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IMPACT OF CLIMATE CHANGE ON DRAINAGE OUTFLOW AND WATER QUALITY IN EASTERN CANADA

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ABSTRACT The potential effects of climate change on the drainage outflow and nitrogen pollution of a 4.2 ha tile-drained experimental field research facility located at St. Emmanuel, Quebec are predicted using the latest version of the DRAINMOD 6.0 model. Under the assumption of no change in land cover and land management, the model is applied in order to simulate annual, seasonal and monthly changes in flow and NO3-N loads under current and future climate conditions. The climate scenario under consideration in this study (1961 to 2100) is based on projections from the Canadian Regional Climate Model (CRCM). The simulation results from the CRCM model suggest an increase in temperature and precipitation in the region being studied. Those changes result in a considerable increase in simulated mean annual subsurface flow in the study area.

Keywords: Drainage outflow, Climate change, Nitrogen pollution.

INTRODUCTION Global warming due to the enhanced greenhouse effect is likely to have significant effects on local hydrologic regimes. The hydrological cycle would be affected with more evaporation and more precipitation; however, the extra precipitation would be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation, or major alterations in the timing of wet and dry seasons. The changes in the hydrological behaviour of ecosystem caused by climate change will also affect nutrient transformation and transport characteristics (Bouraoui et al. 2004). Indeed, if climate change occurs, it will have a significant impact not only on the quantity but also on the quality of surface and subsurface waters, impacting the ecosystem beyond the tolerable threshold, leading potentially to a constant degradation of water quality (Murdoch et al. 2000). Many aspects of the environment, economy and society are dependent upon water resources, and changes in the hydrological resource base have the potential to impact environmental quality, economic development and social well-being (Arnell, 1999). These potential changes caused by climate variations need to be addressed, or at the very least, taken into consideration by policy makers and decision makers when managing water resources in the future.

Since hydrologic conditions vary from region to region, the influences of climatic change on local hydrological processes will differ within localities, even under the same climate scenarios (Zhang et al., 2007). It is primarily at the local and regional level that policy and technical measures could be taken to prevent, or reduce, the negative effects of climate change on the natural environment and society.

Predictions have been made that the Canadian climate, in general, will become warmer, and more variable (Hengeveld, 2000). Some recent examples of climate change impacts on water resources include melting of the permafrost in Northern Quebec, rising sea levels in Atlantic Canada, glacial retreat in British Columbia, and prolonged drought in the Prairies (Mehdi et al., 2006).

The objective of this study was to evaluate the effect of climate change (under an assumption of no change in land cover and land management), based on projections from the Canadian Regional Climate Model (CRCM), on subsurface flow and nitrogen pollution at a 4.2 ha field research facility located at St. Emmanuel, Quebec, using the DRAINMOD 6.0 model.

DRAINMOD 6.0 model was used to simulate drain outflow and NO_3^--N using the historical data and the predicted data from 1961-2008 and 2009-2100, respectively. The data were derived from predictions by the Canadian Regional Climate Model (CRCM 4.2). In general, the weather would become warmer and wetter over the years. In order to assess this climate change impact, the subsurface flow simulated results were analyzed for quantity and quality, in terms of nitrate outputs.

MATERIALS AND METHODS

Site Description The research was conducted on a 4.2 ha privately-owned experimental site, located at St-Emmanuel near Côteau-du-Lac, Quebec, approximately 30 km southwest of the Macdonald Campus of McGill University. Based on wells dug in the region and measurements of soil hydraulic conductivity, the impermeable layer was estimated to be 5 m deep. The site was under pasture prior to 1991, and subsequently under mono-cropped corn (Zea mays L.). Although the topsoil (0–0.25 m) is a well-drained Soulanges sandy loam, clay layers - sandy clay loam (0.25–0.55 m) and clay (0.55–1.0 m) - deeper in the soil profile, impede natural drainage (Elmi et al., 2004). Selected soil physical parameters were determined during a 1992 site survey (Mousavizadeh, 1992) and are shown in Table 1.

