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Impacts of climate change and best management practices on nitrate loading to a eutrophic coastal lagoon

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Anthropogenic climate change and associated increasing nutrient loading to coasts will worsen coastal eutrophication on a global scale. Basin Head is a coastal lagoon located in northeastern Prince Edward Island, Canada, with a federally protected ecosystem. Nitrate-nitrogen ($\text{NO}_3\text{-N}$) is conveyed from agricultural fields in the watershed to the eutrophic lagoon via intertidal groundwater springs and groundwater-dominated tributaries. A field program focused on four main tributaries that discharge into the lagoon was conducted to measure year-round $\text{NO}_3\text{-N}$ loading. These measurements were used to calibrate a SWAT+ hydrologic model capable of simulating hydrologic and $\text{NO}_3\text{-N}$ loads to the lagoon. Several climate change scenarios incorporating different agricultural best management practices (BMPs) were simulated to better understand potential future $\text{NO}_3\text{-N}$ loading dynamics. Results indicate that all climate change scenarios produced increased annual $\text{NO}_3\text{-N}$ loading to the lagoon when comparing historical (1990–2020) to end of century time periods (2070–2100); however, only one climate scenario (MRI-ESM2-0 SSP5-8.5) resulted in a statistically significant (p -value < 0.05) increase. Enlarged buffer strips and delayed tillage BMP simulations produced small (0%–8%) effects on loading, while changing the crop rotation from potato-barley-clover to potato-soybean-barley yielded a small reduction in $\text{NO}_3\text{-N}$ loading between the historical period and the end of the century (26%–33%). Modeling revealed changes in seasonal loading dynamics under climate change where $\text{NO}_3\text{-N}$ loads remained more consistent throughout the year as opposed to current conditions where the dominant load is in the spring. An increase in baseflow contributions to streamflow was also noted under climate change, with the largest change occurring in the winter (e.g., up to a five-fold increase in February). These findings have direct implications for coastal management in groundwater-dominated agricultural watersheds in a changing climate.

KEYWORDS

hydrologic model, SWAT+, climate change, best management practice, nitrate loading

Introduction

Rising water temperatures and increased export of freshwater and nutrients to the coast are expected to exacerbate coastal eutrophication in future years (Rabalais et al., 2009). Anthropogenic changes such as industrialization and increased population are responsible for accelerated climate change and increased nutrient loading to coastal water bodies (Howarth, 2008; Oppenheimer et al., 2019). In addition to the deleterious human and ecosystem health impacts of coastal eutrophication (Cloern, 2001; Sinha et al., 2019), the degradation of coastal waters impacts the ecosystem services provided by the water body such as recreation, tourism, and cultural value (Malone and Newton, 2020).

Agricultural activity and on-site domestic wastewater treatment systems can cause increased nitrate-nitrogen ($\text{NO}_3\text{-N}$) loading in rural watersheds. Soil nitrate can be derived from mineral fertilizers, manures, biological nitrogen fixation and soil organic matter (Zebarth et al., 2015). Since the advent of nitrogen fertilizer for agriculture in the 20th century, global usage has increased to approximately 10 times the rate of consumption in 1961 (Lu and Tian, 2017). Nitrogen in the form of ammonia is applied to agricultural fields through chemical fertilizer where it is readily converted to nitrite, then to nitrate by microorganisms in soil and groundwater (Fetter et al., 2017). Nitrate-nitrogen can be transported by runoff over agricultural fields or through groundwater flow once precipitation infiltrates into the aquifer (Spalding and Exner, 1993). Accordingly, the intensification in nitrogen use has resulted in accelerated coastal eutrophication due to non-point source, diffusive transport of soluble nitrate to the coast (Arhonditsis et al., 2000; Malone and Newton, 2020).

