The most significant change in flow was simulated to take place in April, when streamflow decreases by up to 50% due to the snowmelt in the future gradually taking place in February and peaking during the month of March (instead of in April). As a result, less sediment, TP and NO_3^--N loads are transported from the fields in March and April, and more during the period of November to February, as per the changes in streamflow. We found the sediment loads were closely correlated to streamflow. Michaud and Laverdière (2004) also found higher surface runoff to entail a greater transport of sediments in the basin.

The in-stream concentrations of nutrients are critical for water quality assessments. Thus, future changes of both streamflow and nutrient loadings must be considered. For example, if future streamflows increase strongly, even slightly higher nutrient loads can result in lower in-stream concentrations.

Running SWAT with the future climate simulations caused increases in TP concentrations at the basin outlet to take place predominantly in December, January and February. This was due to the combined effect of higher TP loads stemming from the fields and the greater runoff. Mineral P (particulate P) is transported mainly by surface runoff, and is also highly correlated to suspended solids (Michaud and Laverdière, 2004). Greater precipitation amounts in these months makes TP prone to surface transport. Under future climate conditions, the largest decrease in TP concentration was simulated to take place in April, mainly due to the lower mean TP loads transported in April and the lower mean streamflow, compared to the reference simulation.

For the simulated NO_3^--N concentrations, a decrease took place at the outlet when streamflow was higher than in the reference simulation (i.e. in January), and an increase in mean NO_3^--N concentration took place when streamflow was lower, as was the case in April. Nitrate is highly water soluble and is easily dissolved by and transported by water. In all of the scenarios simulated in SWAT, the NO_3^--N was more variable than the P which is an indication of NO_3^--N being more labile. Therefore, it is a nutrient that is also more sensitive to changes in the basin.

In summary, simulated climate change impacts do not consistently increase the concentrations of nutrients at the outlet of the watershed, compared to the reference simulation. The months in which median TP concentrations increased the most are in winter (December, January and February). Yet, during the month of March and April, TP median concentrations are lower than in the reference simulation, and for the rest of the year they remain relatively unchanged. The good water quality criterion of 0.02 mg/L for TP was almost never achieved.

For NO_3^--N concentrations, climate change had the reverse effect; concentrations decreased in December, January and February. In April, the NO_3^--N concentrations were higher than in the reference simulation. Otherwise, they remained for the most part unchanged. Overall, the water quality criterion of 10 mg/L was rarely exceeded for NO_3^--N.

The agricultural landscape in Québec evolves in a world of perpetual change. Hence, it is futile to forecast, with any precision, an exact portrait of the future progression of Québec's agricultural landscape within the next 20 to 40 years. Nevertheless, it is possible to extract trends, preferences, tendencies, and even driving factors which will strongly influence the direction of changes that may take place in the agricultural sector.

Therefore, the exercise of modelling the driving factors of land use change and how they may influence the outcome of future agricultural landscapes in the watershed in the form of scenarios is a valuable exercise to capture the future trends. The realistic land use scenarios, constructed together with the stakeholders and using the CLUE-S model, portray two possible future agricultural land uses in the Pike River watershed for the near- to mid-term future. Most changes revolved around changing crop quantities and types, and are considered to be subtle changes.

Eckhardt et al. (2003) quantified the minimum proportion of a basin in SWAT that has to undergo a land use change in order for a hydrological response in discharge to be evident. They found that when approximately 20% of the catchment area is changed, the mean surface runoff amount is altered. The land use scenarios were actually a rearranging of the crop land that was simulated, with little significant decrease of crop area, or forested areas. The two scenarios did not differ significantly from each other in terms of how they affected surface water quality. The scenarios were limited in terms of changes that could be made (due to laws protecting forested areas; no space to expand agricultural areas in the watershed; no reforestation planned; etc.).

The results of our extreme "all corn" and "all forest" scenarios found increased mean annual streamflow at the outlet in summer for "all corn", but not in autumn, when mean streamflow was lower (due to less subsurface recharge) than in the reference simulation. In a study in the Chaudière watershed (Rousseau et al., 2007), a strong correlation (r^2=97.2%) was found between annual low flows and the amount of agricultural land in a watershed (and also in the sub basins). In their study, having more agricultural land at the expense of forested areas led to an increase in streamflow, particularly in summer and autumn, which subsequently led to an increase in low flows, particularly in summer.

Most studies examining land use change under climate change conditions have taken approaches of comparing large changes in forested area in the basin (Quilbé et al., 2008; Van Roosmalen et al., 2009), or have determined alterations in urban areas (Pfister et al., 2004), where the impacts on the hydrology are much more evident. In those studies however only the changes to flow were examined.

In our study, water quality was examined. The two realistic land use changes impacted the TP loads by a greater magnitude than they did the NO_3^--N loads. From December to April, TP loads were higher than in the reference simulation. In the months where TP loads were altered, the mean increases were of the same order and magnitude as increases due to climate change simulations. On the other hand, the change brought by the land use scenarios to NO_3^--N loads was roughly 10 times less than with the climate change simulations alone. Yet, no statistically significant differences compared to the reference simulation were detected because of the high standard errors of the monthly nutrient values.

Since the changes in land use involved subtly altering the crop quantities and types (and not the forest or urban areas so much), the water quality was not improved or deteriorated to any significant extent by the two land use change scenarios alone. However, the extreme "all corn" and “all forest” land use scenarios showed that the water quality could be greatly impacted by land use changes.

From our land use change scenarios, nutrient fluctuations were not significantly higher or lower than what is currently observed. And, land use change had little impact on water quality concentrations of TP or NO_3^--N. The median monthly values were similar to the reference simulation. Due to the high interannual variabilty, no significant differences from the reference simulation were found.

Not surprisingly, when combining a climate change simulation with a land use change scenario in the SWAT model, the climate change signal dominated the effects on simulated water quality. However, the combined impacts of climate and land use change showed a non-linear behaviour on surface water quality, which is consistent with results found for climate and land use change impacts on streamflow in southern Alabama (Wang et al., 2013). The compounded impacts were not predictable when the climate change was simply added to the land use change. Thus, it is imperative to study them together since examining the changes separately will not provide an accurate portrayal of the potential scope of change that may occur.

Non-linear processes and dynamic feedbacks made the direction of change non predictable as well.

When a combination of climate change and land use change scenarios was applied, the results were mostly driven by the climate change scenarios (it should be noted however, that the agricultural land use scenarios consisted of relatively small alterations of crop quantities and types, and were originally developed for a less distant future and may thus represent a more conservative trajectory of change). At the monthly time step, the combined climate and land use change simulations had comparable impacts regarding the changes to mean streamflow, sediment and TP loads as their counterpart climate change scenario alone. However, the compounded impacts of both were not the same as adding the mean individual changes to each other: during some months the impacts were less, and during other months greater than the sum. Thus, the magnitude and the direction of the combined change were not predictable as a sum of both effects.

The implementation of adaptation strategies that focus on agricultural management in the basin are a form of land use change, based on managing crops and cover practices. In the future, a longer growing season will provide more flexibility for implementing best management practices at the field level, such as inter-cropping, or fall seeding of a green manure. The adaptation strategies modeled were able to maintain the water quality at levels that are currently observed, but only if rather drastic adaptation practices are applied. Given the climate and land use change scenarios, most of the TP was transported during snowmelt in February and March, and two of the adaptation scenarios (STRAT and OPTIM) were able to significantly reduce TP loads during this time.

All of the adaptation strategies managed to reduce the median concentrations of TP to levels lower or similar than those during the reference simulation (1971-2000) for every month. The water quality criterion for TP (0.02 mg/L) was extremely difficult to attain in light of climate and land use change. Even drastic measures, such as those in the OPTIM scenario - although highly effective - were not able to achieve this goal, which could be a limitation of the SWAT model as the “all forest” scenario pointed to the extent of SWAT to achieve this criterion. Perhaps a

SWAT set-up with calibrated parameters to such adaptation practices would provide different results. The difficulty of attaining the TP criterion may also be due to the GWSOLP parameter in SWAT, which denotes the concentration of soluble P in the groundwater flow (mg P/L). This was fixed at 0.08 mg/L; it was determined based on calibration for historic conditions of intense agricultural areas. This parameter is static in all of the simulations undertaken with SWAT and surely provided a limitation to decreasing the mean TP concentration in the surface water, as was also observed in the FOREST scenario. Future work should examine the effects of reducing this parameter value.

The adaptation scenarios are effective, for the most part, at reducing the median monthly concentrations of NO_3^--N in the watershed. The OPTIM scenario had higher levels of mean NO_3^--N than the other two adaptation scenarios because of the swine manure applied in this scenario. Since the P content in the manure was used to meet crop P requirements, excess amounts of N were applied. Yet, the water quality criterion of 10.0 mg/L was rarely exceeded for NO_3^--N.

Only the OPTIM scenario significantly decreased the mean monthly transport of sediments every month, except for January. The most decrease took place in the winter months, by up to 70%. The STRAT and FEASB scenarios focused on removing agriculture from the 10% of land most vulnerable to non-point source pollution transport, which corresponded to 1795 ha in the basin. This was an effective strategy to significantly reduce mean annual TP loads by approximately 10 (±4) Mg compared to the climate and land use change scenario AHK_EXP. The OPTIM scenario, on the other hand, implemented best management practices as a blanket to the whole watershed, and was more effective at reducing the overall mean annual sediment (2400 (±200) Mg) and TP loads (20 (±4) Mg) in the watershed compared to the AHK_EXP scenario. Certainly an important reason for this decrease was also because the agricultural land on slopes >9% was converted to poplars, which corresponded to 2694 ha (or 4.3 % of the watershed).

Implementing adaptation strategies that focus on changing agricultural management practices can dampen the effects of the simulated changes. All three adaptation scenarios were able to decrease the median TP concentrations at the outlet of the basin to lower levels than in the AHK_EXP scenario. Yet, the 0.02 mg/L was not attained by the STRAT or FEASB scenarios, and only rarely by the OPTIM scenario.

Considering that Québec has agreed to reduce TP loads transported into the Missisquoi Bay by 38.9 Mg/yr (LCBP, 2013) from three watersheds (Pike River (41% of area); Missisquoi River (48% of area); and Rock River (11% of area); OBVBM, 2011a), these strategies only provide a partial contribution towards achieving this reduction in light of the possible future changes that may occur in the basin.

7.1. Model uncertainty

The results contain certain uncertainties embedded within; the major ones are listed below:

There is inherent uncertainty linked to climate change simulations. The modelling uncertainties due to applying climate simulations in hydrological models can be classified into the following categories: i) natural climate variability; ii) greenhouse gas emission scenario; iii) GCM structure; iv) downscaling technique (from GCM to RCM); and v) impact (hydrological) model (Poulin et al., 2011; Wilby, 2005). One possibility of accounting for some of the uncertainty is by using an ensemble of climate models (Harvey, 1997; Meehl, 2007). In this study, the three climate simulations covered approximately 50% of the climate variability from the 16 regional climate models currently available at Ouranos (and less than 50% if the GCM simulations were also considered).

Clearly, there are a number of hypotheses in the elaboration of the land use scenarios that may be questioned. However, the objective of the study was not to explicitly predict the future land use in the Pike River, but rather to establish different possible outcomes of crop types and their spatial distribution. The CLUE-S model also has a number of uncertainties. The model could only be applied for projections for the next 30 years because of the uncertainty surrounding future land use change. As well, the simulations with CLUE-S are difficult to validate because of a lack of historic land use change data for the most part. Finally, the model does not specifically account for actual climate change conditions. The future climate parameters (temperature, precipitation) were taken into account only indirectly through changing crop types, increasing yields, and increasing the growing season in SWAT. Lastly, inserting the land use scenarios developed with CLUE-S into SWAT necessitated using a tool in its beta version (SWAT2009_LUC) which has not been used before.

The SWAT2009_LUC tool has its limitations, and to our knowledge no other studies have so far implemented this recent methodology. The redistribution of the land use change pixels into existing HRUs is not optimized. For example, if no existing HRU with the same characteristics as the new land use (i.e. soil or slope) is identified in the sub-basin, the model will look for an HRU to match with the same land use only (Pai and Saraswat, 2011), so that the new land use will then be simulated on another soil or slope type. We have discussed the distortions introduced by this tool in section 6.3.2.1, yet we see no immediate solution to avoid this problem without compromising the model coherence. We recommend that the tool be investigated further in future applications (and that possible updates of the tool are used).

The hydrological model SWAT is a well suited tool to examine best management practices and their impacts on water quality. However, SWAT may not be the best tool to examine subtle redistributions of cropland changes in a watershed (unless a very high resolution set-up with many HRU's is undertaken). This is due to the configuration of the HRUs which are actually virtual in SWAT: i.e. they have no real spatial allocation in the sub-basins for SWAT (it is a semi-distributed model). Therefore, a field that is adjacent to a water body in reality may not be adjacent when it is represented as part of the larger HRU in SWAT. In order to achieve this level of detail, the model would have to be set-up at a much finer resolution, so that each HRU is only composed of a few fields.

An important source of non-point source pollution transportation takes place during heavy precipitation events. In our SWAT set-up, we used daily precipitation input, therefore SWAT was not able to reproduce intense precipitation events such as due to I_{30} rainfall (30 minute maximum rainfall intensity). The daily rainfall that was used provides lower rates than the peak intensity occurring during a storm event. Also, storm intensities may change stronger than indicated by the daily data used, because climate models typically underestimate intense precipitation (due to the high resolution of these events) and overestimate the frequency of small precipitation events (Gagnon et al. 2013). More intense precipitation will entail greater nutrient transport to surface water bodies.

Although best management practices can be modelled in SWAT, they have not been validated for the Pike River site, due to a lack of field data. Thus, it is not sure if the modifications to the parameters, based on expert judgement and literature, are entirely justified and effective for the watershed.

The increase in atmospheric CO_2 is not accounted for in SWAT. In the model, the ambient CO_2 concentration remains constant at 330 ppmv. Yet, provided sufficient N fertilization is applied to the crops, CO_2 can improve yields of C_3 crops by increasing biomass (Long et al., 2006). In an increased CO_2 environment crops will have greater water use efficiency, and produce less stomata. Yet, their increase in biomass may necessitate more water for growth. Consequently, the evapotranspiration of a plant will also be altered. These feedbacks are not currently considered in SWAT.

Despite the above limitations, models are generally considered the best available tools to address research questions such as the ones in this project, as long as their strengths and limitations are acknowledged.

8. Conclusions

Although a number of challenges were encountered, mainly on the modelling side, some key messages can be extracted from this study:

1. Our model simulation results suggest that overall, climate change may have a larger impact on sediment and on nutrient transport in the Pike River watershed than changes brought about by alterations in the configuration of agricultural land use. Although the land use changes increased TP loads in winter and spring months by the same magnitude as the increases observed with the climate change simulations alone, the results of the land use driven increases were not significant. Also, the climate simulations caused up to 10 times more NO_3^--N transport than the land use change scenarios.
2. Climate change drives streamflow mainly due to the increases in precipitation and the warmer surface air temperatures which affect certain important hydrological processes, such as snowmelt. Climate change indirectly impacts the transport of TP since TP loads are mainly driven by surface runoff as well as by snowmelt. Climate change also drives the changes in the transport of NO_3^--N. Generally, the solubility of NO_3^--N is higher than that of TP, making it more labile as a nutrient since it is conveyed by several hydrological pathways (infiltration, seepage, percolation, groundwater flow, surface runoff).
3. Based on our applied scenarios, land use changes also impact water quality, but not to the extent that climate change does. Land use changes imply a different fertilizer regime being implemented in the basin as well as alterations in the timing of N and P applications to follow crop type changes. Thus, the varied crop types dictate the nutrient input amounts in the basin, whereas the movement of nutrients is governed by the climate. If future land use changes in a watershed are subtle and involve mostly a redistribution of crops, then the impacts of climate change on water quality and hydrology will likely dominate.
4. Specific and tailored changes to land areas, however, can impact water quality to a greater extent, depending on the modifications to the land implemented. For example, targeted alterations such as management practices to reduce erosion in the most vulnerable areas can

improve water quality. Or, drastic changes to the vegetation cover in the watershed will alter the water quality and have demonstrated the limits of the impacts modelled. For example, forested or corn areas are two of the more extreme types of land uses that can impact the hydrology; any major changes in these land uses can bring about significant changes to nutrients.

5. The combined interaction between climate change and land use change are unique and non-linear. Although impacts from the climate change simulations were similar for TP and one order of magnitude greater for NO_3^--N than in the land use change scenarios, the combined effects were unpredictable, both in the direction of change and in the magnitude. Therefore, it is recommended to examine both changes simultaneously.

6. According to the four investigated scenarios of combined climate and land use change, the simulated impacts on surface water quality in the Pike River by 2041-2070 led to a degradation of water at the outlet. Additional mean annual sediment loads ranged from 168 ±220 to 301 ±201 Mg; additional mean TP loads ranged from 6 ±4 to 9 ±4 Mg; and additional mean NO_3^--N loads ranged from 59 ±72 to 151 ±74 Mg.