Surface topography was generally flat with a mean slope of less than 0.5%. Lateral subsurface drains, 76-mm-diameter and 15 m apart on a 0.3% slope, were installed at a maximum depth of 1.0 m. There were three 0.9 ha blocks, each mono-cropped to corn, containing eight adjacent treatment plots (15 m × 75 m). Experimental plots were under a conventional tillage system, the common practice in the region. A 30-m wide strip of undrained land separated the blocks. Blocks were arranged from east to west. The plots were separated by 6-mil (0.6 mm) polyethylene sheeting, installed to a depth of 1.5 m, to

Table 1. Soil physical properties

Depth (cm)	0-25	25-50	50-100
% Clay	10	20	39
% Sand	56	58	32
Textural class	Sandy loam	Sandy clay loam	Clay loam
Bulk density (mg m^{-3})	1.63	1.6	1.49
Saturated hydraulic conductivity, Ksat (cm hr^{-1})	1.88	1.46	0.54

minimize seepage and chemical flow between plots. Drain flow from each pipe was directed to tipping buckets in heated buildings, allowing continuous drainage discharge measurements (Tait et al., 1995), and collection of water samples for flow weighted NO_3^--N determinations. The site was arranged in a split plot design, with two N-fertilizer rates (120 and 200 kg ha^{-1}, N120 and N200), factorially combined with two modes of WTM: sub-irrigation at a WTD of 0.6 m (SI) vs. free drainage at a drain depth of 1.0 m (FD). In addition, adjacent to each WTM treatment were buffer plots with the same drainage treatment. Nitrogen fertilizer was applied in a split dose: 23 kg N ha^{-1} banded as ammonium phosphate (18-46-0) at seeding, and 97 or 177 kg N ha^{-1} broadcast as ammonium nitrate (34-0-0) one month after planting (June 8 1998; June 10, 1999), resulting in rates of 120 kg N ha^{-1} (N120) or 200 kg N ha^{-1} (N200), respectively. All buffer plots received 120 kg N ha^{-1}. The field was seeded to grain corn (Pioneer hybrid 3905) on May 8, 1998 and May 4, 1999 (Table 2), at a planting density of 75,000 plants ha^{-1} and a 0.75-m row spacing.

In this study, simulations are performed for the N120 (120kg N/ha) under the free drainage system. The model input parameters were adapted from the study conducted by Dayyani et al. (2009a) at the same experimental site, evaluating DRAINMOD 5.1 for simulating drain outflow and NO_3^--N transport.

DRAINMOD 6.0 Model DRAINMOD-N II (Youssef et al., 2005) is a field-scale, process-based model that simulates C and N dynamics in drained agricultural lands for a wide range of soil types, climatic conditions, and management practices. The model simulates a detailed N cycle that includes three soil N pools: nitrate-nitrogen (NO_3^--N), ammoniacal-nitrogen (NH_x-N), and organic-nitrogen (ON). Nitrogen processes and

Table 2. Agronomic Practices (N120=120 kg/ha)

Event	1998	Amount (kg ha^{-1})	1999	Amount (kg ha^{-1})
Seeding	May 8th	-	May 4th	-
N_{120}: First application	May 8th	23	May 4th	23
N_{120}: Second application	June 8th	97	June 10th	97
Drains opened for harvesting	Sept. 28th	-	Sept. 17th	-
Field Harvested	Oct. 20th	-	Oct. 22nd	-

transformations considered in the model include atmospheric deposition, application of mineral N fertilizers and ON sources (plant residues/animal waste), plant uptake, N mineralization/immobilization, nitrification, denitrification, ammonia (NH_3) volatilization, and NO_3^--N and NH_x-N losses via subsurface drainage and surface runoff.

DRAINMOD-N II simulates the effects of tillage on C and N dynamics using a tillage intensity factor that reflects the level of soil disturbance caused by tillage operations. At the day of harvest, the model can return plant residues back to the system and update litter pools accordingly. The model can also simulate the application of animal waste to the soil-plant system.

The model simulates urea hydrolysis, nitrification, and denitrification using Michaelis-Menten kinetics. The effect of nitrification inhibitors on the nitrification process is simulated using a response function that modifies process rate according to inhibitor concentration which declines according to a first-order decay rate.

In DRAINMOD-N II the potential N uptake for each crop is empirically estimated and distributed over the days of the growing season. Both NO_3 and NH_4 are assumed to be equally available to plants. If one form is used up before satisfying plant needs, the rest is taken from the other form. If total mineral N is insufficient and crop is not a legume, actual N uptake is set to the available amount of mineral N. Legumes are assumed to fix atmospheric N only when a shortage in soil mineral N occurs.

Model inputs include soil properties, crop and management parameters, and C and N processes and transformations parameters. Model output includes NO_3^--N and NH_x-N concentrations in soil solution and drain flow, OC content of the top 20 cm soil layer, and rates of simulated N processes on daily, monthly, and annual basis. In this study, the input parameters which were not measured at the study site were set to default values.