Climate change is expected to negatively affect agricultural activities across the globe (Bennett et al., 2021; Nelson et al., 2009), impacting moisture availability and plant physiology, and affecting agricultural productivity (Mahato, 2014) due to increasing air temperatures, shifting precipitation regimes, and increasing frequency and severity of extreme events (AghaKouchak et al., 2020; Rivera, 2014; Wang et al., 2022). These hydrometeorological changes could all contribute to changing agricultural practices and productivity. For example, increased temperatures are expected to prolong agricultural growing seasons (AAFC, 2020) and shift the source of irrigation from rainwater to groundwater (Paradis et al., 2016; Afzaal et al., 2020; Bhatti et al., 2022), further stressing vulnerable water resources. Agricultural best management practices (BMPs) have been developed to help confront, among other stressors, the impacts of future climate change (Lal et al., 2011; Wagena and Easton, 2018). While proactive agricultural practices like BMPs help to reduce nutrient losses from agricultural fields, the efficacy of BMPs in mitigating $\text{NO}_3\text{-N}$ contamination in a changing climate is not well understood (Liu et al., 2017; Zebarth et al., 2015). Coastal agricultural watersheds are subject to additional stressors compared to inland watersheds, including the conversion of traditional nutrient sinks like wetlands and riparian zones to agricultural use (Boesch and Brinsfield, 2000) and other phenomena (e.g., seawater intrusion, coastal flooding, soil salinity) that impact agricultural sustainability (Gopalakrishnan et al., 2019; Tackley et al., 2023).

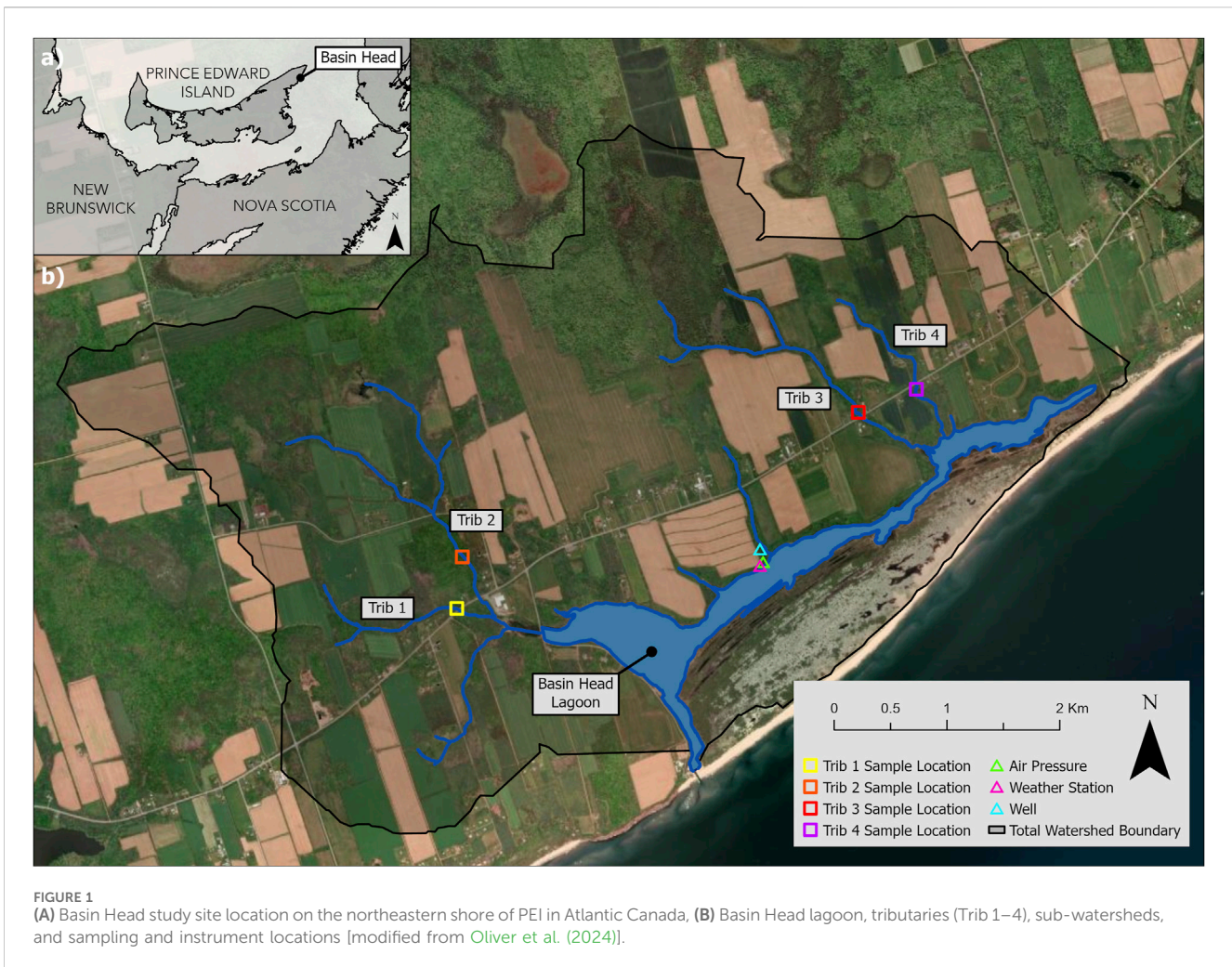
Understanding of nutrient transport dynamics from agricultural watersheds under a changing climate can be developed by using process-based simulation tools that incorporate changes in climate forcing and agricultural practices. The SWAT+ (Soil and Water Assessment Tool) hydrologic model is a time continuous, semi-distributed watershed model that simulates quality and quantity of surface water and groundwater over a three-dimensional domain (Arnold et al., 2012) with the input of land use, soil, elevation, and climate data. The model can simulate spatial and temporal dynamics of non-point source contaminant loading and has proven to be a valuable tool for environmental planning and management (Arnold et al., 2012). The goal of this study is to investigate the effects of climate change and alternative BMPs on $\text{NO}_3\text{-N}$ loading to a shallow, coastal lagoon with a federally protected ecosystem. Projections from an ensemble of downscaled global climate model (GCM) runs were applied to a SWAT+ hydrologic model, and results were analyzed over three 30-year periods: historical (1990–2020), mid-century (2040–2070) and end of century (2070–2100). Buffer strips, delayed tillage of forage and alternative crop rotations were investigated in SWAT+ over these times periods to assess potential changes in $\text{NO}_3\text{-N}$ loading resulting from the implementation of these common BMPs. As agricultural practices will also likely evolve with climate change to account for longer growing seasons, extended dry seasons, and shifting markets, a future agricultural scenario was also modeled in SWAT+ for which fertilizer amounts were increased, and the growing season was extended.