7. If adaptation strategies are implemented to reduce the impacts caused by the most severe combination of climate and land use change scenarios, the transport of mean annual sediments can be reduced by 130 ±219 to 2422 ±217 Mg; the mean TP loads by 11 ±4 to 20 ±4 Mg; and mean NO_3^--N loads can be reduced by 36 ±79 to 114 ±73 Mg. The reduction will depend on the types of management strategies. Targeting the 10% most vulnerable lands prone to erosion and P loss by taking them out of agricultural production is an effective option for reducing sediment and nutrient loads. However, implementing wide reaching practices (e.g. buffer strips, cover crops, crop rotations, agroforestry on steep slopes) reduces TP transport almost twice as much and the amount of sediment transported by up to 7 times.

8. All three adaptation scenarios were able to decrease the median TP concentrations at the outlet of the basin and restore concentrations to lower or similar levels than those of the reference simulation. The period of snowmelt was effectively targeted. At a minimum, strategies that reduce overland flow during the month of February should be implemented in the future, with practices such as cover crops, no-till farming, and crop residue management.

9. Despite the implementaion of a suite of agricultural management changes (adaptations) in the basin, the quality of surface water was not improved enough to meet the water quality criterion of 0.02 mg/L for TP. On the other hand, mean monthly NO_3^--N concentrations rarely exceeded 10.0 mg/L for all adaptation scenarios.

10. Finally, it is important to recognize that there is a considerable amount of inherent uncertainty in this modelling study. Main uncertainties are related to both the applied models and the various scenarios that were developed.

9. Recommendations

9.1. Recommendations for stakeholders

- The methodology outlined here seems suitable at identifying the impacts of future climate and land use changes in a watershed and can be applied to other basins, provided sufficient data are available to run the models. Collecting data at the field level is therefore imperative to conduct such studies.
- Due to non-linear interactions, the impacts of climate and land use change (including adaptation practices) need to be examined in concert to determine the full extent of impacts that may occur to water quality in a basin.
- Our results (using only 4 scenarios of climate and land use change) suggest that the surface water quality may be negatively affected by 2041-2070 in the Pike River. Implementing best management practices at the field level can help to mitigate the effects of climate and land use change to retain - and even somewhat improve - the quality of the water at levels currently observed.
- Implementing targeted best management practices on the agricultural land most prone to the transport of TP especially during winter and spring is effective at reducing non-point source pollution, but may not be sufficient to achieve significant enough reductions to consistently meet the water quality criteria throughout the year for TP. Nevertheless, implementing a soil cover to protect the surface of the field from erosion in the winter and spring months should be mandatory to control surface runoff, especially during spring melt.
- A combination of removing the 10% of the crop land most prone to TP transport from production, as well as planting cover crops after cash crops, implementing buffer strips, and using more organic manure instead of inorganic fertilizer can attenuate the impacts of climate and land use change and maintain water quality levels to lower or similar levels as those in the current climate.
- A key driver of change is the increase in precipitation combined with earlier snowmelt and related increases in streamflow. Thus, best management practices at the field level should be targeted to favour infiltration and reduce overland flow at the source in order to protect the soil and curb the effects of sediment and nutrient transport during the snowmelt period. Possible measures include the planting of cover crops, no-till farming, and crop residue management.

9.2. Scientific recommendations

- Continue to collect water quality data (stations must continue to operate) in the watershed. Collect samples at least once a week (several times per month) throughout the year, and ensure samples are obtained from several outlets in the watershed (e.g. outlets 4, 6, 14, 18, and 23). Applying controlled standards is also necessary to improve the calibration and validation of the water quality component of the hydrological model.
- In addition to water quality data, actual land use information (and the corresponding management practices) is needed to test the adequacy of the model simulations to portray the observed changes. Therefore, monitor the water quality and record the annual land use changes that take place spatially in the watershed. Increasing the length of all data series will help draw links between hydrology, land use and climate change.
- Data on best management practices at the farm level are required to examine how these influence nutrient transport and water quality.

- Conduct a sensitivity analysis on the effect of altering the GWSOLP parameter in SWAT on achieving different TP concentrations at the outlet.
- Further examine if SWAT is able to model the historic increase in TP in the basin, with the historic changes in land use that took place from 1980 to today.
- Set up SWAT with the whole watershed in forest and calibrate the model (using data from a similar basin) to test its true limits. And then repeat with the whole watershed planted to corn.
- Further scrutinize the SWAT2009_LUC tool and work with the developers to resolve the issue of the tool greatly distorting some of the prescribed land use changes when transferring them into SWAT.

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APPENDICES

LIST OF APPENDICES

Appendix 1: Final Parameters used in the Calibration of SWAT

Table A1: Final calibration parameters (best set) for streamflow, calibrated simultaneously at outlets 14 and 18, using the semi-automated calibration program SUFI-2. Applied to all sub-basins, except Walbridge.

Type of change[1]	Parameter Name	Value	Description
r	CN2.mgt[2]	-0.175	SCS curve number to separate rainfall into infiltration or runoff
v	SFTMP.bsn	-2.027	Snow fall temperature (°C)
v	SMTMP.bsn	2.002	Snow melt base temperature (°C)
v	SMFMX.bsn	3.655	Maximum melt rate for snow (mm/(°C day))
v	SMFMN.bsn	3.166	Minimum melt rate for snow (mm/(°C day))
v	TIMP.bsn	0.526	Snow pack temperature lag factor
v	ALPHA_BF.gw	0.844	Baseflow recession constant (days)
v	GW_DELAY.gw	1.790	Groundwater delay to attain shallow aquifer (days)
v	GWQMN.gw	75.347	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)
v	GW_REVAP.gw	0.085	Groundwater re-evaporation coefficient (movement of groundwater towards the overlying unsaturated zone)
v	REVAPMN.gw	187.625	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm H_20)
v	ESCO.hru	0.987	Soil evaporation compensation factor
v	EPCO.hru	0.566	Plant uptake compensation factor
r	SOL_AWC(1).sol	0.225	Soil available water capacity (mm H_2O/mm soil) for the first soil layer
r	SOL_K(1).sol	0.022	Soil saturated hydraulic conductivity (mm/hr) for the first soil layer
r	SOL_BD(1).sol	0.014	Soil bulk density (g/cm^3) for the first soil layer
v	TDRAIN.mgt	24.000	Time to drain soil to field capacity (hours)
v	DDRAIN.mgt	900.000	Depth to sub surface drain (mm)
v	GDRAIN.mgt	12.000	Drain time lag hours (hours)
v	SHALLST.gw	1000.000	Initial depth of water in the shallow aquifer (mm H_2O)
v	DEEPST.gw	2300.000	Initial depth of water in the deep aquifer (mm H_2O)
v	SNO50COV.bsn	50.000	Minimum snow water content that corresponds to 100% snow cover (mm)
v	SNOCOVMX.bsn	1.000	Snow water equivalent that corresponds to 50% snow cover (mm)

[1] r: relative change of default value, v: replacement of default value, a: value added to default value.

[2]CN2.mgt default values were all initially decreased by 20%. A further decrease took place in the calibration process

Table A2: Final calibration parameters (best set) for streamflow, calibrated simultaneously at outlets 4 and 6 (Walbridge), using the semi-automated calibration program SUFI-2. Applied only to Walbridge sub-basin.

Type of change[1]	Parameters	Value	Description
r	CN2.mgt (4)	-0.028	SCS curve number to separate rainfall into infiltration or runoff for the sub basin in parenthesis
r	CN2.mgt (6)	-0.104	
v	SFTMP.bsn	3.462	Snow fall temperature (°C)
v	SMTMP.bsn	-1.802	Snow melt base temperature (°C)
v	SMFMN.bsn	3.174	Maximum melt rate for snow(mm/(°C day))
v	SMFMX.bsn	2.129	Minimum melt rate for snow (mm/(°C day))
v	TIMP.bsn	0.437	Snow pack temperature lag factor
v	SNO50COV.bsn	0.498	Minimum snow water content that corresponds to 100% snow cover (mm)
v	SNOCOVMX.bsn	157.905	Snow water equivalent that corresponds to 50% snow cover (mm)
v	SURLAG.bsn	17.886	Surface runoff lag time
v	ALPHA_BF.gw (4)	0.771	Baseflow recession constant (days) for the sub basin in parenthesis
v	ALPHA_BF.gw (6)	0.481	
v	GW_DELAY.gw (4)	14.764	Groundwater delay to attain shallow aquifer (days) for the sub basin in parenthesis
v	GW_DELAY.gw (6)	3.575	
v	GWQMN.gw (4)	208.176	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O) for the sub basin in parenthesis
v	GWQMN.gw (6)	255.770	
v	GW_REVAP.gw (4)	0.193	Groundwater re-evaporation coefficient (movement of groundwater towards the overlying unsaturated zone) for the sub basin in parenthesis
v	GW_REVAP.gw (6)	0.079	
v	REVAPMN.gw (4)	117.609	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm H_20) for the sub basin in parenthesis
v	REVAPMN.gw (6)	222.042	
v	RCHRG_DP.gw (4)	0.297	Deep aquifer percolation fraction (%)for the sub basin in parenthesis
v	RCHRG_DP.gw (6)	0.327	
v	ESCO.hru (4)	0.912	Soil evaporation compensation factor for given sub basin in parenthesis
v	ESCO.hru (6)	0.970	
v	EPCO.hru	0.586	Plant uptake compensation factor
v	CH_K1.sub (4)	42.158	Effective hydraulic conductivity in tributary channel (mm/hr) for the sub basin in parenthesis
v	CH_K1.sub (6)	20.000	

v	CH_K2.rte (4)	50.000	Effective hydraulic conductivity in the main channel (mm/hr) for the sub basin in parenthesis
v	CH_K2.rte (6)	23.747	
v	TDRAIN.mgt (CORN)	45.750	Time to drain soil to field capacity (hours) for the crop in parenthesis
v	TDRAIN.mgt (SOYB)	32.625	
v	TDRAIN.mgt (SWHT)	45.555	
v	TDRAIN.mgt (STRW)	32.763	
v	TDRAIN.mgt (POTA)	38.258	
v	TDRAIN.mgt (AGRL)	32.536	
v	TDRAIN.mgt (AGRR)	35.475	
v	TDRAIN.mgt (SWCH)	35.475	
v	DDRAIN.mgt	900.000	Depth to sub surface drain (mm)
v	GDRAIN.mgt	12.000	Drain time lag hours (hours)
v	SHALLST.gw	1000.000	Initial depth of water in the shallow aquifer (mm H_2O)
v	DEEPST.gw	2300.000	Initial depth of water in the deep aquifer (mm H_2O)

[1] r: relative change on default value, v: replacement of default value, a: value addition to default value

[2]CN2.mgt default values were all initially decreased by 20%. A further decrease took place in the calibration process

Table A3: Final calibration parameters (best set) for sediments, TP, and NO_3^--N at the monthly step at outlets 4, 6 and 23 (Walbridge and Pike River). Applied to all sub-basins.

Type of change[1]	Parameters[2]	Value	Description
v	ADJ_PKR.bsn	0.505	Peak rate adjustment factor for sediment routing in the main channel
v	CH_EROD.rte	0.050	Channel erodibility factor
v	CH_COV.rte	0.451	Channel cover factor
v	CH_N2.rte (4)	0.279	Manning roughness n values for the main channel, for the sub basin in parenthesis
v	CH_N2.rte (6)	0.275	
v	CH_N1.sub (4)	0.258	Manning roughness n values for the tributary channel, for the sub basin in parenthesis
v	CH_N1.sub (6)	0.185	
r	USLE_K(1).sol	-0.396	USLE soil erodibility factor for the first soil layer
a	SLSUBBSN.hru (4)	-8.995	Average slope length for the sub basin in parenthesis
a	SLSUBBSN.hru (6)	38.000	
r	HRU_SLP.hru	-0.049	Average slope steepness
r	OV_N.hru	-0.080	Manning roughness n values for overland flow
v	BIOMIX.mgt	0.025	Biological mixing efficiency
v	P_UPDIS.bsn	65.150	Phosphorus uptake distribution
v	PPERCO.bsn	15.576	Phosphorus percolation coefficient ($10m^3$/Mg)
v	PHOSKD.bsn	160.050	Phosphorus soil partitioning coefficient (m^3/Mg)
v	PSP.bsn	0.6	Phosphorus availability index
v	RSDCO.bsn	0.072	Residue decomposition coefficient
v	ERORGP.hru (4)	3.633	Phosphorus enrichment ratio for loading with sediment for the sub basin in parenthesis
v	ERORGP.hru (6)	1.843	
v	GWSOLP.gw	0.08	Concentration of soluble phosphorus in groundwater contribution to streamflow from sub-basin (mg P/L)
v	SOL_SOLP.chm	0	Initial soil P concentration (mg P/kg soil). If value is 0, the initial soil P is defined as being 5 mg P/kg soil
v	RS5.swq	0.028	Organic phosphorus settling rate in the reach at 20 °C/day
v	BC4.swq	0.372	Rate constant for biological oxidation of NH4 to NO2 in the reach at 20 °C in well aerated cond.
v	RCN.bsn	1.076	Concentration of nitrogen in rainfall (mg/L)
v	CMN.bsn	0.001	Rate factor for humus mineralization of active organic nutrients (N and P)

v	CDN.bsn	0.001	Denitrification exponential rate coefficient
v	NPERCO.bsn	0.320	Nitrate percolation coefficient
v	N_UPDIS.bsn	64.432	Nitrogen uptake distribution parameter
v	SDNCO.bsn	0.132	Denitrification threshold water content
v	ERORGN.hru (4)	2.212	Organic N enrichment ratio for loading with sediment for the sub basin in parenthesis
v	ERORGN.hru (6)	3.070	
v	SHALLST_N.gw (4)	25.064	Initial concentration of nitrate in shallow aquifer (mg N/L) for the sub basin in parenthesis
v	SHALLST_N.gw (6)	72.288	
v	AI1.wwq	0.073	Fraction of algal biomass that is nitrogen (mg N/mg alg.)

[1] r: relative change on default value, v: replacement of default value, a: value addition to default value

Appendix 2: Questionnaire for Farmers

This questionnaire is intended for the person managing the farm on a daily basis. This questionnaire is anonymous and all answers shall remain strictly confidential. It is composed of 23 questions regarding crop choices and farm land use. It should take less than 30 minutes to fill out the questionnaire. If you do not have all of the information requested, you may answer to the best of your knowledge.

The farm business

1. What kind of farm would describe yours as (*please check the relevant boxes*)?

   Diary ☐/ Swine- or hog finishing ☐ / Poultry ☐/ Cash crops ☐ / Vegetable☐ / Fruit and vegetable processing ☐ / Mixed ☐ (*which?*) ____ / Other (*please describe*) ____

2. How many people assist with making decisions regarding this farms' operations, in the following age categories (including yourself):

   __ Younger than 20 yrs old

   __ 20-40 years old

   __ 40-60 years old

   __ Older than 60 years

3. How long have you been farming?_____________ years
   a. How long have you been on this particular piece of land? ___________ years

4. Have you sold ☐ / acquired or rented more land since you started farming? (*please circle the answer*) **yes** **no**
   a. If so, what is the total percentage of crop land that you own today compared with when you started? ________________ % more , or ___________________ % less

Information on field crops

5. What % of your agricultural crop land does not provide your farm with any direct income (e.g. brush, forested land, abandoned land)? ________________ %
   a. How much percent land do you currently have in pasture or hay? _________________%

b. Did the amount of pasture/hay land on your farm change over the past 10 years? (*please circle your answer*) **yes** **no**

If yes, by approximately how much more___________ *% more, or* _______________**%** less?

6. In a typical year, normally what crops do you grow? ____

____

____

   a. Which would you say are your two main crops?

   ____

   b. Do you plan on continuing to grow these same crops as your main crops in the future? (*please circle your answer*) **yes** **no** **unsure**

      i. If not, or if unsure, why?

      ____

      ____

7. List all the additional crops that you have grown on this particular farm since you started farming the land (*as far as you can remember*)?