Climate Data The climate data used in this paper is provided by Ouranos organization, and the climate change modeling is not part of this study. The climatic parameters used to run DRAINMOD model are: precipitation and min/max temperature. The simulation used in this study has the following specifications: CRCM4.2.0 time-slice simulation for 1961-2100 ('adj' run) driven by CGCM3 (The Third Generation Coupled Global Climate Model), following IPCC "observed 20th century" scenario for years 1961-2000 and SRES (Special Report on Emission Scenarios) A2 scenario for years 2001-2100 over the North-American domain (201x193) with a 45-km horizontal grid-size mesh, 29 vertical levels and spectral nudging of large-scale winds. The CRCM is a limited-area nested model, originally developed at Université du Québec à Montréal, based on the fully elastic nonhydrostatic Euler equations. These equations are solved using a noncentered semi-implicit and semi-Lagrangian numerical algorithm (Caya, 1996; Laprise et al., 1998; Caya and Laprise, 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, with a typical 45-km grid mesh (true at 60°N), and its vertical resolution is variable using a Gal-Chen scaled height terrain-following coordinate. The model characteristics are described in (Music and Caya, 2007). The CRCM_V4.2 is mostly based on CCCma GCM3 package (Scinocca and McFarlane, 2004). The results obtained in this study are expected to provide more insight into the characteristics of

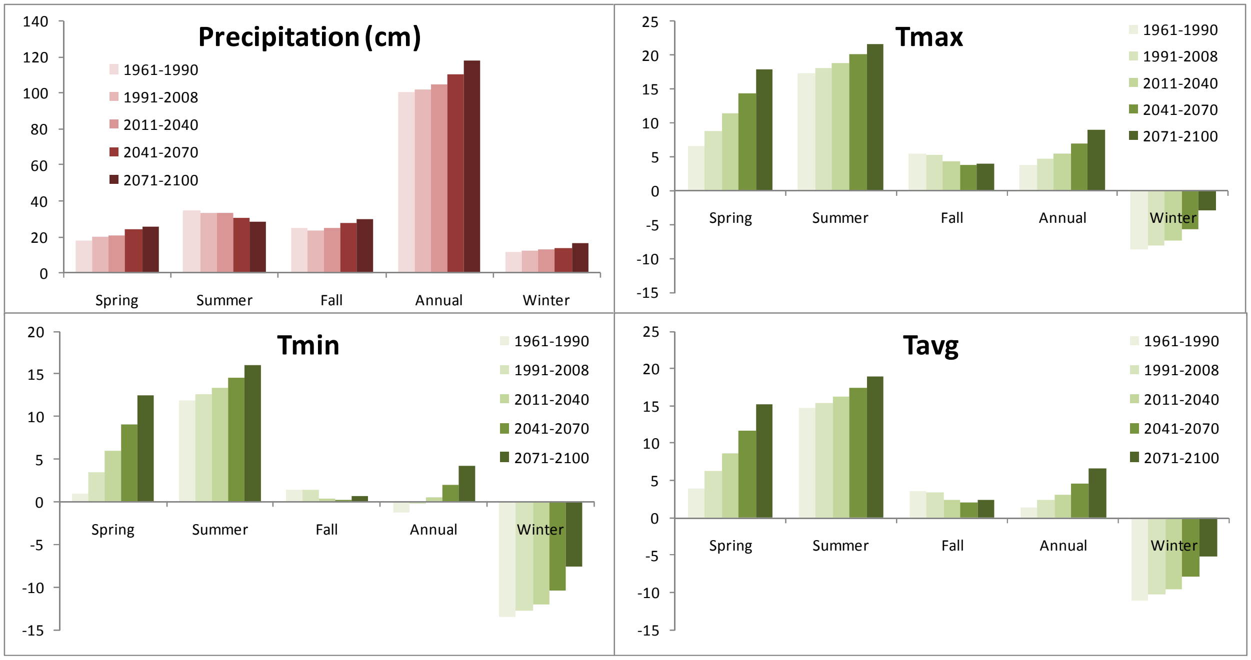

Figure 1. The historical (1961-1990) and future (2011-2100) predicted annual and seasonal average precipitation, and max/min/average temperature

future flow and nitrogen pollution, and to provide local water management authorities with a planning tool.

RESULTS AND DISCUSSION CRCM climate-change projections indicate an increase in the average annual precipitation and temperature (Figs. 1,2). Precipitation is increasing in all the seasons except in summer. The Mann-Kendall (MK) test was performed on this data set by Dayyani et al. (2009b) and the results (Table 3) showed a non-significant increasing trend for precipitation over the historical period (1961-2008), but a significant increase over the future period (2009-2100). A significant increase is also noted in the annual temperature for both historical and future data. The MK test results also indicate that seasonal max/min/average temperatures are increasing significantly except in fall, which is showing a decreasing trend although it is non-significant (Dayyani et al., 2009b). The MK results also indicated that the minimum temperature is increasing