Methods

Study site

Eutrophic conditions in estuaries in the province of Prince Edward Island (PEI), Canada have been documented since 2002 with the implementation of the PEI Estuaries Survey (Bugden et al., 2014), although they have been anecdotally noted for decades prior. PEI is intensively cultivated for potatoes, accounting for 25% of Canadian potato exports (Government of Prince Edward Island, 2020). Potatoes require high fertilization rates but have poor nitrogen (N) uptake efficiency (Delgado et al., 2001), which causes significant leaching and runoff of N into surface and groundwater (De Notaris et al., 2018; Jiang et al., 2011; Zebarth et al., 2009). The island is characterized by well-drained soils and shallow aquifers that are highly susceptible to N contamination in the form of $\text{NO}_3\text{-N}$ (Puckett et al., 2011). Rainfall, snowmelt, and associated recharge elevate water tables in PEI and drive discharge of N-rich groundwater to streams and, eventually, PEI coastal waters (Pavlovskii et al., 2023). Under current agricultural practices, groundwater $\text{NO}_3\text{-N}$ concentrations in PEI are predicted to continue to increase as $\text{NO}_3\text{-N}$ penetrates deeper into bedrock aquifers (Jiang and Somers, 2009; Zhang and Hiscock, 2011). This could deleteriously impact potable water quality in this province, which is fully dependent on groundwater for drinking water supply (Council of Canadian Academies, 2009), as well as the health of coastal ecosystems that receive contaminated groundwater.

Amidst growing public concern surrounding the health of PEI's environment, the province has implemented some mandatory



agricultural BMPs since the early 2000s. For example, 15 m buffer strips are required around any watercourse (Government of PEI, 2016), and the Agricultural Crop Rotation Act (Government of PEI, 2002) states that potatoes can only be grown on the same parcel of land once every 3 years. The Province of PEI also provides funding through the Agriculture Stewardship Program for farmers wishing to implement BMPs under the categories of manure and livestock management, agroforestry, water and supply management and integrated pest management (Sustainable CAP, 2023). Examples of BMPs currently employed in PEI are cover cropping, incorporating N-fixing plants into crop rotations, improving liquid manure application, implementing edge of field treatment systems such as buffer strips, constructed wetlands and vegetative swales. Research into the effects of alternative crop rotations to the traditional Potato-Barley-Clover (PBC) rotation on PEI has revealed that replacing red clover with soybeans, a legume, adds an additional cash crop, while reducing $\text{NO}_3\text{-N}$ leaching and increasing potato tuber yield (Azimi et al., 2022; Liang et al., 2019).