____

____

____

8. If relevant, can you name some of the deciding factors why you <u>do not</u> choose to plant certain crops on your farm anymore? For example (*please check the appropriate boxes*)

   ☐ Monetary reasons (including subsidies)

   ☐ Demand for product

   ☐ Pests, diseases

   ☐ Replacement of crops by biofuel crops

   ☐ Climate factors

   ☐ Rotation

   ☐ Other (*please specify*)____

9. Which crops are you growing this year? *(for each crop type, please indicate the % of area of each*)

Crop	% surface cultivated	Crop	% surface cultivated
______________________	________________%	______________________	________________%
______________________	________________%	______________________	________________%
______________________	________________%	______________________	________________%
______________________	________________%	______________________	________________%
______________________	________________%	______________________	________________%

10. In your opinion, how much influence do the following factors have on the choice of which types of crops to grow on your farm? (*Please rank: 1= large influence, 2= medium, 3=little influence*)

Economic return of the crop	1	2	3
The custom or tradition of your farm	1	2	3
The farm experience that you (or your family) have	1	2	3
The time expenditure required to cultivate the crop	1	2	3
Access to farm equipment, machinery and technology	1	2	3
Access to markets for the crop	1	2	3
Available information relevant for the cultivation of the crop	1	2	3
Other (*please explain*)____	1	2	3

Changes in cultivation

11. What has prompted you, in the past 10 years, to grow crops that you previously had not grown on the farm before? *(please circle all relevant factors by ranking the following where 1=very important, 2 = medium, and 3=low. If nothing has changed in the past 10 years, tick this box:* ☐

Speaking with farmers/neighbors/friends	1	2	3
Advice from agronomists/experts/government officials	1	2	3
Minimize the risk from crop failure	1	2	3
Financial factors or incentives (including government subsidies)	1	2	3
Market factors (e.g. sale difficulties, changing demands)	1	2	3
Pests, diseases, weeds	1	2	3
Climate factors	1	2	3
Access to new information (e.g. production guides, internet)	1	2	3
Access to new technology (e.g. new machines)	1	2	3
Other (*please explain*)____	1	2	3

12. Are you planning on growing any new crops in the future that were not grown on your farm until now? (*please circle your answer*) **yes** **no**

    a. If yes, which ones? ____

b. If they require irrigation, will you install an irrigation system? (*please circle your answer*)

    yes **no**

    i. If so, for what area? ____ha

13. What would influence your decision to cultivate other or additional types of crops from the ones you have grown? (*please determine the importance of all relevant factors by ranking the following where 1=very important, 2 = medium, and 3=low*).

Market opportunities	1	2	3
Government subsidies	1	2	3
Acquired new land	1	2	3
Climate factors (precipitation, temperature, sunshine, etc.)	1	2	3
Speaking with farmers/neighbors/friends	1	2	3
Access to new agronomic information about the crop	1	2	3

Other agricultural changes

14. If you plan to expand or intensify your current production, will you (*please check all relevant boxes*):

- ☐ Purchase new farm land?
- ☐ Lease more land?
- ☐ Intensify your existing operations (i.e. intercropping)
- ☐ Other (*please specify)*____?

15. Are you concerned with any potential negative future impacts that might occur on your farm? (any developments at the local, regional or national levels?) (*please circle your answer*) **yes** **no**

    a. If so, which ones?

    ____

    ____

    b. When the impacts occur, are you planning on taking protective measures? (*please circle your answer*) **yes** **no**

    (or are you already taking any protective measures? (*please circle your answer*)

    yes **no**)

    i. If so, which ones?

    ____

16. If the growing season length would increase by four weeks due to changes in the future climate, do you think this would this affect your crop choice decisions, or change your agricultural practices? (*please circle your answer*) **yes** **no**

    a. If yes, in which ways?

    ____

    ____

17. In the past thirty years, have you noticed a change in the climate? (*please circle your answer*)

    yes **no**

    If yes,

    a. What has changed?

    ____

    ____

    b. Have the changes affected your farm production? (*please circle your answer*) **yes** **no**

        i. If yes, how so? ____

    ____

18. Which erosion protection measures are you implementing on your agricultural land?

    ____

    a. Have you noticed a decrease or even a prevention of soil erosion through the implementation of these measures? (*please circle your answer*) **yes** **no**

General questions:

19. What are your plans for the farm over the next 30 years? (*please check the appropriate boxes*)

☐ Family member (or other) will take over and continue farming

☐ Abandoning the farm is likely

☐ Growing and expanding the farm

☐ The land will be developed on from urban areas

☐ Other (*please specify*) ____

20. How would you estimate the overall quality of the topsoil on your agricultural land?

☐ good ☐ average ☐ rather poor

21. In which township or village are the majority of your agricultural fields located?

____

22. Is your farm currently benefitting from any government subsidies that are available for your production?

(*please circle your answer*) **yes** **no**

or from environmental protection measures (measures against soil erosion for example available in the Prime-Vert)? (*please circle your answer*) **yes** **no**

23. Where do you obtain advice and recommendations for your agricultural business with regards to the optimizing your farm productivity?

☐ Agronomists

☐ Government sources

☐ Agricultural magazines

☐ Internet

☐ Other (*please specify*)____

Thank you for your participation!

This questionnaire is anonymous and your answers will remain strictly confidential and serve only to improve my scientific research. If you have questions or comments, you are welcome to contact me:

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Other comments:

____

____

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Questionnaire Pour Les Producteurs

Ce questionnaire est destiné à la personne qui gère la ferme sur une base quotidienne. Ce questionnaire est anonyme et toutes les réponses sont strictement confidentielles. Il est composé de 23 questions qui portent sur le choix des cultures et sur l'utilisation des terres agricoles de la ferme. Le temps nécessaire au remplissage du questionnaire est évalué à moins de 30 minutes. Si vous ne possédez pas toute l'information demandée, vous pouvez répondre au meilleur de vos connaissances.

L'exploitation

24. Comment décririez-vous votre entreprise (*svp, cochez toutes les cases appropriées*)?

Laitière ☐/ Porcine ☐/ Volaille ☐/ Cultures commerciales ☐/ Maraîchère ☐/ Fruits et légumes de transformation ☐/ Mixtes ☐ *lesquels*) :___________________________________

Autre (*svp, décrivez*) : ____

25. Combien de personnes participent à la prise de décision concernant les opérations menées dans votre entreprise par groupe d'âge (en vous incluant) ?

__ Moins de 20 ans

__ 20-40 ans

__ 40-60 ans

__ Plus de 60 ans

26. Depuis combien d'années êtes-vous dans le métier ?_____________________ ans

   a. Depuis combien de temps exploitez-vous les terres de votre ferme actuel?

   __________________ ans.

27. Avez-vous déjà vendu ☐ / acheté ou loué plus de terres depuis que vous avez commencé à exploiter ces terres (*svp, entourez la bonne réponse*) ? **oui** **non**

   a. Si oui, quel est le pourcentage de terre cultivée que vous possédez aujourd'hui par rapport à vos débuts sur cette exploitation? ____________ % en plus ou

   ____________ % en moins

Les cultures

28. Quel pourcentage de vos terres ne fournit pas de revenu pour votre entreprise (par ex. : jachère, forêts, terres abandonnées)? __________%
    a. Quel est le pourcentage des terres en production de foin ou en pâturage? _______%
    b. Est-ce que la surface de vos terres en production de foin ou en pâturage a évolué dans les dernières 10 ans (*svp, entourez la bonne réponse*) ? **oui** **non**

       Si oui, quelle a été, approximativement, l'évolution de vos terres en pâturage ?

       _________ % en plus, ou __________% en moins ?

29. Quelles sont les cultures, normalement présentes sur votre exploitation?

    ____

    ____

    a. Parmi ces cultures, quelles sont vos deux cultures principales?

       ____

    b. Dans le futur, pensez-vous conserver ces deux cultures comme cultures principales (*svp, entourez la bonne réponse*) ? **oui** **non** **ne sait pas**

30. Si non, ou si incertain, pourquoi?

    ____

31. Listez toutes les autres cultures que vous avez cultivées depuis vos débuts sur cette exploitation *(d'aussi loin que vous pouvez vous souvenir*).

    ____

    ____

32. Si pertinent, pouvez-vous nommer les raisons pour lesquelles vous ne cultivez plus certaines cultures (*svp, cochez toutes les cases appropriées*)?

    ☐ Rentabilité de la culture (incluant des subventions)

    ☐ Demande pour la production

    ☐ Ravageurs, maladies

    ☐ Remplacement par des cultures pour la production de biocarburant

    ☐ Facteurs climatiques

    ☐ Rotation

    ☐ Autres (*svp, précisez*)____

33. Quelles cultures faites-vous pousser cette année? (*svp, indiquez pour chaque culture, quel % de votre surface cultivée elle représente*) :

Culture	% surface cultivée	Culture	% surface cultivée
____________________	________________%	____________________	________________%
____________________	________________%	____________________	________________%
____________________	________________%	____________________	________________%
____________________	________________%	____________________	________________%
____________________	________________%	____________________	________________%

34. Selon votre opinion, à quel point les facteurs suivant influencent vos choix de mise en culture? (*svp, entourez les réponses appropriées 1= Influence importante, 2= influence moyenne, 3=peu d'influence*)

Rentabilité économique de la culture	1	2	3
Tradition de l'entreprise	1	2	3
Expérience que vous ou votre famille avez	1	2	3
Temps disponible pour cultiver la culture	1	2	3
Accès à l'équipement, la machinerie ou la technologie agricole	1	2	3
Accès au marché pour la culture	1	2	3
Informations pertinentes disponibles pour la culture	1	2	3
Autres (*svp, précisez*) ____	1	2	3

Modifications apportées aux cultures

35. Qu'est-ce qui vous a poussé, dans les dix dernières années, à choisir de nouvelles cultures que vous n'aviez jamais cultivées auparavant (*svp, entourez les réponses appropriées 1= très important, 2= moyennement important, 3=peu important*) ?
(Si vous n'avez pas cultivé de nouvelles cultures au cours des dix dernières années, svp, cochez cette case : ☐)

En parlant avec des agriculteurs/voisins/amis	1	2	3
Recommandation d'agronomes/experts/représentant du gouvernement	1	2	3
Minimiser les risques liés aux cultures	1	2	3
Incitatif ou autre facteur financier (incluant les subventions gouvernementales)	1	2	3
Facteurs liés aux marchés (par ex. vente difficile, modification de la demande)	1	2	3
Ravageurs, maladies, mauvaises herbes	1	2	3
Facteurs climatiques	1	2	3
Accès à de nouvelles informations (par ex. guide de production, internet)	1	2	3
Accès à de nouvelles technologies (par ex. machinerie)	1	2	3
Autres (*svp, précisez*) ____	1	2	3

36. Dans la future, pensez-vous cultiver de nouvelles cultures jamais cultivées auparavant (*svp, entourez la réponse appropriée*) ? **oui** **non**
    a. Si oui, lesquelles? ____
    b. Est-ce que vous prévoyiez installer un système d'irrigation pour ces cultures? (*svp, entourez la réponse appropriée*) ? **oui** **non**
        i. Si oui, pour quelle superficie?
        ____ ha

37. Qu'est-ce qui influencerait votre décision de cultiver des cultures différentes de celles que vous cultivez en ce moment (*svp, entourez les réponses appropriées 1= très important, 2= moyennement important, 3=peu important*)

Opportunités de marché	1	2	3
Subvention du gouvernement	1	2	3
Acquisition de nouvelles terres	1	2	3
Facteurs climatiques (pluie, température, ensoleillement, etc.)	1	2	3
Discussion avec des agriculteurs/voisins/amis	1	2	3
Accès à de l'information nouvelle sur la culture	1	2	3
Autres (*svp, précisez*) ____	1	2	3

Autres modifications apportées à l'exploitation

14. Si vous planifiez accroître vos superficies cultivées ou augmenter votre production, comment vous y prendriez-vous? (*svp, cochez toutes les cases appropriées*):

☐ Acheter de nouvelles terres

☐ Louer plus de terres

☐ Intensifier vos pratiques culturales (par ex. : plus de cultures annuelles)

☐ Autres (svp, précisez) _____________________________________ ____________________

15. Êtes-vous inquiet/inquiète des impacts éventuels futurs qui pourraient affecter votre entreprise (des développements à l'échelle local, régional ou national)? (*svp, entourez la réponse appropriée*) **oui** **non**

a. Si oui, lesquels?

____

____

____

b. Pensez-vous prendre des mesures pour que votre entreprise puisse faire face à ces risques *(svp, entourez la réponse appropriée*)? **oui** **non**

(ou avez-vous déjà commencé à mettre en œuvre ces mesures sur votre exploitation (*svp, entourez la réponse appropriée*) ? **oui** **non**

i. Si oui, lesquelles?

____

____

16. Si la saison de croissance s'allongeait de quatre semaines à cause des changements climatiques, pensez-vous que cela affecterait vos décisions quant à vos choix de cultures ou vos pratiques culturales (*svp, entourez la réponse appropriée*) ? **oui** **non**

    a. Si oui, de quelles façons?

    ____

    ____

17. Lors des trente dernières années, avez-vous noté un changement dans les conditions climatiques (*svp, entourez la réponse appropriée*)? **oui** **non**

    a. Si oui, qu'est-ce qui a changé?

    ____

    ____

    b. Et est-ce que ces changements ont affecté votre entreprise (*svp, entourez la réponse appropriée*) ? **oui** **non**

       i. Si oui, comment?

       ____

    ____

18. Quelles mesures de conservation des sols utilisez-vous sur vos terres?

    ____

    a. Avez-vous noté une diminution de l'érosion des sols depuis l'utilisation de ces mesures (*svp, entourez la réponse appropriée*) ? **oui** **non**

Informations générales:

19. Quel avenir envisagez-vous pour votre entreprise pour les 30 prochaines années? (*svp, cochez toutes les cases appropriées*)

    ☐ Des membres de la famille (ou autre) prendront la relève de l'exploitation

    ☐ Les terres seront certainement laissées à l'abandon

    ☐ Une expansion de l'entreprise ou de la ferme est prévue

    ☐ Les terres seront absorbées par l'urbanisation

    ☐ Autres (*svp, précisez*)

    ____

20. Comment estimez-vous la qualité générale des sols arables de votre exploitation (*svp, entourez la réponse appropriée*) ?

    ☐ Bonne ☐ Moyenne ☐ Mauvaise

21. Dans quel village ou municipalité (MRC) se situe la majorité des terres que vous exploitez ?

    ____

22. Est-ce que votre entreprise bénéficie de subventions gouvernementales pour supporter votre revenu ou améliorer votre production? (*svp, entourez la réponse appropriée*)? **oui** **non**

    Ou pour la protection de l'environnement (mesures pour contrer l'érosion par exemple disponibles dans Prime-vert (*svp, entourez la réponse appropriée*)? **oui** **non**

23. D'où obtenez-vous des conseils et des recommandations pour optimiser la productivité de votre entreprise? (*svp, cochez toutes les cases appropriées*)

    ☐ Conseillers agricoles

    ☐ Sources gouvernementales

    ☐ Magazines agricoles

    ☐ Internet

    ☐ Autres (svp, précisez)

    ____

Merci de votre participation!

Ce questionnaire est anonyme et vos réponses demeureront strictement confidentielles et serviront uniquement à alimenter la réflexion de ma recherche scientifique. Si vous avez des questions ou des commentaires pendant ou après le remplissage du questionnaire, n'hésitez pas à me contacter :

Mme. B. Mehdi Département de Géographie Université McGill 805 rue Sherbrooke ouest Montréal, Quebec, H3A 2K6	E-mail: bano.mehdi@mail.mcgill.ca Site web: http://www.geog.mcgill.ca/grad/mehdi/mehdi.html

Autres commentaires:

____

____

____

____

____

____

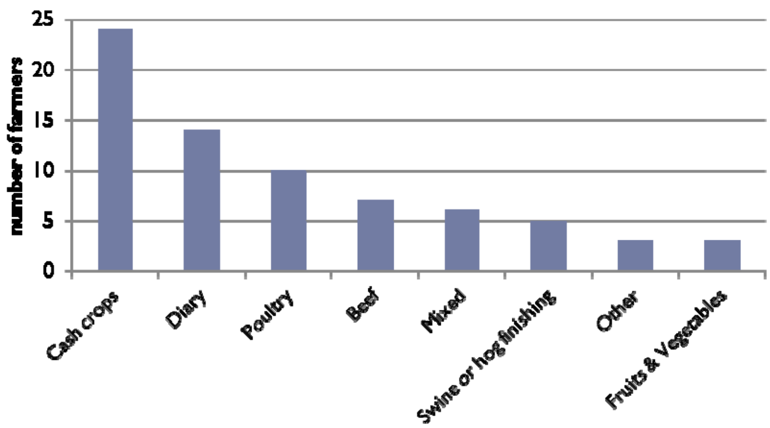
____

Appendix 3: Results of Farmer Questionnaires

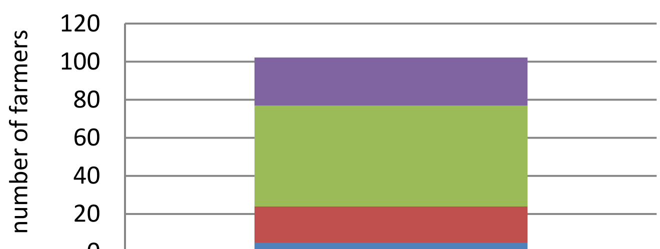
- Group 1 consisted of farmers in the Pike River watershed (area 630 km^2), Québec. The questionnaires were sent directly to farms in the watershed by the local office of the Ministère de l'Agriculture des Pêcheries et de l'Alimentation (Bedford). In total, 210 questionnaires were sent to full-time farmers. A response rate of 24% was obtained.
- Group 2 consisted of 23 young farmers enrolled in their last year of the Farm Management Technology Program at Macdonald College, in Ste-Anne-de-Bellevue, Québec (one student was from a farm in the Pike River watershed). The questionnaire was distributed to students in one of their classes, and each student answered the questionnaire in class.