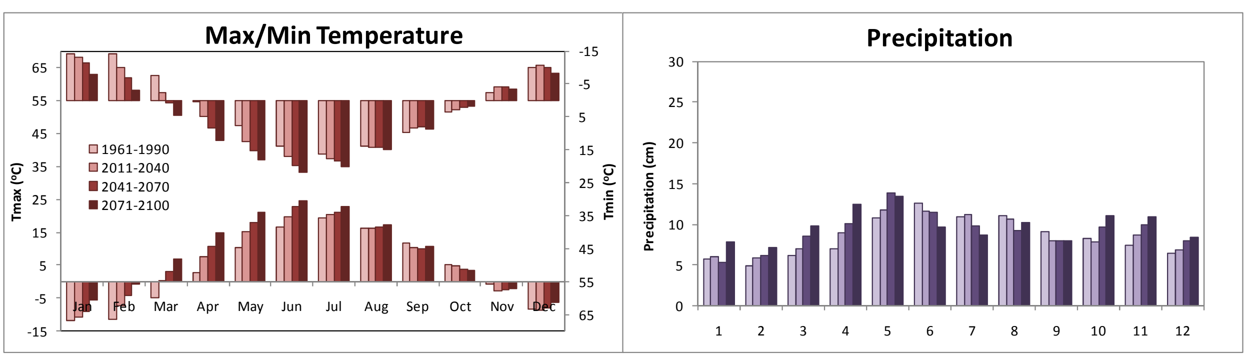

Figure 2. The historical (1961-1990) and future (2011-2100) predicted monthly average precipitation, and Max/Min temperature

Table 3. MK test results adapted from Dayyani et al. (2009b)

Parameter			U or Z rank (Mann-Kendall)	Trend	Significant/Non-significant
Annual Precipitation	Historical Data		0.35	I	NS
	Future Data		4.03	I	S
Annual Tmax	Historical Data		4.01	I	S
	Future Data		10.45	I	S
Annual Tmin	Historical Data		4.63	I	S
	Future Data		10.42	I	S
Annual Tavg	Historical Data		4.42	I	S
	Future Data		10.44	I	S
Seasonal Precipitation	Historical Data	Spring	2	I	S
		Summer	-2.09	D	S
		Fall	-1.35	D	NS
		Winter	0.8	I	NS
	Future Data	Spring	3.7	I	S
		Summer	-2.7	D	S
		Fall	3.66	I	S
		Winter	4.93	I	S
Seasonal Tmax	Historical Data	Spring	5.36	I	S
		Summer	3.25	I	S
		Fall	-0.88	D	NS
		Winter	2.48	I	S
	Future Data	Spring	10.5	I	S
		Summer	8.35	I	S
		Fall	-1.18	D	NS
		Winter	8.5	I	S
Seasonal Tmin	Historical Data	Spring	5.58	I	S
		Summer	3.8	I	S
		Fall	-0.2	D	NS
		Winter	2.47	I	S
	Future Data	Spring	10.8	I	S
		Summer	8.5	I	S
		Fall	-0.46	D	NS
		Winter	8.12	I	S
Seasonal Tavg	Historical Data	Spring	5.56	I	S
		Summer	3.55	I	S
		Fall	-0.74	D	NS
		Winter	2.5	I	S
	Future Data	Spring	10.6	I	S
		Summer	8.58	I	S
		Fall	-0.59	D	NS
		Winter	8.33	I	S

significantly in all seasons except fall. The average annual temperature for the watershed for the future period is 3.4 ^{o}C warmer relative to the historical climate. Similarly, the average annual precipitation is also expected to be 9% higher for the future climate.

The climate-change impact on hydrology of the St. Emmanuel experimental site is estimated by running the DRAINMOD 6.0 model using climate data from 1961 to 2100. Water balance components of the 48-year (1961-2008) historical and 92-year (2009-2100) future simulations by DRAINMOD 6.0, including precipitation, evapotranspiration, surface and subsurface flows are presented in Figure 3. Unsurprisingly, the evapotranspiration tends to increase with the years, as the temperatures are seen to increase. The yearly subsurface flow is also seen to increase, whereas the surface runoff decreases. It can be seen that there is a certain correlation between rainfall and subsurface flow, as temporal increases in rainfall are associated with similar increases in subsurface flow of water.

From Figures 4 which presents the monthly subsurface flow, we observe two distinct patterns. In the first case, we can see that peak period for drainage outflow for the historical period from 1961 to 1990 is around the month of June, whereas by 2071-2100 the peak has shifted to the month of April. In addition to this, the magnitude of the peak for the latter period is significantly larger than for the historical period. Also, we see increases in the subsurface flow in winter months, which might indicate that the soil is not as deeply frozen as in the past.