Basin Head lagoon, located on the northeastern coast of PEI (Figure 1A), has been experiencing declining ecosystem health (Connolly, 2002). Accordingly, the lagoon was designated as a federal Marine Protected Area in 2005 with the goal of protecting the endemic giant Irish moss, a unique morphotype of

Irish moss (*Chondrus crispus*), from declining ecosystem health and water quality (DFO, 2009). More prevalent and sustained hypoxic events have been noted over recent years, particularly in the shallower and more poorly mixed northeast arm of the lagoon throughout the spring and summer months (DFO, 2021). Hypoxic or anoxic conditions can result in irreversible changes to aquatic community structure (Coffin et al., 2018) and can threaten the health of the Irish moss in the Basin Head Marine Protected Area.

The Basin Head watershed is 14.6 km² (Figure 1B) with agriculture (41%) and forest (31%) comprising most of the land cover (KarisAllen et al., 2022). This study focuses on the four major tributaries that discharge into the lagoon with a collective drainage area of 7.2 km² (Figure 1B), and does not include direct runoff to the lagoon. The Charlottetown soil series is the most abundant throughout the entire province (MacDougall et al., 1988), and is the dominant soil type in the Basin Head watershed (95%). It is classified as a well-drained sandy loam located on gentle slopes (4%–9%) and is extremely well suited for agriculture (MacDougall et al., 1988). The porosity of the Charlottetown soil series varies from 30% in the till layer below 0.5 m (Francis, 1989; Heath, 1983; MacDougall et al., 1988) to approximately 50% in the upper, macroporous zone (Carter, 1987; MacDougall et al., 1988). Depth to bedrock, based on historical well data in the Kings County region, has been observed to

TABLE 1 Description, data sources and resolution for SWAT+ spatial inputs (topography, land use, and soil).

Watershed characteristic		Value	Source	Resolution (m)
Topography	Area	7.2 km ²	Province of PEI (2008)	10
	Elevation	Average 34.7 MASL (Minimum 6 MASL, Maximum 59 MASL)		
	Slope	0%–10%		
Land use	43% forest, 44% cropland, 7% shrubland, 3% wetland, 1% grassland, 1% barren, 1% transportation	Annual Crop Inventory (ACI) (AAFC, 2021)	30	
Dominant soil type	Charlottetown series, USDA-SCS class C, Slope phase: 2%–5%, Dominant surface texture: sandy loam (<8% clay)	The National Soil Database (AAFC, 2022)	5	

range from 0 to 6.2 m (Government of PEI, 2019; Joostema, 2015) and was measured to be 4.6 m at a shallow monitoring well in the watershed installed near the lagoon (KarisAllen et al., 2022) (Figure 1B). The bedrock aquifer that underlies PEI is primarily comprised of sandstone (80%–85%) and interbedded mudstone which is fractured, creating preferential flow paths (Francis, 1989). The fractured sandstone aquifer functions as a dual-porosity system, which presents challenges with characterization of aquifer effective porosity, specific yield, and hydraulic conductivity. However, equivalent porous medium approaches are commonly applied when modeling PEI groundwater systems (e.g., Stanic et al., 2024).

The climate of PEI is characterized as temperate and humid, with a mean annual precipitation of 1,173 mm at the Charlottetown weather station (1971–2000) and mean annual air temperature of 5.3°C (Paradis et al., 2016). Most precipitation (75%) falls as rain (Paradis et al., 2016), and precipitation is relatively uniformly distributed throughout the year, averaging between 80 and 120 mm per month (ECCC, 2023). Baseflow typically contributes 60%–70% of streamflow annually on PEI, and up to 100% in the summer months (Benson et al., 2007; DELJ, 2013); hence groundwater is critical to quantifying PEI water balances and nutrient transport. The fractured sandstone aquifer in the Basin Head watershed provides baseflow to the four tributaries that are the focus of this study (Figure 1) and provides flow for the 30+ intertidal springs that discharge directly into the lagoon (KarisAllen and Kurylyk, 2021; Oliver et al., 2024). The lagoon is tidally pumped and experiences mixing from waves, surges, and current during coastal storms (Bonnington et al., 2023).