<u>Responses to some of the questions from Group 1</u>

Q1. What kind of farm would describe yours as?

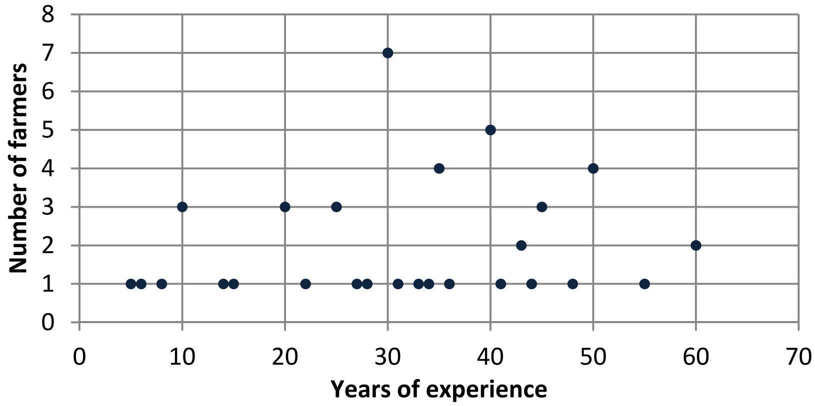


Q2. How many people assist with making decisions regarding this farms' operations, in the following age categories (including yourself)?



> 60 years old	25
40-60 years old	53
20-40 years old	19
< 20 years old	5

Q3. How long have you been farming?

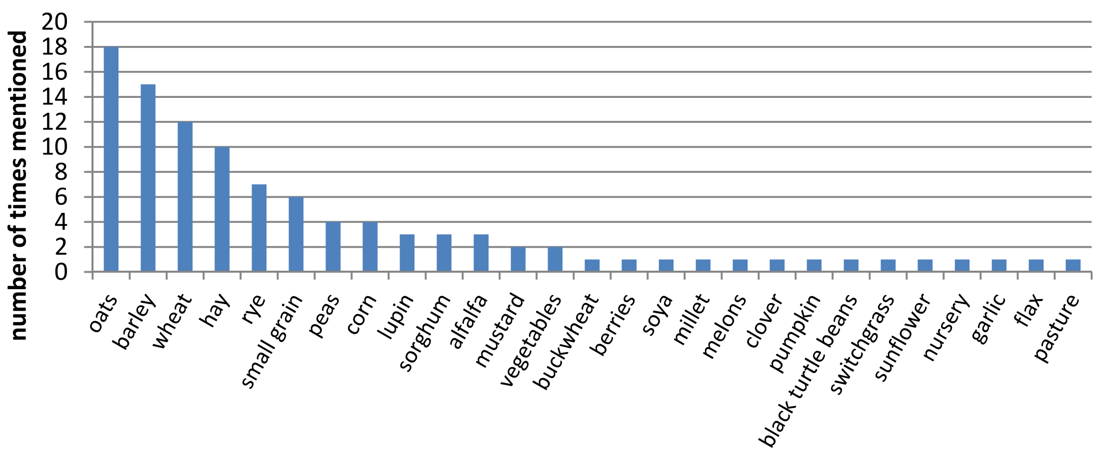


Q6. In a typical year, normally what crops do you grow?

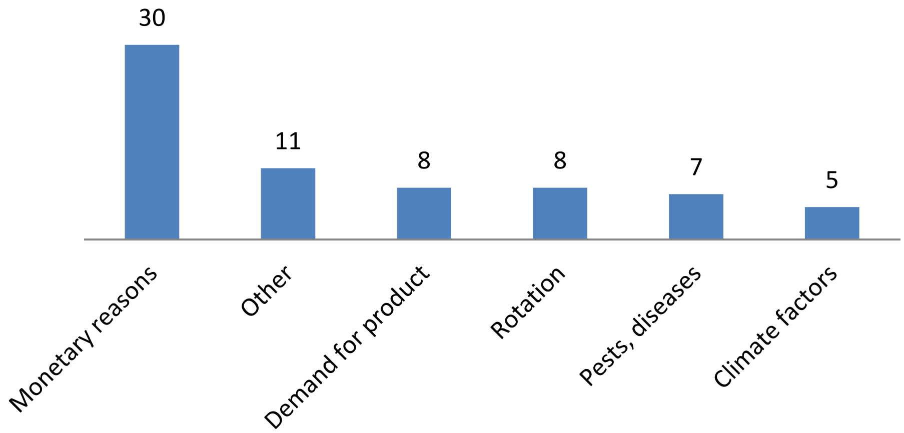
	Main crop 1	Main crop 2
Corn	32	6
Hay	9	2
Pasture	2	2
Wheat	2	1
Soybean	1	27
Apples	1	0
Berries	1	1
Wood	0	1
Vineyards		1

Q6b. Do you plan on continuing to grow these same crops as your main crops in the future? Answer: 4 were not going to keep planting what they were, 2 were unsure (one looking for someone to take over farm, and one considering planting soya). Reasons for not planting crops anymore: stop planting wheat since it was not strong this year; no more corn due to too much monetary loss involved).

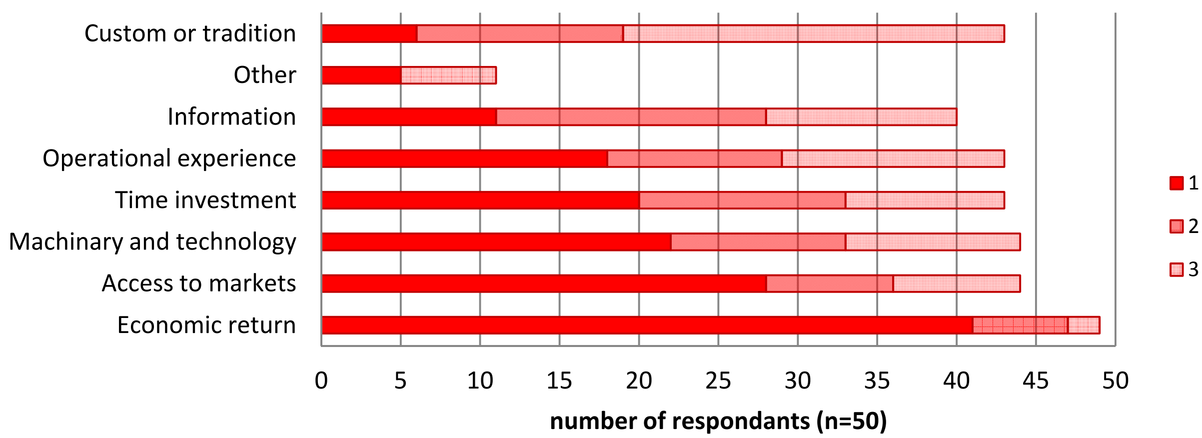
Q7. List all the additional crops that you have grown on this particular farm since you started farming the land (as far as you can remember)?



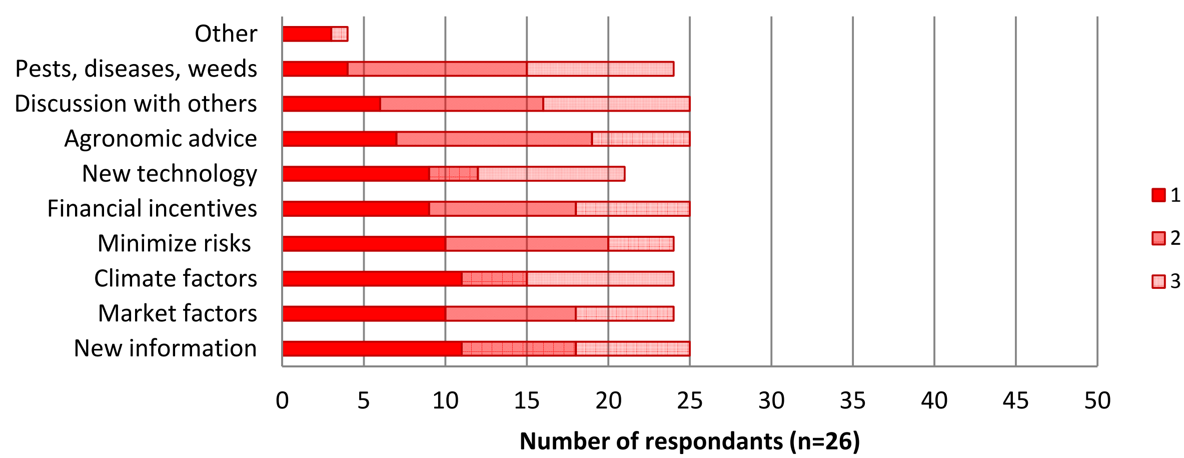
Q8. If relevant, can you name some of the deciding factors why you do not choose to plant certain crops on your farm anymore?



Q10. In your opinion, how much influence do the following factors have on the choice of which types of crops to grow on your farm? (Please rank: 1= large, 2=medium, 3=little influence).



Q11. What has prompted you, in the past 10 years, to grow crops that you previously had not grown on the farm before? (rank the following where 1=very important, 2 = medium, and 3=low)

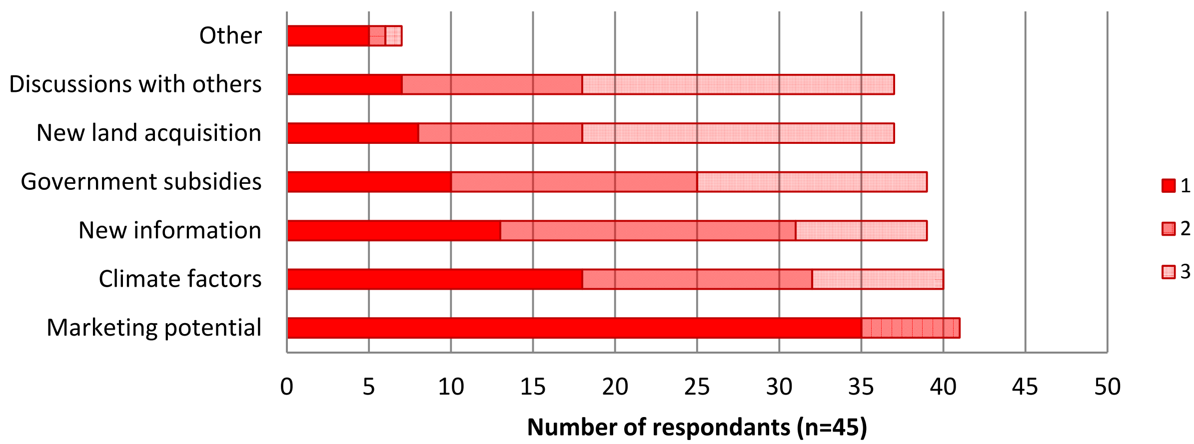


Q12. Are you planning on growing any new crops in the future that were not grown on your farm until now? If yes, which ones?

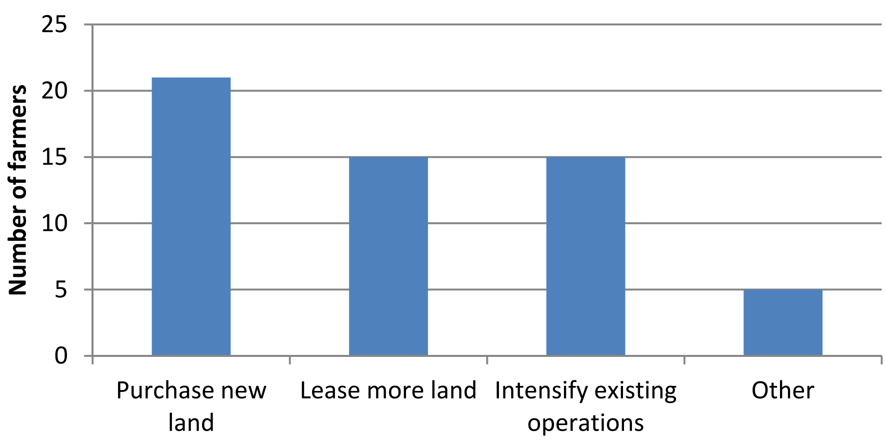
Answer: 16 farmers responded they would grow new crops, while 33 responded would not. New crops included corn, cereals, soybeans (2), hops, cherries, wheat (2), nursery, bioenergy crops (3), and 3 were not sure.

Q13. What would influence your decision to cultivate other or additional types of crops from the ones you have grown? (rank the following where 1=very important, 2 = medium, and 3=low).

Note: 25 farms had no change (data not shown).



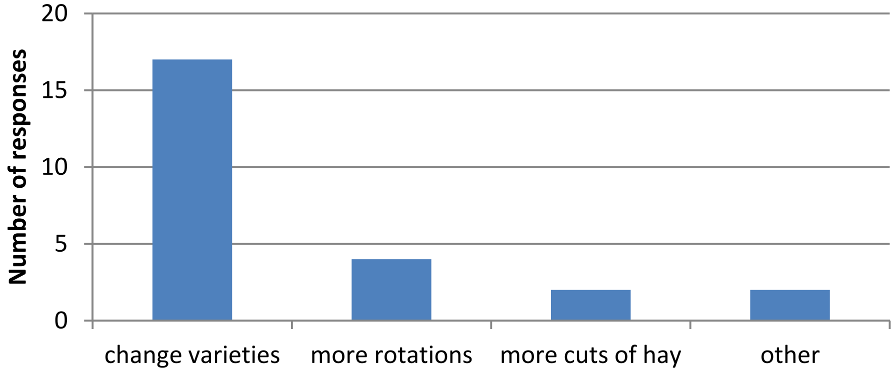
Q14. If you plan to expand or intensify your current production, will you:



Q15. Are you concerned with any potential negative future impacts that might occur on your farm? (any developments at the local, regional or national levels?)
15a. If so, which ones?

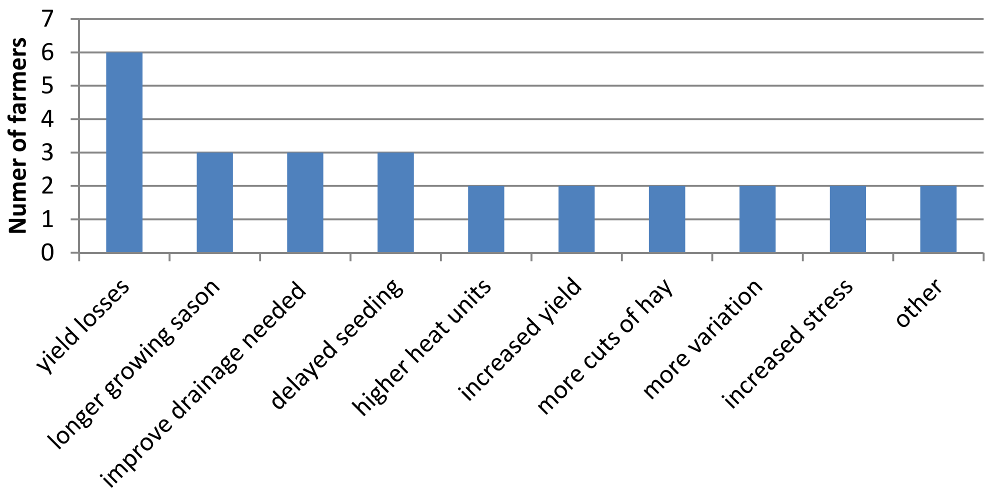
Answer: 20 farmers are concerned (27 are not) about the negative impacts.
They are concerned about: climate (4), lack of support for small farms, competition (2), milk support, the environment, laws (3), markets (6), price of land too high, declining income (2).

Q16. If the growing season length would increase by four weeks due to changes in the future climate, do you think this would this affect your crop choice decisions, or change your agricultural practices? If yes, in which way?

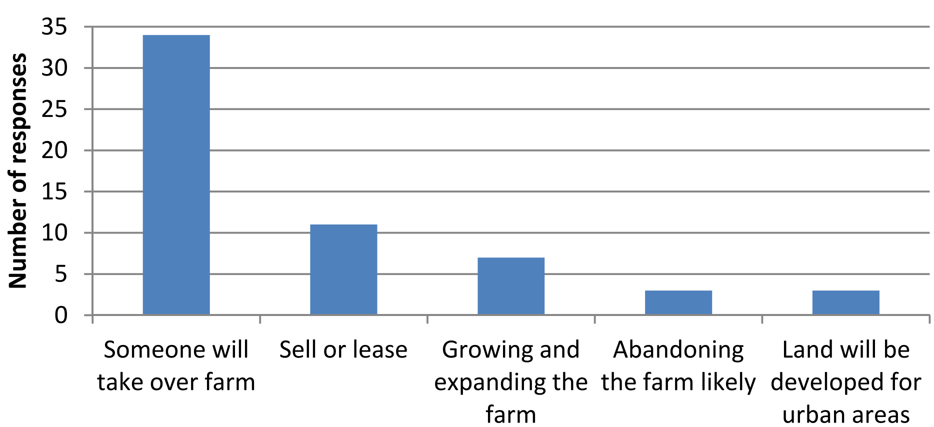


Q17. In the past thirty years, have you noticed a change in the climate?
Answer: 37 responded Yes, and 7 responded No.