Figure 5 presents the 30-year-annual and seasonal average of subsurface flow for 4 different 30 year periods. The model simulations show a considerable increase in annual flow. The increase in winter is mainly during March and December (Fig. 4). Although precipitation is increasing during March, the flow is increasing at a higher rate. The min/max temperatures are increasing in winter, causing more rainfall dominated regimes and less snow accumulation. The frequency analysis performed by Dayyani et al. (2009b) on the same climatic data set, showed that the rainfall intensity is increasing during the summer and fall, that might lead to a decrease in infiltration rate and increase in runoff volume causing a rise in surface flow and a decline in subsurface flow during the period.

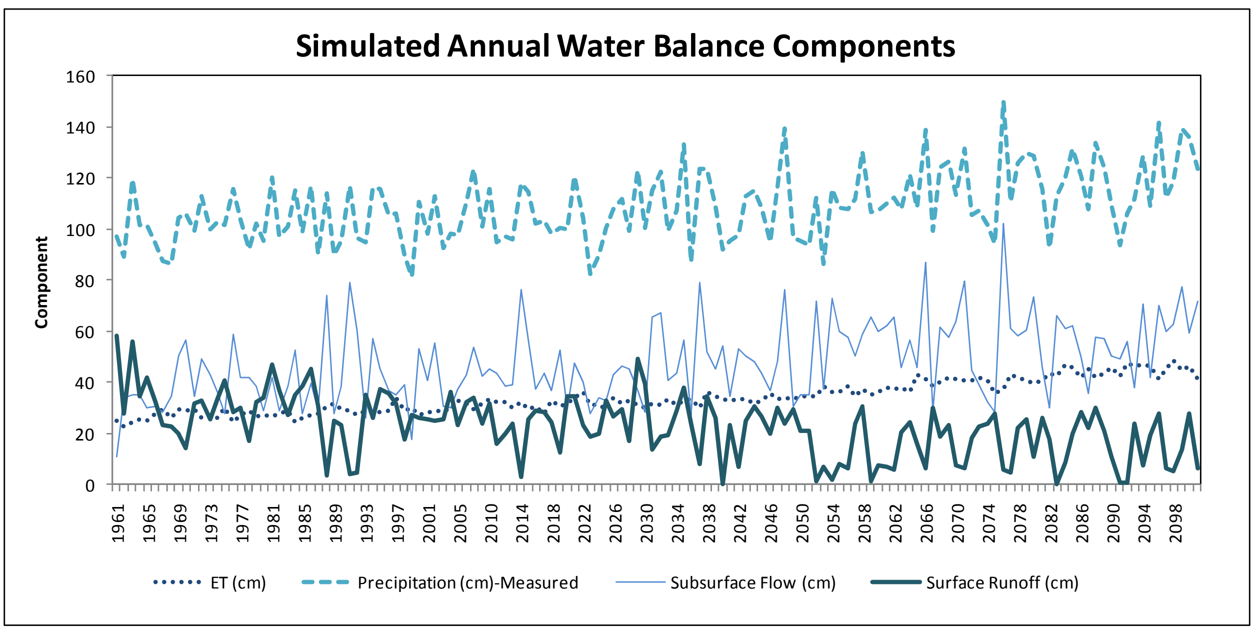

Figure 3. DRAIN-WARMF simulated water balance components (precipitation, ET, surface and subsurface flows) for 1961-2100