Model inputs

The SWAT+ model (Arnold et al., 2012) requires climate variable inputs as well as GIS-based inputs for topography (i.e., Digital Elevation Model, DEM), land use and soils. A summary of the spatial data used to construct the SWAT+ model is presented in Table 1. Full maps of DEM, soil, and land use are provided in Supplementary Figures S1–S3. Figure 2 displays all soil types within the watershed boundaries; however, for simplicity in the model, the Charlottetown series was chosen to represent the entirety of the watershed due to its relative abundance (95%). Precipitation and maximum and minimum daily air temperature

records were obtained from a weather station (Onset HOBO) installed at Basin Head (Figure 1B). This weather station did not provide accurate precipitation in winter months (December to March) as it did not possess a heated rain gauge; therefore, the record was supplemented with values from the nearest Environment and Climate Change Canada (ECCC) weather stations at East Point (ECCC ID 7177) and St. Peters (ECCC ID 7177), which are 12 km and 36 km from Basin Head. The East Point station was used to develop a local weather generator within the model (Neitsch et al., 2011) to simulate other variables such as solar radiation, wind speed and relative humidity. The weather generator uses statistical monthly measures for air temperature, precipitation, solar radiation, dew point, and more to develop representative daily climate data for a subbasin.

SWAT+ models three major forms of nitrogen in the soil profile and shallow aquifer: (1) organic nitrogen associated with humus, (2) mineral forms of nitrogen held by soil colloids, and (3) mineral forms of nitrogen in solution. The movement of nitrogen between two ‘pools’ (i.e., valence states) of inorganic nitrogen, ammonium (NH₄⁺) and nitrate (NO₃⁻), and three pools of organic nitrogen is simulated. Nitrate transport in SWAT+ is simulated only in the mobile water layer, which includes water transported by surface runoff, lateral flow (i.e., groundwater flow within the soil profile) or percolation (i.e., water moving past the lowest soil profile layer and into the shallow aquifer). The mobile water layer nitrate concentration, $conc_{NO_3, mobile}$, is multiplied by the flow from each pathway (surface runoff, lateral flow and percolation) to determine nitrate load from each source in the soil layer. Important parameters in these partitioning equations are θ_e , the fraction of porosity where anions are excluded, and SAT_{ly} , the saturated water content of the soil layer (mm H₂O), which determine nitrate load from each source in the soil layer, and δ_{gw} , the delay time associated with overlying geologic formations (days), which determines nitrate load in the shallow aquifer.

Another important input to the SWAT+ model is agricultural practices. Fertilizer amount, type, and application timing, as well as crop rotation timing influences the forcing of chemical leaching into soils and surface water runoff, and hence NO₃-N concentrations in receiving water bodies. Several groups with local knowledge of agricultural practices in Kings County, PEI, where Basin Head is located (i.e., Souris Wildlife, PEI Potato Board, and Fisheries and Oceans Canada) were contacted to develop representative agricultural practices for model inputs. Cropland in the

watershed is assumed to adhere to local industry standard crop rotations of potato, a grain (e.g., barley), and a forage (e.g., clover) on a 3-year rotation (herein PBC) as is mandated by the province (Azimi et al., 2022). Although in recent years clover has been replaced with a mix of legumes including alfalfa, sudangrass, pearl millet, and ryegrass, red clover was simulated to maintain consistency over the period of interest (1990–2100). Standard fertilizer application to potato crops in PEI is 155 kg N ha⁻¹ (PEI Analytical Laboratories, Department of Agriculture and Fisheries, PEI). A 15-15-15 Nitrogen-Phosphorous-Potassium fertilizer was chosen based on availability in the SWAT+ interface and given the similarity to the 17-17-7 fertilizer employed by Liang et al. (2020) who studied N dynamics in PEI under different crop rotations. The application method of broadcast, which refers to fertilizer being spread uniformly over the entire field, was chosen based on local practices in the Basin Head watershed, Supplementary Table S1 provides a summary of the agricultural operations incorporated in SWAT+.