Q17b. Have the changes affected your farm production? If yes, how so?

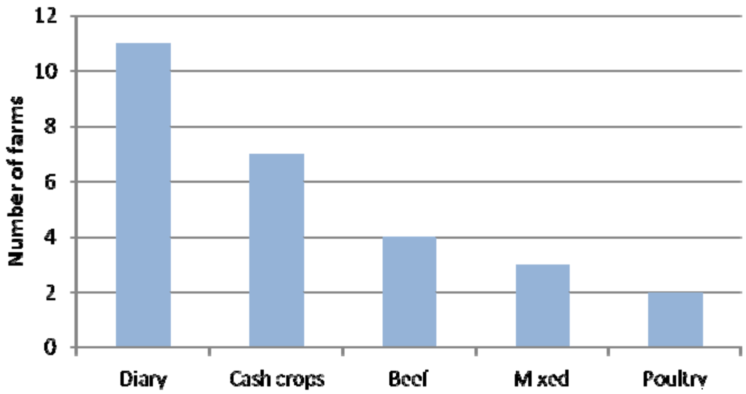


Q19. What are your plans for the farm over the next 30 years?

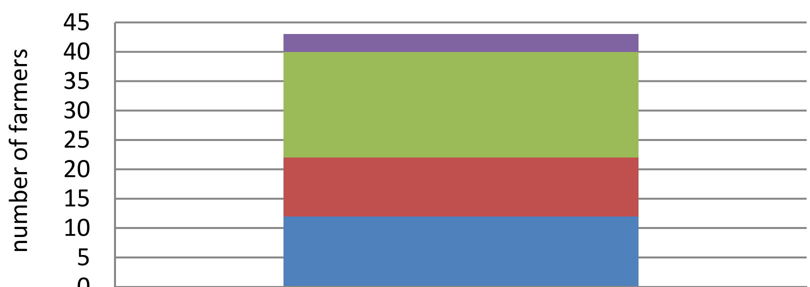


Responses to some of the questions from Group 2

Q1. What kind of farm would describe yours as?

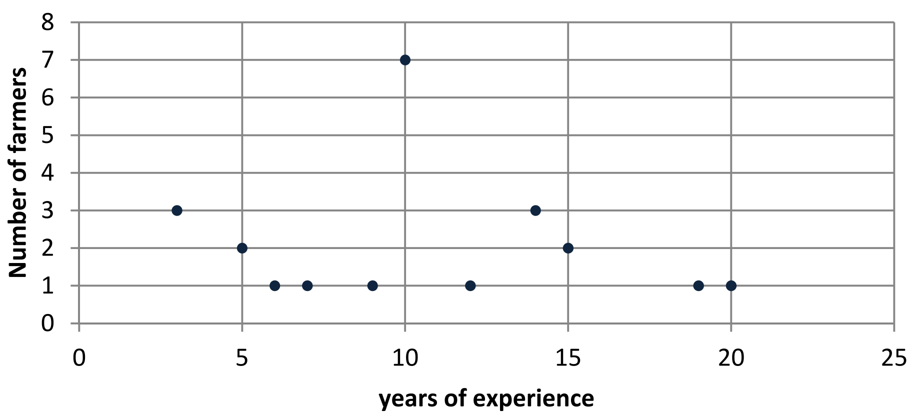


Q2. How many people assist with making decisions regarding this farms' operations, in the following age categories (including yourself)?



> 60 years old	3
40-60 years old	18
20-40 years old	10
< 20 years old	12

Q3. How long have you been farming?

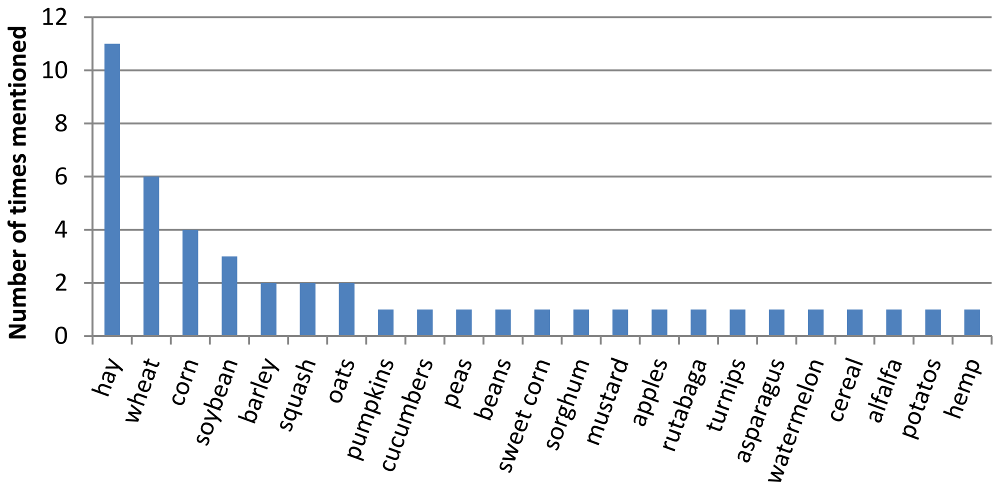


Q6. In a typical year, normally what crops do you grow?

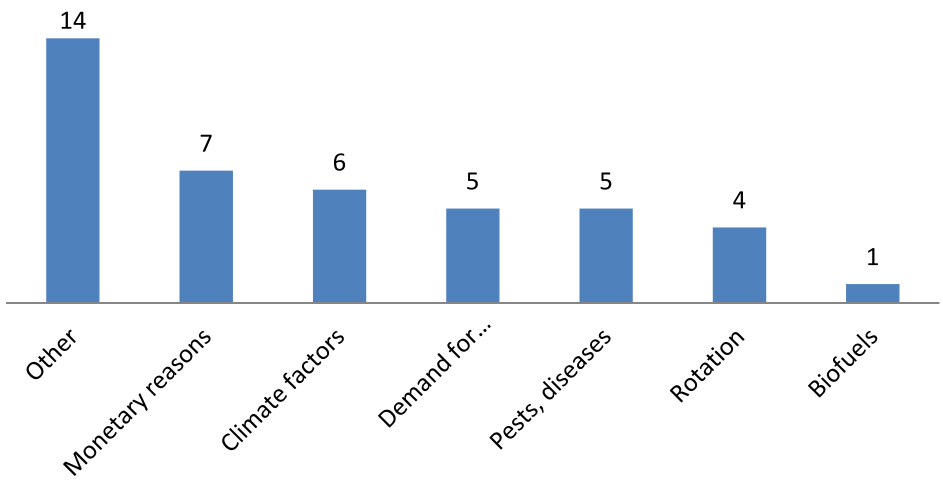
	Main crop 1	Main crop 2
Corn	10	6
Hay	8	5
Pasture	2	2
Soybean	1	6
Vegetables	1	1
Alfalfa	1	1
Oats	0	1

Q6b. Do you plan on continuing to grow these same crops as your main crops in the future? Answer: 18 were planning to continue growing these crops, while 4 were unsure. Reasons for not being sure were: Start-up operation, not sure if enough land available, needs to increase hay production, and rotations.

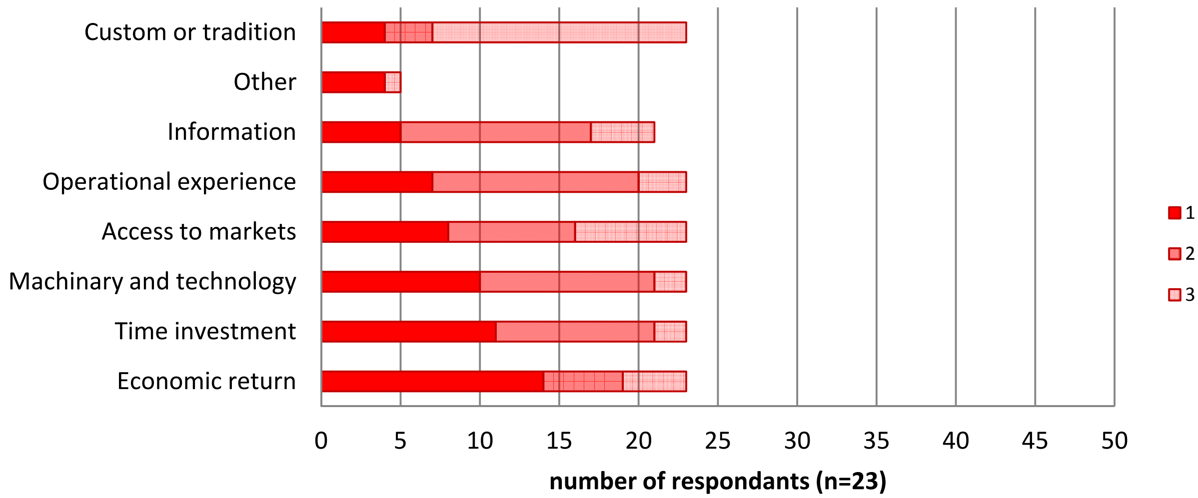
Q7. List all the additional crops that you have grown on this particular farm since you started farming the land (as far as you can remember)?



Q8. If relevant, can you name some of the deciding factors why you do not choose to plant certain crops on your farm anymore?

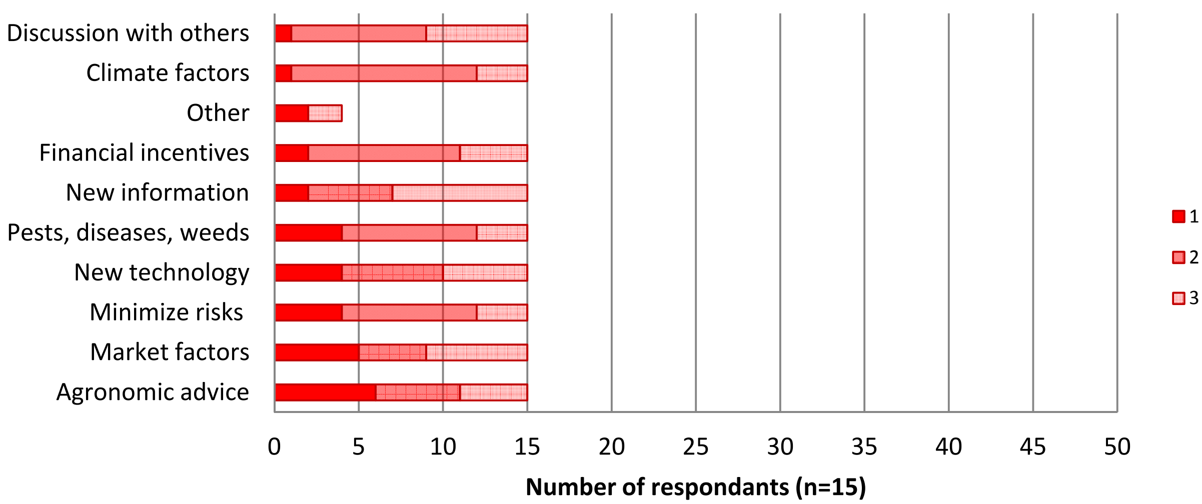


Q10. In your opinion, how much influence do the following factors have on the choice of which types of crops to grow on your farm? (Please rank: 1= large, 2=medium, 3=little influence).



Q11. What has prompted you, in the past 10 years, to grow crops that you previously had not grown on the farm before? (rank the following where 1=very important, 2 = medium, and 3=low).

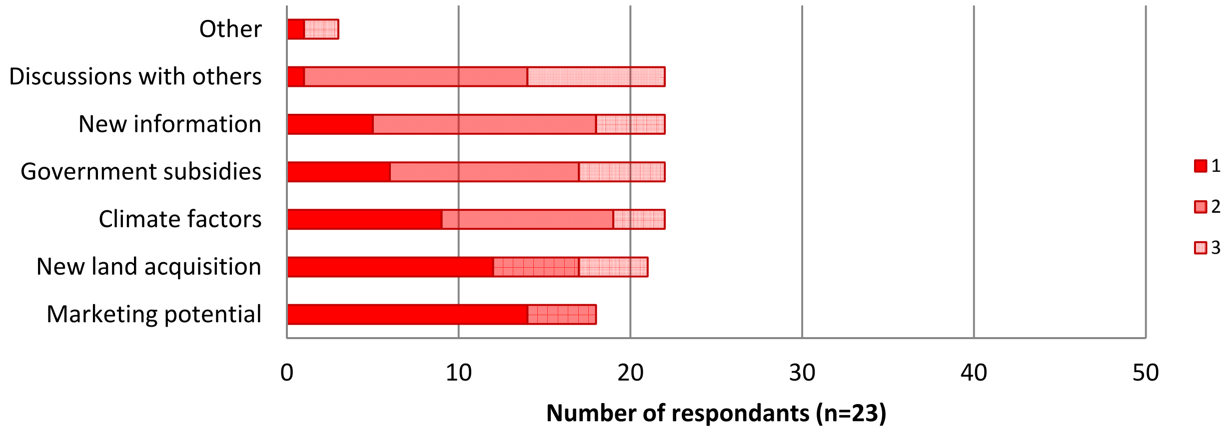
Note: 8 farms had no change (data not shown)



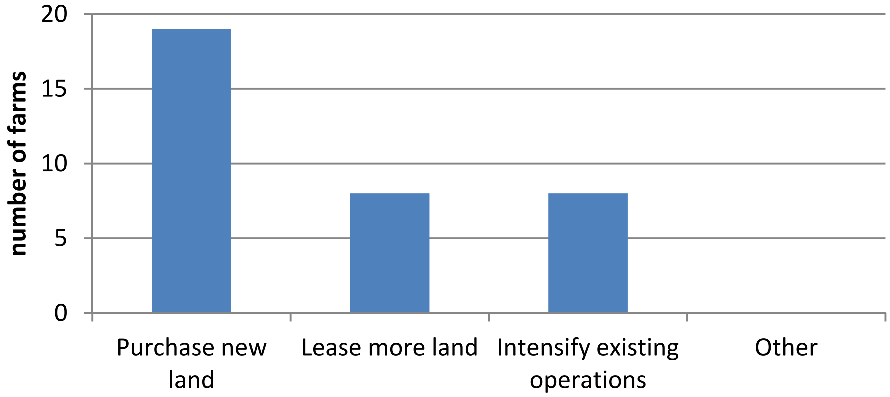
Q12. Are you planning on growing any new crops in the future that were not grown on your farm until now? If yes, which ones?

Answer: 9 were going to grow new crops (14 were not). New crops included: hay, cover crops (3), soybeans (2), market garden/vegetables (3), and sweet potato.

Q13. What would influence your decision to cultivate other or additional types of crops from the ones you have grown? (rank the following where 1=very important, 2 = medium, and 3=low).

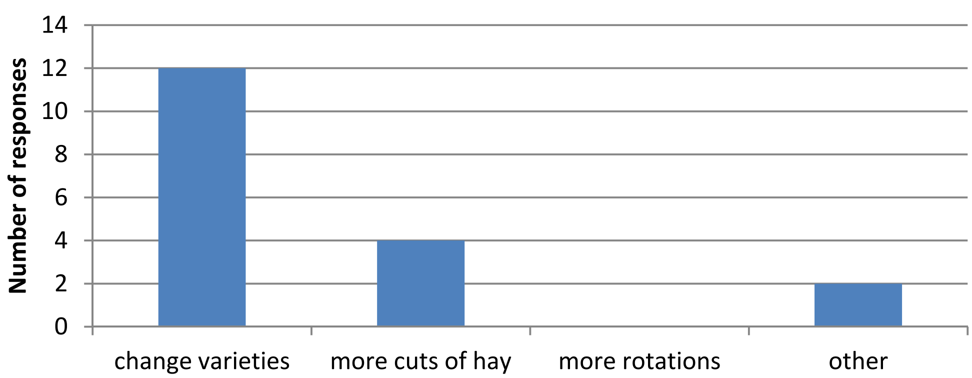


Q14. If you plan to expand or intensify your current production, will you:



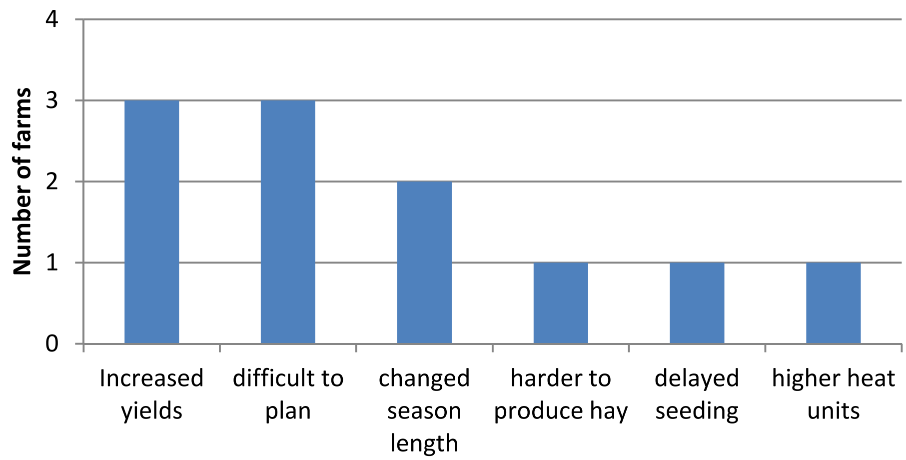
Q15. Are you concerned with any potential negative future impacts that might occur on your farm? (any developments at the local, regional or national levels?) 15a. If so, which ones? Answer: 12 are concerned; 10 were not. Reasons for concern included: markets (4), urban expansion (6), laws, no land to buy, and climate (2).