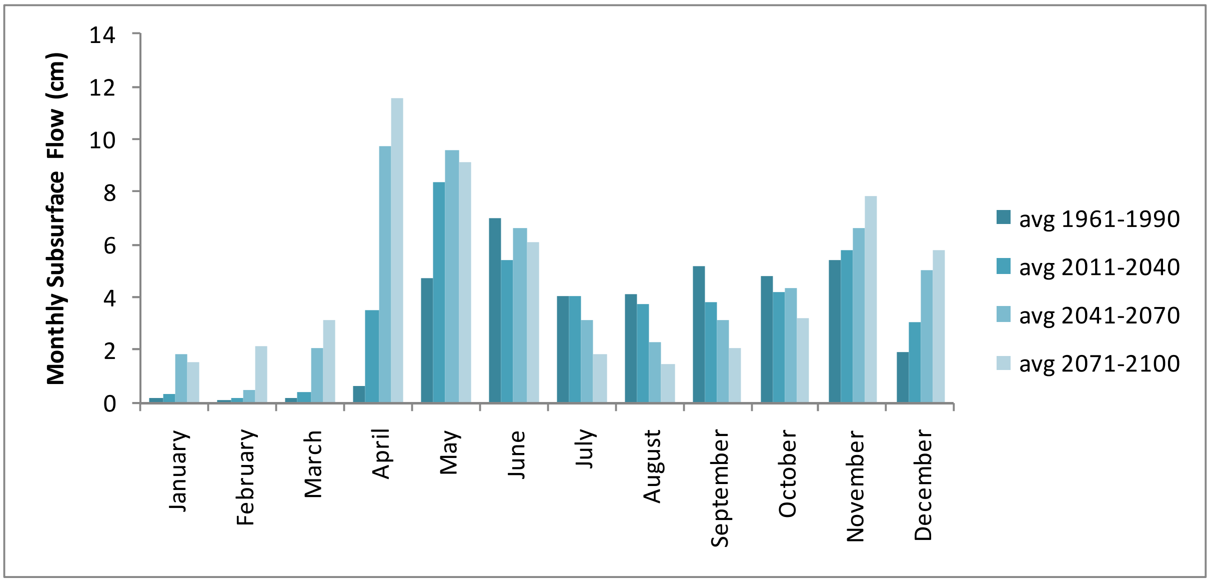

Figure 4. The historical (1961-1990) and future (2011-2100) predicted monthly average precipitation and simulated subsurface flows

Total flow is increasing significantly during March and April over the future period (Fig. 4). Although precipitation increased in these months, flow increased to a greater extent as compared to precipitation. This is because the snowmelt is occurring earlier (in March and April) as compared to historical period. The decline in subsurface flow during June might be due to the fact that warming is occurring earlier; the groundwater flow would take place earlier.

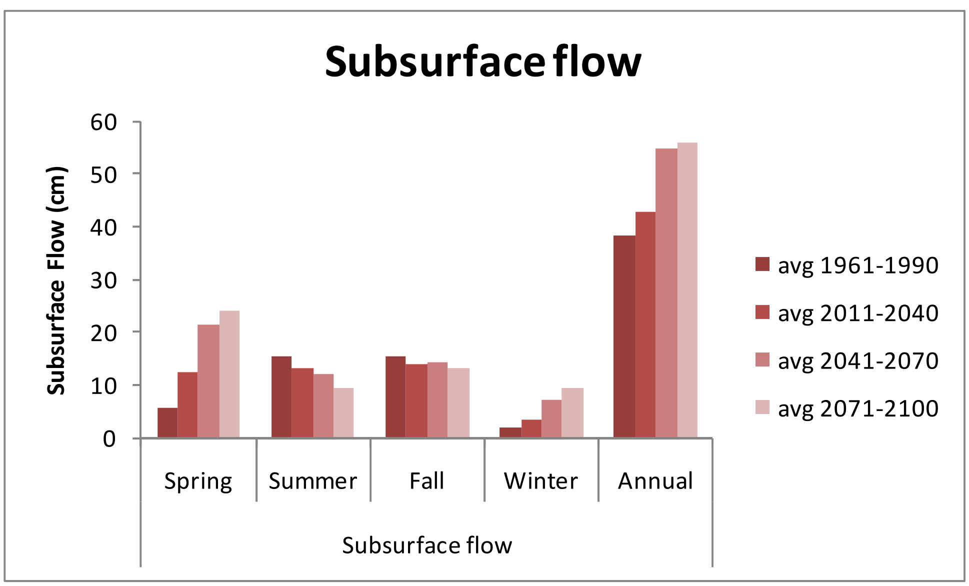

Figure 5. The historical (1961-1990) and future (2011-2100) simulated annual and seasonal average subsurface flows