Data collection and model calibration

Discrete water samples were collected at the four main (i.e., highest flows) tributaries on 15 occasions covering diverse flow conditions from 11 November 2021, to 28 November 2023 (Figure 1B). Samples were analyzed for NO₃-N using the cadmium reduction colorimetric method-APHA Method 4500-E (APHA, 2022). These grab samples were also analyzed for total suspended solids (TSS) using Standard Method 2450D (APHA, 2022). Continuous stream stage measurements were recorded using Onset HOBO loggers at 15-min intervals. Stage was barometrically compensated with a HOBO air pressure logger (Figure 1B). Instantaneous stream discharge measurements were obtained using the velocity-area method (Turnipseed and Sauer, 2010) during the period of 26 June 2019, to 14 October 2023. Stage-discharge relationships were developed for each tributary (Supplementary Figure S4) and used to convert stage to flow. Monthly streamflow (Supplementary Figure S5) was used to calibrate the SWAT+ model hydrology, which is a standard interval for such SWAT+ applications (Ricci et al., 2023; Van Liew et al., 2012), while water quality measurements on a daily basis (i.e., sample concentration) were used to calibrate SWAT+ parameters for NO₃-N and TSS.

In groundwater-dominated watersheds, generally the most sensitive streamflow model parameters relate to groundwater and soil moisture. A literature review for SWAT+ modeling found the SCS curve number (cn2), baseflow recession constant (alpha), fraction of root zone percolation that reaches deep aquifer (perco), and soil evaporation compensation factor (esco) to be most sensitive (Ahmad et al., 2011; Liang et al., 2020; Spruill et al., 2000). These parameters, along with others identified in a sensitivity analysis conducted in SWAT+ Toolbox (Supplementary Table S2), were chosen to calibrate streamflow (James, 2022). Evaluation statistics used to assess model performance included the Nash-Sutcliffe efficiency (NSE), RMSE-observation standard deviation ratio (RSR), and percent bias (PBIAS) (Moriassi et al., 2007). Moriassi et al. (2007) states that for streamflow, an RSR less than 0.7 is satisfactory, an NSE over 0.4 is satisfactory, and PBIAS

less than 10 is very good. The corresponding equations are presented below, where Y_i^{obs} is the observed streamflow and Y_i^{sim} is the simulated streamflow generated by SWAT+.

$$NSE = 1 - \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2} \right] \quad (1)$$

$$RSR = \left[\frac{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2}} \right] \quad (2)$$

$$PBIAS = \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^n Y_i^{obs}} \right] \quad (3)$$

Grab sample concentrations (Supplementary Table S3) were used to calibrate NO₃-N outputs from SWAT+. Daily NO₃-N mass (kg/day) output from each tributary from SWAT+ were converted to a concentration (mg/L) by dividing the mass by the daily total flow. Modeled concentrations were compared to 11 grab sample concentrations from 11 November 2021, to 5 July 2023, and Root Mean Squared Error (RMSE) was calculated for the modeled vs. measured concentrations:

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_i - y_i)^2}{n}} \quad (4)$$

where \hat{y}_n are predicted values, y_n are observed values, and n is the number of observations. RMSE was used as the statistical performance metric for NO₃-N and TSS calibration as continuous measurements were not available for these parameters. A SWAT study conducted on the relatively nearby Wilmont River watershed in southwestern PEI (Liang et al., 2020) was used as a reference for the calibration in the present study due to the similarity in study region and hydrologic conditions. Supplementary Table S4 shows the parameters used in the sensitivity analysis and calibration in Liang et al. (2020), which were chosen as a starting point for the calibration of NO₃-N at the study site.

Once the model is calibrated satisfactorily, projected results using climate change data can be analyzed to determine patterns in seasonality of flow and NO₃-N loading, and trends to baseflow index (BFI). BFI is calculated by dividing the total volume of baseflow by total streamflow for a period. The SWAT+ outputs of lateral flow (flo) and shallow groundwater flow (latQ) sum to determine baseflow, and total streamflow is the summation of water yield (waterYld) and lateral flow (flo) into the channel. The 'half-flow date', T50, is a measure of streamflow timing and is defined as the date by which 50% of streamflow for a given water-year (i.e., October 1 to September 30) has passed (Court, 1962). This measure has been used to characterize flow regimes in the neighboring province of Nova Scotia (Johnston et al., 2022), and was calculated in this study for the three model periods.