Q16. If the growing season length would increase by four weeks due to changes in the future climate, do you think this would this affect your crop choice decisions, or change your agricultural practices? If yes, in which way?

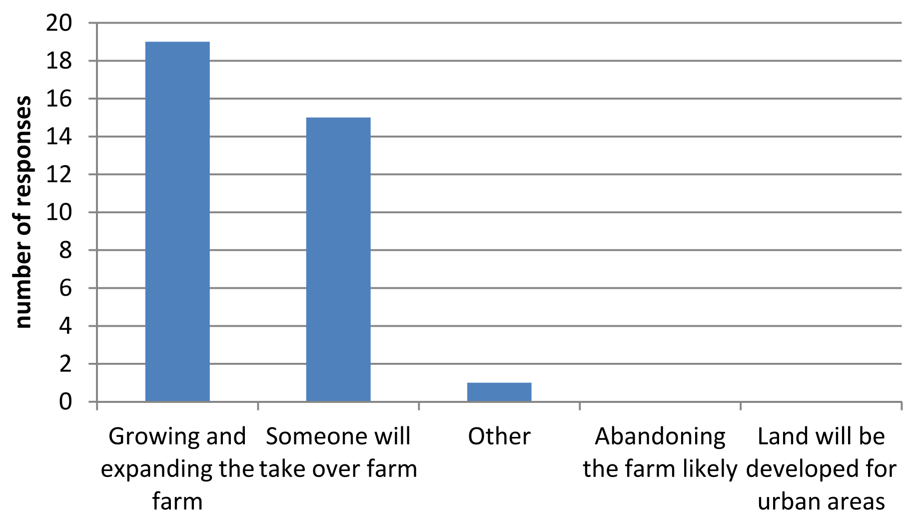


Q17. In the past ten years, have you noticed a change in the climate?
Answer: 18 responded Yes, and 3 responded No.

Q17b. Have the changes affected your farm production? If yes, how so?



Q19. What are your plans for the farm over the next 30 years?



Appendix 4: Drivers of Land Use Change in Québec

A literature review was conducted to determine the drivers of agricultural land use change in the region.

The following historic drivers for land use change were obtained from research articles pertaining to southern Québec (Ruiz and Domon, 2009; Jobin et al., 2010).

- Technological improvements have increased the average size of the farm
  - Increased field sizes, so that fewer orchards and less hedges are present due to increased mechanization, and implementation of subsurface drainage (1950-1970)
  - Increased specialization of farm which requires more space
- Better hybrids: corn varieties are planted which require more heat units
- Agricultural policies
  - Shift from diary to swine production (1970-1980)
  - Increase in swine production caused a 10 fold increase in annual crop production between 1993-2001
  - Diary remains intensive on rich soils (along valleys)
- Globalization, and environmental factors
  - Decrease in swine production (starting in 2000)
- Diseases
  - Dutch Elm disease caused some reduction in forested areas (1960-1980)
- Climate
  - Removal of woodlots after ice storm 1998, led to more corn production.

The future drivers of agricultural land use change were obtained from the following reports:

- *Donner le goût du Québec : Livre vert pour une politique bioalimentaire* (MAPAQ, 2011)
- *Agriculture et agroalimentaire : assurer et bâtir l'avenir* (Commission sur l'avenir de l'agriculture et de l'agroalimentaire québécois, 2008).
- *Activité bioalimentaire au Québec en 2011 : Bilan et perspectives* (MAPAQ, 2012)
- *Profils régionaux de l'industrie bioalimentaire au Québec, Estimation 2009* (MAPAQ 2010).

- Buying local produce and agro-tourism is being encouraged by the government.
  - Implementation of awareness programs (Le Québec dans votre assiette), and gourment trails (Des routes gourmandes).
  - New products, such as mead, ciders, wine, blueberry products, squash and flax, as well as several local farmer markets are emerging.
  - The Quebec government would like to promote Quebec products abroad and remain competitive in global markets. It also aims to contribute to feeding Quebecers. The Government places great emphasis on crop diversity and health.

- Biofuels
    - An ethanol production plant in Varennes (located 96 km away from Bedford) is accepting local (currently approximately 70 km radius) corn as a feedstock.
    - If the demand of second generation biodiesel increases, new feedstocks may emerge (lignocellulosic biomass, such as switchgrass or agricultural residues).
- The threat of expanding urban areas is considered to be a major threat for the agricultural sector
    - The factors threatening agricultural lands in the vicinity of Montréal are the construction of the highways 30 and 35, the further development of the intermodal system of transportation (railway, roads), and the wind farm in the Montérégie

To complement the information from the literature review, a discussion with the project stakeholders (UPA, MAPAQ, Ouranos, IRDA, McGill) during a meeting on March 12, 2012 shed light the driver found to date and provided supplemental drivers of land use change:

New varieties

- The emergence of dwarf cherry trees in the region has been observed (a dozen of varieties).

Expansion of agricultural land

- There is very little available land onto which crop land can expand in the region. The price of land in the Pike River watershed is amongst the most expensive in the region. As is the land on the east side of the Richelieu River. The price of 15 000 $ per ha was mentioned.
- At the Québec scale, the area of agricultural crop land is decreasing by 4000 ha per year, at the expense of urban expansion (suburbs), despite the protection of agricultural land. In the watershed, it does not appear that the agricultural land is very threatened, except for certain zones close to urban neighbourhoods. This point was mentioned by several farmers in the questionnaire.

Financial factors

- There are some concerns among farmers regarding the loss in revenue caused by the global markets and competition (Brazil), in particular the fact that market prices may be less than their production costs. This will depend on their type of production.
    - Policies are usually a reflection of social pressure (for example the switch from the milk production industry to the pork production system)
- The switch from milk production towards pork was essentially made possible due to the subsidies provided by the insurance program ASRA (Assurance Stabilisation des Revenues Agricoles).

- For farmers, the ASRA is perceived as revenue, while crop insurance is a risk management tool.
- The only financing tool available for farmers at the moment is the ASRA, from the provincial government. The ASRA is an important player in the market forces. The future evolution of the ASRA program is unknown.
- In Québec, there is talk about compensating farmers for the protection of environmental goods and services, as is practiced in the United States, however this is not yet very advanced in Québec.

Climate, diseases and insects

- In the past years, farmers almost never experienced drought. The difficulties were mainly related to excessive soil moisture early in the growing season. As such, producers began to drain their fields. If there are more droughts, almost no one is undertaking controlled drainage (or water table management) in summer for sub irrigating (as this requires very specific soil conditions).
- The Dutch elm disease is not a problem for farmers are there are few elm trees in agricultural regions. These trees are mainly found in cities. The trees most affected in rural areas by diseases and insects are spruce that are damaged due to the spruce bud worm.

Biofuel production

- If more biodiesel production occurs, it will take place with crop residues or from material stemming from marginal land (not adequate for food production) to increase the value of these lands. The industry is closely looking at biodiesels from second generation feedstocks. However, soybean has a higher value on the international market than for biodiesel production.
- The production of biofuels must not come into competition with the production of crops for food purposes.
  - There are some pilot projects underway. Every project is scrutinized, and if there is a conflict with food production, the project is abandoned.
  - The buffer strips planted along the Pike River could be used to provide feedstock for biofuels.

Deforestation and protected lands

- Between 1997 and 2002 deforestation increased after the adoption of the legislation of the PAEF (Plan agroenvironnemental de Fertilisation) for manure spreading (which restricted the amount and time of manure application in the year). Many farmers required twice as much land to meet the standards of manure application. To counter the reduction of forested land, deforestation was banned in agricultural regions in 2004. This explains the sudden decrease in forested areas around 1997, and suddenly there is a halt to this reduction.

- There are protected areas in the watershed. There is an ecological reserve and a protected wetland area. The OBVBM has a map of these areas. They will not be used for agricultural purposes in the future.

Policies and regulations

- New policies will mostly be felt at the local scale and its impact will depend on the financial means that will be attributed to the policy in the national budget.
- The latest policies are outlined in the report "*Donner le goût du Québec : Livre vert pour une politique bioalimentaire*" (MAPAQ, 2011) which highlights important areas, such as:
  - Primary mission is to assist in nourishing Quebeckers
  - Reduce risks associated with farming
  - Diversify agriculture
  - Support farmers with insurance and income stability
  - No future dominance of small, medium or large farms
  - Sustainable development
  - Food and health
  - Globalisation, exterior markets are future growth factors
  - Promote Québec products

Appendix 5: Management Operations Simulated in SWAT

Table A4: Schedule of field operations (conventional practices) during the calibration and validation periods for the main crops simulated in SWAT.

Crop	Year	Manure application pre-seeding (45%)	N mineral fertilization (50%)	Spring harrowing	Seeding and P mineral fertilization	Manure post-emergence (36%)	N mineral fertilization (50%)	Harvest	Manure application fall (19%)	Fall ploughing
Soybean	1998			Apr 30	May 12			Sep 25		Oct 6
	1999			May 2	May 14			Sep 26		Sep 28
	2000			May 16	May 21			Sep 18		Sep 30
	2001			May 3	May 5			Sep 18		Oct 1
	2002			May 6	May 19			Sep 18		Sep 26
	2003			May 4	May 5			Sep 18		Oct 7
	2004			May 9	May 13			Sep 27		Oct 8
	2005			May 13	May 19			Oct 2		Oct 5
	2006			May 8	Jun 14			Nov 3		Nov 6
	2007			May 12	May 25			Oct 4		Oct 18
	2008			May 2	May 11			Oct 6		Oct 19
	2009			Apr 27	May 19			Oct 18		Oct 27
	2010			May 12	May 24			Oct 11		Oct 19
	2011			Jun 3	Jun 7			Oct 10		Oct 27
Cereals	1998	Apr 23	Apr 23	Apr 30	May 12		Jul 6	Aug 31	Sep 17	Sep 25
	1999	Apr 29	Apr 29	May 2	May 14		Jun 22	Aug 25	Sep 1	Sep 12
	2000	Apr 30	Apr 30	May 16	May 21		Jun 14	Aug 22	Sep 7	Sep 10
	2001	Apr 27	Apr 27	May 3	May 5		Jun 14	Aug 22	Sep 7	Sep 15
	2002	Apr 24	Apr 24	May 6	May 19		Jun 30	Aug 21	Sep 7	Sep 18
	2003	Apr 29	Apr 29	May 4	May 5		Jun 17	Aug 21	Sep 7	Sep 10
	2004	Apr 29	Apr 29	May 9	May 13		Jun 28	Sep 4	Sep 13	Sep 14
	2005	May 5	May 5	May 13	May 19		Jun 30	Aug 26	Sep 5	Sep 10
	2006	Apr 28	Apr 28	May 8	May 28		Jul 9	Aug 29	Sep 7	Sep 11
	2007	May 5	May 5	May 12	May 25		Jun 26	Aug 28	Sep 4	Sep 13
	2008	Apr 22	Apr 22	May 2	May 11		Jun 25	Aug 21	Aug 29	Sep 5

	2009	Apr 16	Apr 16	Apr 27	May 4		Jun 6	Aug 26	Sep 3	Sep 11
	2010	Apr 24	Apr 24	May 2	May 13		Jul 4	Aug 19	Aug 29	Sep 5
	2011	May 9	May 9	Jun 3	Jun 7		Jul 14	Aug 18	Sep 1	Sep 10
Corn	1998	Apr 23	Apr 23	Apr 30	May 12	Jun 10	Jun 10	Oct 22	Oct 22	Oct 25
	1999	Apr 29	Apr 29	May 2	May 14	Jun 22	Jun 22	Oct 28	Oct 28	Oct 29
	2000	Apr 30	Apr 30	May 16	May 21	Jun 14	Jun 14	Oct 13	Oct 13	Oct 21
	2001	Apr 27	Apr 27	May 3	May 5	Jun 14	Jun 14	Oct 20	Oct 20	Oct 30
	2002	Apr 24	Apr 24	May 6	May 19	Jun 30	Jun 30	Oct 12	Oct 12	Oct 23
	2003	Apr 29	Apr 29	May 4	May 5	Jun 17	Jun 17	Oct 12	Oct 12	Oct 24
	2004	Apr 29	Apr 29	May 9	May 13	Jun 28	Jun 28	Oct 26	Oct 26	Oct 27
	2005	May 5	May 5	May 13	May 19	Jun 30	Jun 30	Oct 30	Oct 30	Nov 3
	2006	Apr 28	Apr 28	May 8	May 28	Jul 9	Jul 9	Nov 3	Nov 3	Nov 6
	2007	May 5	May 5	May 12	May 25	Jun 26	Jun 26	Nov 3	Nov 3	Nov 4
	2008	Apr 22	Apr 22	May 2	May 11	Jun 25	Jun 25	Nov 1	Nov 1	Nov 5
	2009	Apr 16	Apr 16	Apr 27	May 12	Jun 6	Jun 6	Nov 7	Nov 7	Nov 9
	2010	Apr 24	Apr 24	May 12	May 20	Jul 4	Jul 4	Nov 3	Nov 3	Nov 11
	2011	May 9	May 9	Jun 3	Jun 7	Jul 14	Jul 14	Oct 28	Oct 28	

Table A5: Schedule of simulated field operations (conventional practices) during the calibration and validation periods for hay simulated in SWAT.

Crop	Year	Manure application	First hay harvest	Manure application	Second hay harvest	Manure application	Third hay harvest	Manure application
Hay	1998	Apr 23	Jun 9	Jun 10	Aug 5	Aug 6	Sep 18	Sep 24
	1999	Apr 29	Jun 12	Jun 13	Aug 10	Aug 11	Sep 3	Sep 4
	2000	Apr 30	Jun 13	Jun 14	Jul 6	Jul 7	Sep 18	Sep 19
	2001	Apr 27	Jun 6	Jun 7	Jul 19	Jul 20	Sep 15	Sep 16
	2002	Apr 24	Jun 30	Jul 1	Aug 5	Aug 10	Sep 18	Sep 19
	2003	Apr 29	Jun 21	Jun 22	Aug 15	Aug 16	Sep 18	Sep 20
	2004	Apr 29	Jun 27	Jun 28	Aug 15	Aug 16	Sep 2	Sep 29
	2005	May 5	Jun 26	Jun 27	Aug 18	Aug 19	Sep 23	Sep 24
	2006	Apr 28	Jul 7	Jul 8	Aug 16	Aug 17	Oct 8	Oct 9
	2007	May 5	Jun 12	Jul 13	Jul 24	Jul 25	Sep 18	Sep 19
	2008	Apr 22	Jun 26	Jun 27	Aug 16	Aug 17	Sep 23	Sep 24
	2009	Apr 16	Jun 23	Jun 24	Aug 15	Aug 16	Sep 7	Sep 9
	2010	Apr 24	Jul 5	Jun 6	Aug 12	Aug 13	Sep 19	Sep 20
	2011	May 9	Jul 15	Jul 16	Aug 12	Aug 13	Oct 6	Oct 7

Tables A6: Schedule of simulated field operations (conventional practices) for the reference period 1971-2000 for a) main crops b) hay and switchgrass. (Note: since the exact dates for the management operations were missing for the entire period, a representative date was applied for each operation).

a)	Pre-seeding manure (45%)	Mineral N (50%)	Harrowing	Seeding	Mineral P	Post-emergence manure (36%)	Mineral N	Harvest	Fall manure (19%)	Ploughing
Cereals	Apr 23	Apr 23	Apr 30	May 12	May 12		Jun 10	Aug 31	Sep 17	Sep 25
Grain corn	Apr 23	Apr 23	Apr 30	May 12	May 12	Jun 10	Jun 10	Oct 22	Oct 22	Oct 25
Soybean			Apr 30	May 12				Sept 25		Oct 6
Berries					Jun 6		Jun 6	July 13	July 25 (mineral N)	
Vegetables			May 16	May 21	May 21	May 21 (mineral N)	July 30	Sep 18		
Orchard					May 15	May 15				

b)	Manure application	First harvest	Manure application	Second harvest	Manure application	Third harvest	Manure application
Hay	Apr 23	Jun 9	Jun 10	Aug 5	Aug 6	Sep 18	Sep 24
Switchgrass		May 5	May 6 (mineral N)				

Table A7: Schedule of simulated field operations (conventional practices) for the future period 2041-2070 for a) main crops b) hay and switchgrass.