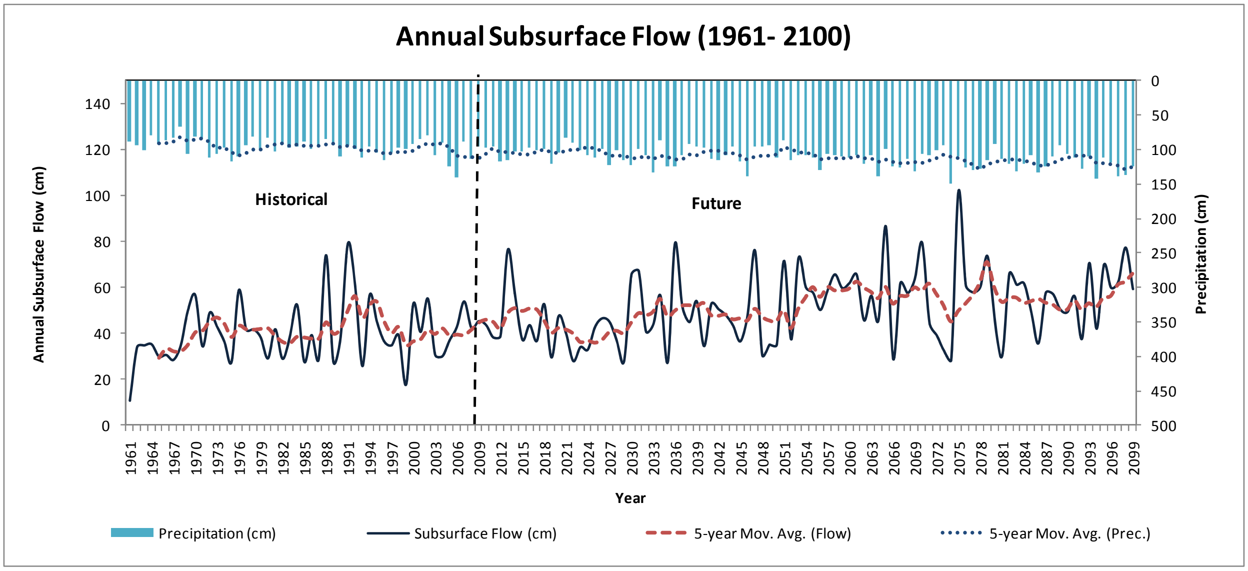

Figure 6: Annual comparison of the historical (1961-2008) and future (2009-2100) predicted precipitation and simulated flow

As stated before, the increase in min/max temperatures in winter causes more rainfall dominated regimes and less snow accumulation. This might lengthen the growing season. It is an important finding that climate change seems to alter both the magnitude and the seasonality of flow. Overall, climate change affects more winter and spring hydrology (Fig. 5). Figure 6 shows the annual trend of the subsurface flow for both historical and future data. The increasing trend is evident from the plot of the moving average.

The impact of changed hydrology on NO_3^--N losses was assessed using the DRAINMOD 6.0 model. The seasonal and monthly results of model prediction are presented in Figures 7 and 8, respectively. From figures we can see that the peaks shift to earlier periods, as in the subsurface flow, in the future. However, in the 3rd and 4th time periods, the losses are becoming significantly less, which might be explained in several different ways. In fact, DRAINMOD 6.0, with its DRAINMOD-N II feature, calculates nitrogen losses including many different variables, and simulating a detailed nitrogen cycle. This includes soil pH, which in this case has been set to be “reset” every year, crop uptake, nitrogen from rainfall, etc. As the NO_3^--N losses are significantly higher in the second period, especially at the time where the crop is planted and the fertilizer is applied, there is a possibility that the subsequent applications of fertilizer are not sufficient for the crop, and that it is uptaking more of the nitrogen from the soil, which might explain why less nitrogen is being lost through the drains during the growing season. Also, more nitrogen is being lost during the winter months, as there is a greater outflow of water from the drains due to higher temperatures and greater precipitations. Overall, on an annual basis, the nitrogen losses increase slightly in the first 30 years of the future, and then decrease until the end of the simulation period in 2100. The nitrogen loss monthly patterns also seem to be highly correlated to the drain outflow monthly patterns. The DRAINMOD-N II also considers the effects of soil temperature on nitrogen processes, where higher temperatures tend to increase the microbial process rates, giving another explanation as to why more NO_3^--N might be lost during the winter months in the future.