a)	Pre-seeding manure (45%)	Mineral N (50%)	Harrowing	Seeding	Mineral P	Post-emergence manure (36%)	Mineral N (50%)	Harvest	Fall manure (19%)	Ploughing
Cereals	Apr 23	Apr 23	Apr 28	May 1	May 1		Jun 1	Aug 22	Aug 23	Aug 24
Grain corn	Apr 23	Apr 23	Apr 28	May 1	May 1	Jun 1	Jun 1	Oct 20	Oct 21	Oct 22
Soybean			Apr 28	May 1				Oct 1		Oct 8
Berries					Jun 6		Jun 6	July 30	Aug 4 (mineral N)	
Vegetables			May 1	May 5	May 5	May 5 (mineral N)	July 30	Sep 18		
Orchard					May 15	May 15				

b)	N and P manure application	First harvest	N and P manure application	Second harvest	N and P manure application	Third harvest	N and P manure application	Fourth harvest
Hay	Apr 23	May 25	May 26	July 10	July 11	Aug 23	Aug 24	Oct 5
Switchgrass		May 5	May 6 (mineral N)					

Table A8: Schedule of simulated field operations (conventional practices) for the future period 2041-2070 for crops under a) no-till and b) reduced tillage.

a)	Pre-seeding manure (100%)	Mineral N (50%)	Seeding	Mineral P	Post-emergence manure (100%)	Mineral N (50%)	Harvest
Cereals	May 7	May 7	May 8	May 8		Jun 12	Aug 22
Grain corn			May 8	May 8	Jun 12	Jun 12	Oct 20
Soybean			May 8				Oct 1

b)	Pre-seeding manure (55%)	Mineral N (50%)	Mulch tilling	Seeding	Mineral P	Post-emergence manure (45%)	Mineral N (50%)	Harvest	Mulch tilling (soil group D)
Cereals	Apr 23	Apr 23	Apr 24	May 1	May 1	Jun 1	Jun 1	Aug 22	24 Aug
Grain corn	Apr 23	Apr 23	Apr 24	May 1	May 1	Jun 1	Jun 1	Oct 20	22 Oct
Soybean		Apr 24	May1					Oct 1	Oct 8

Table A9: Specifications for the tillage practices simulated in SWAT

	Tillage type and SWAT tillage ID	Depth of tillage (cm)	Tillage mixing efficiency
No-till (soil groups A and B)	No-till (ID #4): Generic No-till mixing at seeding	25	5%
Reduced tillage (soil group C)	Spring tillage (ID #85): Disk chisel (Mulch tilling)	150	55%
Reduced tillage (soil group D)	Spring tillage (ID #6): Field Cultivator Ge15ft (Harrowing)	100	30%
	Fall tillage (ID #85): Disk chisel (Mulch tilling)	150	55%
Conventional tillage (all soil groups)	Spring tillage (ID #6): Field Cultivator Ge15ft (Harrowing)	100	30%
	Fall tillage (ID #61): Disk plow Ge 23ft (Ploughing)	200	95%

Appendix 6: Implementation of Adaptation Strategies in SWAT

Strategic Adaptation Scenario (STRAT) Implementation in SWAT

This scenario is based on scenario #21 in Michaud et al. (2007) which simulated a 41% reduction in TP using observed climate data in SWAT.

To replicate this scenario, soil conservation practices were randomly applied on 45% of the cultivated area. Table A10 shows the areas under soil conservation practice per soil hydrological group. Hydrological groups are described below.

Table A10: Area assigned to soil conservation practices per hydrological soil group A, B, C and D for each cultivated HRU within the Pike River watershed.

	Hydrological Soil Group	HRU area (ha)	Area%
No soil conservation practice	A	205.45	A and B: 9
	B	1322.75	
	C	597.18	C and D: 45
	D	2110.18	
Soil conservation practice	A	83.96	A and B: 7
	B	1179.33	
	C	4456.25	C and D: 38
	D	2155.09	

Table A11: Soil hydrological group description and characteristics (adapted from Michaud et al., 2008)

Hydrological Soil Group	Dominant texture and other characteristics	Infiltration rate for saturated soil	Surface runoff potential
A	Coarse (sand and gravel)	High	Low
B	Fine to moderately coarse (silt, fine sand)	Moderate	Moderate
C	Fine (silt). Soils with a layer that impedes downward movement of water.	Low	High
D	Very fine (clay). Soils with a permanent water table or a clay layer at or near the surface, or shallow soil over nearly impervious material.	Very low	Very high

Table A12: Crop area (ha) under soil hydrological group A, B, C and D.

Land use	A	B	C	D	*Total (ha)*
Agricultural Land (generic)	1.49	0.54	2.83	0.45	*5.31*
Agricultural Land (row crops)	0.27	0.18	1.71	0.54	*2.70*
Corn	111.67	1564.40	7563.75	3312.54	*12552.36*
Forest	3998.95	5011.48	14538.30	1620.62	*25169.35*
Hay	764.78	3972.45	7358.73	1959.41	*14055.37*
Orchard	111.66	675.72	302.21	10.62	*1100.21*
Vegetables		0.45	1.26	21.33	*23.04*
Range-brush	25.77	16.58	191.26	170.45	*404.06*
Soybean	9.49	260.89	775.95	510.15	*1556.48*
Berries	0.36	0.36	1.35	0.63	*2.70*
Switchgrass	0.27	0.09	1.53	0.81	*2.70*
Cereals	187.90	1006.82	2810.37	882.89	*4887.98*

Buffer strips

HRUs on which vegetated filter strips (VFS) were to be implemented were determined by using ArcGIS and intersecting the river network shape file with the HRU shapefile from SWAT. Filter strips were implemented only on the HRUs entirely or partially connected to the river network. The function used in ArcGIS was “intersect” with the option to obtain point locations from the resulting intersections. This procedure identified the HRUs where buffer strips were to be implemented.

In SWAT, vegetative filter strips are implemented using 3 variables: the VSFratio, the VSFcon and VSFch (White and Arnold, 2009). The VSFratio is the area of the drained area (in the HRU) divided by the area of the VSF. A value of 40 is suggested but can vary between 0 and 300. The VSFcon is the fraction of HRU which is drained by the 10% of the VSF receiving the greatest amount of runoff and nutrients. A VSFcon value of 0.5 is suggested, but can range from 0.25 to 0.75. Finally, the VSFch is the fraction of runoff that goes through the 10% of the VSF which is channelized. A value of 1 is suggested; however this can vary between 0 and 100.

Five tests were performed with different combinations of these values (Table A13) on the Morpion sub-basin (#1) located in intensively cultivated areas on a flat portion of the watershed.

To find an optimal value for the VSF, preliminary tests in SWAT were carried out. A VSF ratio was calculated for the Pike River watershed by assuming that the average field dimensions were: 250 m wide and 1250 m long (area of 312 500 m^2) so that a VFS would be 250 m long and 3 m wide for an area of 750 m^2. The ratio of these two areas provides a VSF of 417. As well, a range of values between 60 and 300 were arbitrarily tested.

In the past, it has been observed that only a small portion of the VSF received runoff from more than 50% of the drained area (Aubert Michaud, pers. comm. February 20, 2013), therefore, the first 3 tests were performed with a VSFcon value of 0.75. The value of 0.5 was also tested since it was the value suggested in the literature.

The VSFch recommended value was kept at 1 because a sensitivity analysis showed that it was not a sensitive parameter in our case.

Table A13: Test values of the vegetative filter strip parameters.

	Test 1	Test 2	Test 3	Test 4	Test 5
VSF ratio	417	300	60	60	300
VSFcon	0.75	0.75	0.75	0.5	0.5
VSFch	1	1	1	1	1

Tests 1, 2 and 3 had the reverse effect of what was expected, that is to say that an increase in sediments and nutrient exportation were observed after VSF were implemented in the model. Tests 4 and 5 provided reductions in sediments and TP for most of the affected HRUs in the sub-basin, however some HRUs continued to show an increase in exportation. Table A14 shows a summary of the results for TP obtained with tests 4 and 5.

Table A14: Changes in TP exportation for sub-basin 1 after implementation of VSF tests 4 and 5.

Change in exportation for TP	Test 4	Test 5
Average	-11%	-5%
Standard Deviation	10%	13%
Maximum	2%	27
Minimum	-40%	-35%

The performance of VSF at the field and sub-basin scale is difficult to measure (White and Arnold, 2009; Aubert Michaud, pers. comm. February 20, 2013). Michaud et al. (2007) used a pollutant trapping-efficiency coefficients (PTECs) of 9% applied on sediment P outputs. This PTEC was set according to measurements done within the sub-basin 19 before and after a combination of filter strips and runoff control structures (Hickenbottom inlets) were installed. On average, test 4 was closer to the reductions observed within sub-basin 19. However, test 5 was ultimately chosen because the VSF ratio (300) was closer to the physical reality. As well, due to uncertainty surrounding the VSF sediment and TP trapping efficiency, we decided to err on the side of caution.

Values from the 3 parameters from test 5 were therefore applied to all HRUs in the watershed that had a VSF.

Runoff control structures

Runoff control structures cannot be directly simulated in SWAT. Therefore, as per Michaud et al. (2007), a PTEC of 5% and 4 % were applied to the STRAT simulation outputs of sediment and TP, respectively, at the outlet of the watershed.

Feasible Adaptation Scenario (FEASB) Implementation in SWAT

This scenario was created with a mixture of field practices that were the most realistic for producers to implement in the short term.

Winter cover crops

Soybean

Within the report *Projet de culture intercalaire* (Audet, 2012), rye was planted after silage corn and is described as a suitable winter cover crop, because of its hardiness. It germinates ≥4°C and grows quickly which leaves enough time for it to take root, provided it is seeded later in the season. It is suggested to seed it before mid-September; however successful seedings were also observed with seeding dates until November (Jannasch, 2012). Rye is known for its allelopathic effects, therefore only a few crops, such as soybean, can be grown in spring after rye however they must be seeded 2 weeks after rye is incorporated into the soil.

Because rye is a cereal that can be planted relatively late in the season, it was therefore chosen as a cover crop after soybean. It should be seeded no later than September 5 in real life because winter cereals should be seeded before soybeans loose their leaves in fall. However, SWAT does not support the growth of two crops within the same HRU, therefore rye was seeded in SWAT, on October 2, the day after the harvest of soybean. With this method it is possible to implement the biomass and LAI that rye should have on October 2 in SWAT, provided it was seeded on September 5.To determine its biomass and LAI in October, a test simulation was run within which soybeans were harvested mid-August and rye seeded September 5. The 30-year average biomass and LAI for September during the period 2041-2070 were used as input values on October 2. Table A15 shows the variables entered in SWAT to simulate cover crops.

Cereals

A red clover (*Trifolium Pratense L*) was chosen to be seeded as an intercrop with cereals. Its biomass and LAI were calculated in the same way as above for rye in soybean. Usually in Quebec, mustard or radish are seeded after cereals, however the SWAT crop database has limited choices of such crops, so it was decided to use red clover which is also a suitable cover crop.

Grain corn

Tests of intercropping ryegrass with silage corn were performed in Québec (Audet, 2012). However, cases of the intercropping associated with grain-corn in Québec are rare. Only one study was identified (Zhou et al. 1997) where intercropped ryegrass was grown with grain-corn in southwestern Quebec. The MAPAQ Montérégie-Ouest distributed a document promoting successful intercropping approaches in Ohio (Martin et al., 2011). A mix of mustard, rye and forage peas or pasture as well as vetch or ryegrass are encouraged as intercrops with grain-corn. Although, the climate in Ohio is milder, such practices could be considered in a future climate in Québec. Ryegrass was therefore chosen as an intercrop, and it was seeded when the first three or four leaves of the corn appeared in mid-June. Its biomass and LAI were calculated using the same method as above for rye in soybean. In addition, no-tillage (soil groups A and B) and reduced tillage (soil groups C and D) was carried out on all grain corn HRUs that were intercropped.

Table A15: Seeding dates of the cover crops and their simulated 30 year-average biomass and LAI values at the dates of the main crop harvest, for the AHK scenario (2041-2070).

Crop	Actual seeding dates [a]	Seeding dates in SWAT	Days to maturity (from actual dates)	PHU (from actual dates)	Harvest of the main crop	LAI value used in SWAT	Dry biomass (kg/ha) implemented in SWAT
Ryegrass	June 7 or 15[a]	October 22	Same as cereals	1350[b]	October 20	2.5	3210
Red clover	May 1 or 8[a]	August 24	90[c] (GDD_{base} 1°C)	1580	August 22	1.6	4290
Rye	September 5	October 2	90[d] (GDD_{base} 0°C)	1005	October 1	2.5	940

a) The first dates are reduced tillage and the second no-till. No-till always takes place later because the soil needs more time to dry. Seedling dates are 2 weeks earlier because the growing season increased. Harvest dates are kept as for historical except for the soybean because the main crop after rye could not be seeded two weeks earlier in spring due to the allelopathy effect of rye.

b) Griffith et al. (2001)

c) and d) Sauriol (2009), plants heats units were calculated based on days to maturity and temperature records from January 1996-to December 2007.

Flood plain protection

The protection of floodplains, the protection of drinking water sources, and the implementation of sediment retention basins were discussed with the stakeholders and were proposed for implementation in the FEASB scenario, however they were not modelled in SWAT because of limitations encountered in the modelling process.

In this scenario, regions prone to flooding were to be converted into rangeland (its natural state). Two shape files delimiting flood regions were provided by the OBVBM. The area of the floodplain in the basin was in the order of 1160 ha, of which almost 50% was already in its natural state (wetland, forest or hay).

Of the 1160 ha that requires protection, 493 ha (42.5%) was water (includes wetland), 194 ha (17%) is forested and 167 ha (14%) is hay. Corn, cereals and soybean cover 212 ha (18%), 58 ha (5%) and 34 (2.9%) ha, respectively.

Due to the nature of the SWAT set-up with HRUs as the smallest unit that can be converted from one land use to another, it was only possible to select the entire areas of the HRUs adjacent to the rivers to implement the floodplain protection. This meant choosing over 15 756 ha of land to covert to rangeland in the SWAT model.

As an HRU is an indivisible entity, its entire area had to be converted into range brush, although it is unlikely that the whole area would be prone to flooding. Table A16 shows the flood plain area per crops vs. the entire area that would have to be converted in SWAT.

Because the conversion of floodplains into natural land with the actual SWAT set-up would require abandoning unrealistically high amounts of agricultural land (over 8000 ha), it was chosen not to implement the protection of floodplains in this project. If floodplain protection has to be implemented, this would require a new set-up of SWAT with a finer delineation of the HRUs.

Table A16: Flood plain area per land use vs. area of the HRU that will be converted to rangeland.

Land use	Flood Plain Area (ha)	Area of the HRU (ha)
Agricultural Land (row crops)	0.00	0.09
Range-brush	0.05	0.18
Strawberries	0.06	0.09
Agricultural Generic Land	0.09	0.18
Vegetables	0.09	0.18
Switchgrass	0.18	0.18
Urban	0.28	13.77
Soybean	34.13	242.60
Cereals	57.78	1304.59
Hay	167.19	3792.85
Forest	194.70	6327.01
Corn	211.99	2883.11
Water	493.14	1192.03
Total	**1159.69**	**15756.86**

Sedimentation basins

Sedimentation basins are typically installed to reduce sediment and nutrient loads from reaching a river after a storm event. Such events which are capable of transporting sediments and nutrients are intense and typically last one hour to a few hours, at most. For the project, precipitation input was provided to SWAT on a daily basis, therefore it was suspected that, in our case, the effectiveness of sedimentation basins could not be captured by SWAT (François Chretien, pers. comm., March 6, 2013). Especially since SWAT does not simulate intense events because the time resolution is too coarse even at a daily step.

Furthermore, the methodology to implement sedimentation basins in SWAT effectively was not possible to implement within the time constraints of the project. Sedimentation basins are simulated in SWAT by creating a unique pond for a sub-basin. This pond represents a virtual collection of sedimentation basins inside a sub-basin. The challenge is that sedimentation basins in SWAT cannot be specifically located. In a report on the implementation of sedimentation basin in agricultural areas in Québec, Rivard and Rinfret, (2011) underscore that the effectiveness of a sedimentation basin depends on the scale of the draining area, the dimensions of the sub-basin, as well as their positions in the landscape. Such details in the SWAT set-up could not be captured.

Optimistic Adaptation Scenario (OPTIM) Implementation in SWAT

Rotation and winter cover crops

When corn, soybeans, cereal or alfalfa was planted, a rotation was implemented for all affected HRUs in the watershed in SWAT consisting of the following: corn- soybean- cereals - alfalfa.

As well, red clover (*Trifolium Pratense L*) was seeded after corn on October 21, the day after corn harvest. The initial biomass and LAI of red clover were implemented at 0, contrary to the FEASB scenario. After soybean, no winter crop was implemented because the only crop that could be implemented in SWAT was cereal rye which has an allelopathy effect on the following cereals. Reduced tillage and no-till were implemented instead of cover crops, to ensure a minimum soil protection. Finally, alfalfa (*Medicago Sativa L*) was seeded directly after cereal harvest on August 23. The following year, alfalfa was harvested four times a year: on May 20, June 17, July 22 and September 2 without any fertilization application.