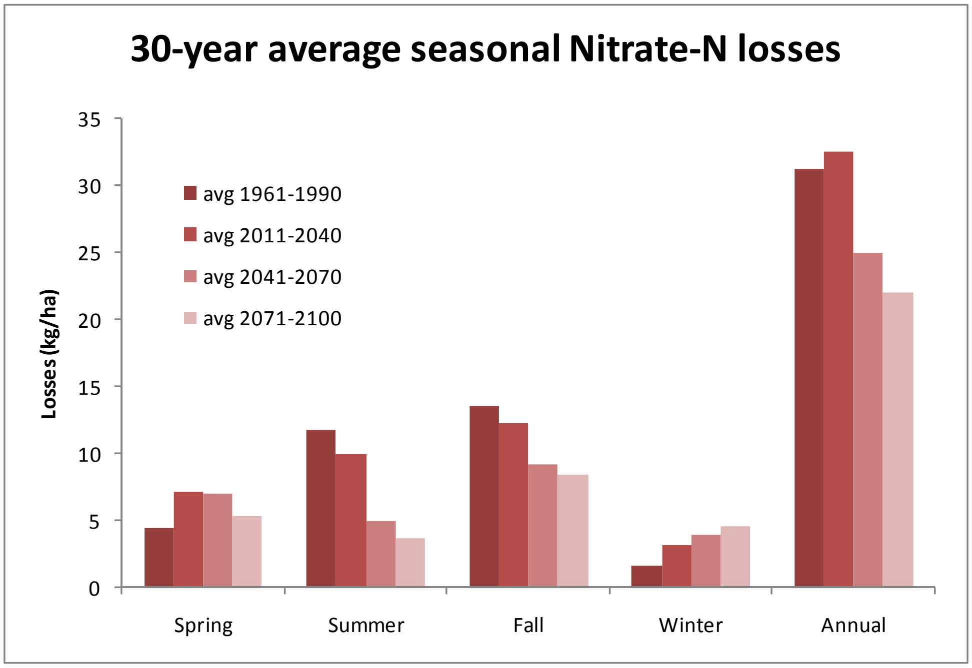

Figure 7. The historical (1961-1990) and future (2011-2100) simulated annual and seasonal average subsurface nitrate-N losses.

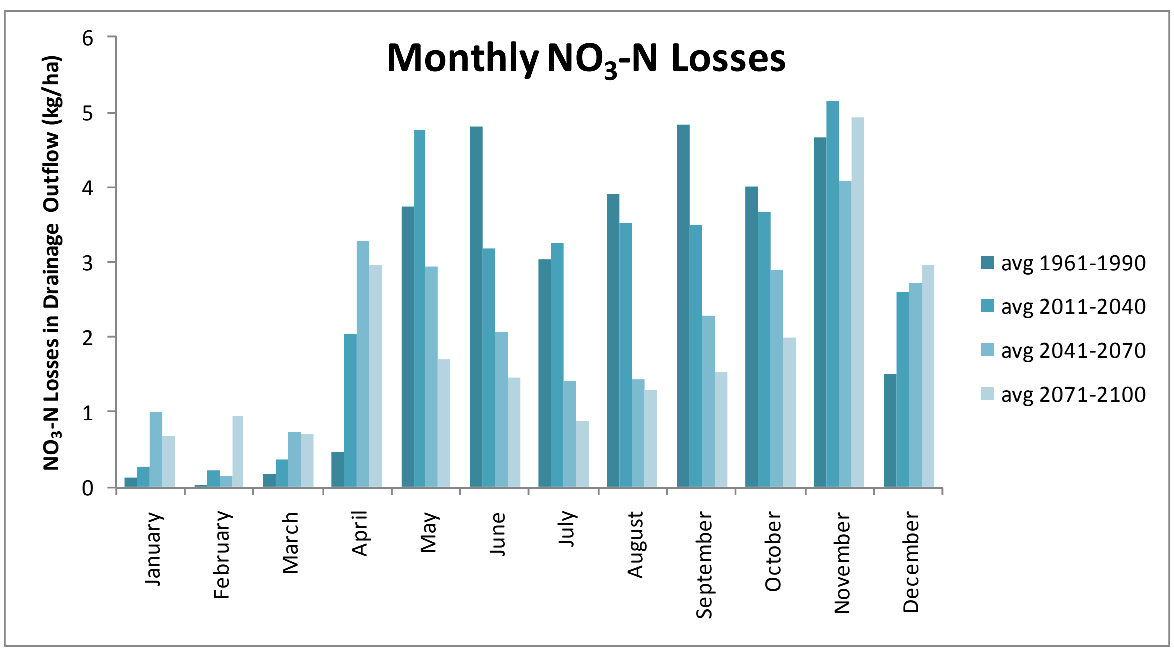

Figure 8. The historical (1961-1990) and future (2011-2100) simulated monthly average nitrate-N losses

CONCLUSIONS This study presents the results of an application of the DRAINMOD 6.0 model in evaluating the effects of potential climate change on subsurface flow and nitrogen transport at an tile-drained experimental site in Quebec, Canada. The simulations were performed based on projected climate change conditions developed by the CRCM4.2.0 model for 1961 to 2100. The projected annual temperature and precipitation changes indicate that the climate in the study area would generally become warmer and wetter. Warmer temperatures would alter the hydrologic cycle, with uncertain implications for precipitation, runoff, and the intensity and frequency of floods and droughts. For the future hydrological assessment and NO_3-N losses, the DRAINMOD model was adopted. The simulation results show an increase in the average annual drainage outflows, based on climatic data projected by Canadian CRCM4.2.0. The nitrogen losses will be decreasing after a certain period, as the user chose not to recycle the organic matter in its simulations. In addition, losses are more likely to occur earlier in the spring, as the temperatures are increasing and the soil is not freezing as deeply in the future as it had historically, and with higher precipitations than before.

Overall, DRAINMOD 6.0 seems to have great potential, but data acquisition will need to be modified to consider the new inputs to the model, and more work has to be done to be able to find adequate values for all the variables in DRAINMOD-N II where the default values were being used.

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