The biomass of the winter cover crop was killed in SWAT on April 19 and incorporated into the soil during the tillage operation a few days later depending on the soil, tillage and management type. The soil under no-till was chisel plowed in spring to incorporate the biomass into the soil.

Manure fertilization scheme

In this scenario, no mineral fertilizers were added, instead only organic manure was applied. In this case, swine manure was chosen as the organic fertilizer, which had a P:N of almost 1:3. The nutrient needs of the crops were met by matching the P requirements in the manure to the P needs of the crop. This led to an over application of N for the crop in most cases. However, this is often a compromise of using manure as the only source of fertilization.

The P inputs from the manure had to equal the previous mineral and organic P applications. It was assumed that P inputs of green manure (cover crops) were negligible. Based on historical applications used in the reference scenario, a new quantity of swine manure application rate was calculated.

No manure was applied in fall anymore. The total historical manure amounts were divided between spring (55% of total P manure) and summer (45% of total P manure) applications. Using the concentration of mineral and organic P in swine manure the new quantities for spring and summer were calculated as follow:

$Qsw = (Q_{TP} * 0.011) + (Q_{TP} * 0.005)$

where:

Qsw is the quantity of swine manure applied

Q_{TP} is the historical quantity of P applied for the reference scenario

0.011 is the concentration of mineral P in swine manure from the SWAT fertilizer database.

0.005 is the concentration of organic P in swine manure from the SWAT fertilizer database.

Agro-forestry

To simulate agroforestry practices, poplar (*populous spp.*) was planted on May 15 in all HRUs with a slope greater than 9%. This corresponded to 2694 ha (or 4.3% of the basin area). Every four years, the poplars were fertilized with 77 kg/ha of N (with swine manure) on June 16, and partially harvested (20% of biomass) for wood on October 15.

Protection of drinking water sources

Eight drinking water intakes are located within the watershed. In all cases, the water stems from groundwater, from tubular well. Table A17 shows the well number and their location.

Table A17: Identification on existing well within the watershed

Well ID	Location	Land use
5	School of St-Joseph Well #1	Crops
6	School of St-Joseph Well #2	Crops and forest
7	Community Center of St-Ignace	Mainly crops and forest
8	Camping Caravelle Well # 1 (Ste Sabine)	Mainly urban, some forest and crops
9	Camping Caravelle Well # 2 (Ste Sabine)	Mainly urban, some forest and crops
10	Camping Chute Hunter	Mainly forest, some crops, on moderate slopes (0.5 to 7%)
11	Centre Vallee Rustique 2000	Mainly forest, some crops, on moderate slopes (0.5 to 7%)
12	Vignoble les Blanc-Côteau	Crops, orchard and forest

We had no further information about the water abstractions of these wells. Because of the nature of the supply, it was assumed the water extracted was for more than 20 persons. In this case, the regulation on groundwater abstraction of the MDDEFP stipulates that the perimeter of protection must be respected around these wells to avoid drinking water contamination (www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=3&file=/Q_2/Q2R6.htm).

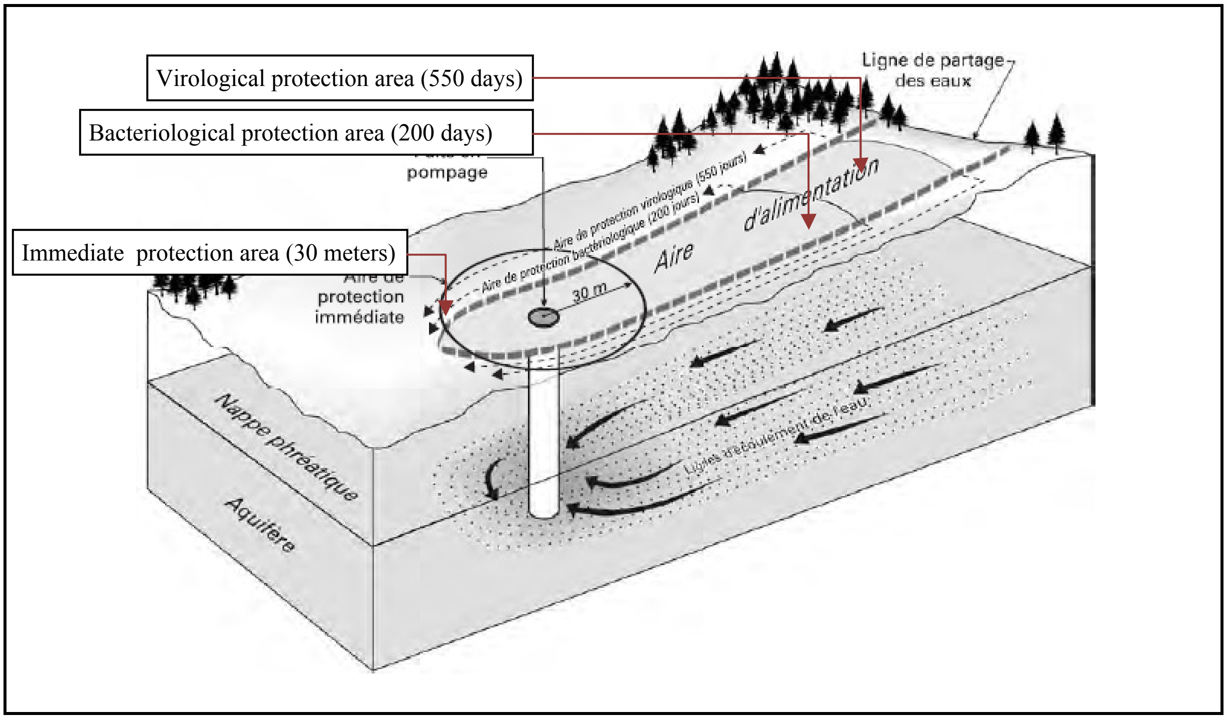
The regulation requires three types of conservation areas:

- Immediate conservation area : 30 m (article 24)
- Bacteriological protection area (depending on average pumping rate)
- Virological protection area (depending on average pumping rate)

For an abstraction over 75 m^3 per day, the two last points correspond to a portion of the upstream area draining towards the well (Figure A1). This portion is calculated according groundwater migration during 200 days for bacteriological protection and 550 days for virological protection. For abstractions less than 75 m^3 per day, these areas are set to 100 m and 200 m for the bacteriological and virological protection, respectively.

The regulation also requires that the risk of contamination in these areas be determined using the DRASTIC method, as well, an inventory of all activities that may potentially contaminate groundwater (fertilizing application or storage, wastewater treatment system, etc.,) must be conducted. A map of groundwater vulnerability to contamination was in preparation but did not yet exist to determine the perimeter of protection (Johanne Bérubé, pers. comm. February 28, 2013).

Figure A1: Illustration of the bacteriological, virological protected area. Source: *Guide technique captage d'eau souterraine pour des résidences isolées*. MDDEP, 2008.



In addition, two articles of the regulation stipulate specific conditions to protect the wells in agricultural areas. A minimum distance of 30 m between a well and an agricultural plot must be respected (article 8), and the storage of manure, compost or fertilizing material directly on the soil within a perimeter of 300 m around the well or within the vulnerable area of bacteriological protection is forbidden (article 30).

Therefore, in the absence of precise data delimiting the protection areas of the wells within the watershed, a protection zone of 300 m in which no agricultural activities would occur, was developed in ArcGIS.

Similarly to the flooded areas, well water protection areas are difficult to accurately protect due to the HRUs which are indivisible and scattered in the sub-basins. Hence, the protection of drinking water sources could not be implemented since it was impossible to target the actual protection area with SWAT. To convert crops to rangeland inside the 300 m buffer protection zone, the entire HRUs adjacent to the well have to be converted. So that an area of 226 ha needed protecting in the watershed, but SWAT can only protect a minimum of 6300 ha. The area of the entire HRUs, typically, represents an extent too large compared to what have to be protected. Table A18, shows the targeted area (300 m zone) which should realistically be implemented versus what is possible with our SWAT set-up.

Table A18: Areas (ha) of land to be protected with a 300 m protection zone around water drinking sources, and area of SWAT HRUs which contain the 300 m zone.

	Well ID							
	5		6		7		8	
Land use	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)
Agricultural Land (generic)								
Agricultural Land (row crops)	0.09	0.09	0.09					
Corn	1.86	93.32	1.99	540.22	13.92	344.12	2.70	371.67
Forest	2.08	26.23	1.98	0.48	2.69	11.20	1.94	517.53
Hay	8.53	259.27	8.21	115.67	4.05	83.18	10.66	365.85
Orchard								
Soybean					0.01	2.74		
Cereals	4.55	43.70	4.67	82.75	7.51	72.85	12.78	176.32
Urban	11.14	10.89	11.32	6.30	0.09	0.09	0.09	0.09
Total	28.26	433.50	28.26	745.42	28.26	514.18	28.17	1431.46

	9		10		11		12		Grand Total	
Land use	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)	Targeted (ha)	HRU (ha)
Agr. Land (generic)							0.09	0.09	0.09	0.09
Agr. Land (row crops)									0.18	0.09
Corn	8.66	3.01	0.27	183.34			0.32	16.77	29.72	1552.4
Forest	6.87	5.30	21.88	1566.7	20.76	138.22	3.24	128.83	61.43	2394.5
Hay	10.22	2.42	2.57	574.19	6.11		5.61		55.95	1400.6
Orchard							7.11	297.31	7.11	297.31
Soybean	1.49	12.14							1.50	14.88
Cereals	1.02	1.32	3.55	227.08	1.40		11.90	18.49	47.38	622.52
Urban									22.64	17.37
Total	28.26	24.19	28.26	2551.3	28.26	138.22	28.26	461.49	226.00	6299.8

If drinking water resource protection within SWAT has to be implemented, the SWAT set up has to be done with smaller HRUs, and a greater number of sub-basins. This would require a new set-up of the SWAT model. Furthermore, a precise delimitation of the protection areas around each well will help improving the implementation.

Runoff Reduction due to Conservation Practices

In the three adaptation scenarios (STRAT, FEASB, OPTIM), soil conservation practices protect soils against erosion by reducing runoff. Therefore, the curve numbers (CN) of HRUs under reduced tillage, no-till or with soil cover (intercrops, green manure, or cover crops) were decreased by 3 units. The coefficient of Manning's overland flow (OV_N) were increased as per Table 5 in Michaud et al, (2007) to account for an increase in soil roughness due to increased residue on the field. When crop substitutions were implemented, the CN and OV_N values were updated for the crop being substituted.

Appendix 7: Mean Annual Water Balances for the Scenarios

Scenario	Precipitation (mm)	Evapo transpiration (mm)	Water yield (surface runoff + subsurface) (mm)	*Surface runoff (mm)*	Percolation to deep aquifer (mm)	Water balance (mm)	Water balance error (%)
Reference	1184.1	566.6	511.0	*29.1*	118.0	-11.5	-0.9
ACU	1250.5	606.3	532.3	*24.8*	125.7	-13.6	-1
AGR	1282.5	608.1	562.2	*25.3*	130.6	-18.4	-1
AHK	1286.0	614.3	549.0	*24.3*	132.9	-10.2	-0.7
HIST	1183.6	565.2	516.9	*32.5*	116.3	-14.8	-1
EXP	1183.6	565.5	513.8	*30.2*	117.4	-13.1	-1
FOREST	1183.7	633.4	410.4	*3.9*	125.1	14.8	1
CORN	1183.7	533.8	633.6	*73.4*	83.6	-67.3	-6
AGR_HIST	1282.5	606.5	569.0	*27.6*	128.5	-21.5	-2
AGR_EXP	1282.5	610.2	562.4	*25.7*	129.1	-19.2	-1
AHK_HIST	1286.0	614.4	552.5	*26.6*	130.9	-11.8	-0.9
AHK_EXP	1286.0	614.5	549.9	*24.6*	131.9	-10.3	-0.9
STRAT	1286.0	599.1	572.5	*20.3*	133.6	-19.2	-1
FEASB	1286.0	615.1	549.8	*21.3*	132.5	-11.4	-0.8
OPTIM	1286.0	626.9	541.9	*17.5*	130.1	-12.9	-1

All values are mean values for the entire watershed (i.e. averaged over all land use types).

Water balance = precipitation – (evapotranspiration + water yield + percolation to deep aquifer)

Water balance error = water balance / precipitation

Appendix 8: Monthly Snowmelt Balances (mm) for the Climate Simulations

Simulation	Month	Precip.	Snowfall	Snowmelt	Surface Runoff	Percolation
Reference	1	98.17	65.26	16.06	3.76	30.21
	2	76.41	50.11	23.20	2.54	29.27
	3	90.11	35.36	102.89	13.51	81.61
	4	91.50	2.37	52.11	4.52	62.73
	5	94.70	0	0.03	0.03	25.09
	6	95.94	0	0	0.22	14.22
	7	117.44	0	0	0.45	11.07
	8	115.07	0	0	0.31	14.58
	9	105.97	0	0	0.29	27.11
	10	98.44	0.01	0.01	0.82	43.86
	11	99.38	11.95	4.69	0.65	51.83
	12	100.95	61.78	13.50	1.98	29.64
ACU	1	106.56	40.73	22.65	5.63	51.87
	2	65.66	24.00	24.85	3.41	37.32
	3	109.36	12.17	43.63	7.17	72.77
	4	101.86	0.10	2.11	0.17	43.60
	5	109.48	0	0	0.10	26.68
	6	104.73	0	0	0.86	16.07
	7	108.79	0	0	0.17	8.04
	8	107.98	0	0	0.40	15.92
	9	104.69	0	0	0.64	29.24
	10	94.02	0	0	0.65	36.22
	11	116.32	6.24	3.27	0.82	59.83
	12	121.02	30.54	11.48	4.06	54.41
AGR	1	114.96	46.05	22.20	5.69	51.95
	2	85.53	33.36	22.72	5.12	41.02
	3	101.49	9.52	54.09	8.81	71.68
	4	121.83	0.47	2.41	0.53	52.49
	5	107.58	0	0	0.02	25.23
	6	92.46	0	0	0.20	9.44
	7	106.80	0	0	0.06	8.02
	8	118.69	0	0	0.29	16.58
	9	103.86	0	0	0.64	30.28
	10	112.52	0.02	0.02	0.74	48.87
	11	107.92	5.45	2.81	0.78	56.89
	12	108.91	20.18	7.16	2.37	54.60
AHK	1	91.75	41.79	14.21	4.17	38.46
	2	83.64	25.99	37.05	6.00	56.23
	3	97.21	10.49	32.11	5.71	58.29
	4	106.66	0.04	1.64	0.29	48.07
	5	109.27	0	0	0.32	30.27
	6	119.54	0	0	0.98	20.42
	7	125.78	0	0	0.15	10.11
	8	119.82	0	0	0.46	22.12
	9	112.63	0	0	2.19	35.23
	10	97.67	0	0	0.86	41.76
	11	125.62	1.75	0.95	1.34	72.70
	12	96.42	16.98	6.27	1.81	49.61

Appendix 9: Mean Annual Nutrient Loadings

Table A19: Mean Annual Nutrient Loadings for Reference Scenario

Land use	Area	Sediments	NO_3^--N	Total P	Particulate P	Soluble P
	ha	Mg/ha	kg/ha			
Unknown small spaced row crops	5.30	0.04	26.15	0.32	0.02	0.3
Unknown large spaced row crops	2.78	0.01	24.14	0.57	0.02	0.54
Corn	12545.56	1.04	19.75	1.89	1.38	0.51
Hay	14054.39	0.12	54.4	0.67	0.2	0.46
Cereals	4892.04	0.82	22.73	1.65	1.2	0.45
Soybean	1562.26	0.98	15.46	1.05	0.84	0.21
Orchard	1102.28	0	30.41	0.37	0	0.37
Rangeland	404.44	0	71.75	0.56	0	0.56
Vegetables	22.98	0.28	26.99	1.37	0.69	0.68
Berries	2.85	0	21.23	0.39	0	0.39
Switchgrass	2.81	0	15.83	0.21	0	0.21
Forest	25153.99	0	13.06	0.3	0	0.3
Water	3030.62	0	0	0	0	0
Urban	403.48	0.14	3.05	0.49	0.08	0.41
Total	**63185.78**	**0.32**	**24.39**	**0.81**	**0.43**	**0.38**

Table A20: Mean annual Nutrient Loadings for the Adaptation Scenarios

Adaptation scenario	Area	Sediments	NO_3^--N	Total P	Particulate P	Soluble P
	ha	Mg/ha	kg/ha			
STRAT	63185.91	0.14	24.87	0.59	0.20	0.39
FEASB	63185.91	0.17	25.81	0.64	0.26	0.38
OPTIM	63185.91	0.04	25.89	0.40	0.07	0.33

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