It should be noted that SWAT studies in other small (<10 km²) watersheds have been noted to yield unsatisfactory results (Spruill et al., 2000), largely due to characteristically low times of concentration and a propensity toward 'flashiness' in peak runoff (Uzeika et al., 2012). Chu et al. (2004) noted that characterizing baseflow correctly can be more important in small watersheds. Bailey et al. (2020) outlines limitations to the current groundwater algorithms in SWAT+ and proposes an amendment

to the standard SWAT+ module to improve model accuracy, particularly in baseflow-dominated watersheds where model performance can be poor (Bosch et al., 2010; Luo et al., 2012). Despite the challenges in applying SWAT+ in small, baseflow-dominated systems, this model is widely used and still provides useful insight into the hydrology and transport dynamics in these environments.

Model scenarios

Climate change scenarios

Changes to climate forcing will drive changes in hydrologic processes and agricultural practices (Gordon et al., 2008), which can be represented in SWAT+. An analysis by the Pacific Climate Impacts Consortium [of 26 downscaled Coupled Model Intercomparison Project (CMIP) 6 Global Climate Models (GCMs)] (Eyring et al., 2016) and three Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017) was completed to select models projecting low, moderate, and high changes to precipitation and temperature. Climate data for these models were downloaded from the NASA Climate Data Services (NASA, 2023), and, for the sake of downscaling consistency, only models downscaled using Bias Correction/Constructed Analogues with Quantile Mapping Reordering (BCCAQv2) (Maurer et al., 2010; Cannon, 2015) were considered. The scenarios from the IPSL-CM6A-LR and EC-Earth3-veg GCMs were removed from consideration because they are deemed 'hot' models, projecting much greater warming than is generally expected (Rahimpour Asenjan et al., 2023). UKESM1-0-LL was removed for simplicity since it only represents a 360-day year, and BCC-CSM2-MR was missing from the NASA dataset. The remaining six models were compared based on their average annual precipitation for each modeled time period (1990–2020, 2040–2070 and 2070–2100) (Supplementary Table S5), and three representative models (INM-CM5-0, FGOALS-g3, and MRI-ESM2-0) were chosen for low, moderate, and high climate change scenarios (Figure 2). Two SSPs per climate model, SSP2-4.5 (RCP 4.5) and SSP5-8.5 (RCP 8.5), were chosen to represent mid-range and high emissions scenarios, yielding a total of six climate change scenarios with a wide range of possible climate outcomes. The climate data representing each scenario was entered in SWAT+, and the calibrated model was run from 1990 to 2100, with outputs from representative periods of historical (1990–2020), mid-century (2040–2070) and end of century (2070–2100) used for further analysis. The observation period GCM results for each climate scenario were used for the 1990–2020 comparison period rather than historic data in the watershed because the climate station in the watershed was only operational since 2018, and there is no nearby long-term climate station or one with very similar measurements to the Basin Head climate station (Figure 1B) during its operation. Therefore, the climate change analysis presented herein should be considered a sensitivity analysis to plausible future projections of climate change when compared to historic-period output for the same downscaled GCMs. A one-way ANOVA was conducted in Minitab (2021) to generate monthly pairwise comparisons of the NO₃-N loading between each period (N = 30) to determine if results were significantly different ($p < 0.05$) among scenarios.

Future agricultural practice scenario

It is important to consider societal changes that may arise due to climate change. Climate change will result in extended growing seasons in Atlantic Canada, defined by the number of days per year where the air temperature is over 5°C, with a projected increase in growing season length of 11% by 2050 and 18% by 2080 (Richards and Daigle, 2011) using climate data from the nearest station to Basin Head (East Baltic, 46.43N 62.17W). In SWAT+, these percentages were rounded to a 10% increase in growing season length for the mid-century period (2040–2070) and a 20% increase for the end of century period (2070–2100). To account for a longer growing season and potential loss in plant productivity, an additional percentage of fertilizer applied to crops was also incorporated. Arbitrarily, an increase in fertilizer application of 10% and 20% were applied for mid-century and end of century periods, respectively, to align with the projected increase in growing season length (Richards and Daigle, 2011). This future agricultural scenario was only run for the MRI-ESM2-0 SSP5-8.5 GCM to consider changing agricultural practices for a more extreme climate scenario. All model runs are listed in Supplementary Table S6 with corresponding weather inputs.

Best management practices

BMPs are implemented widely across PEI and include crop rotations, buffer strips, cover crops, farmable berms, and terraces. Three common BMPs were modeled in SWAT+ from 1990 to 2100 under the climate change scenario with the highest cumulative precipitation (MRI-ESM2-0 SSP5-8.5) to understand how NO₃-N loading could be mitigated in a 'worst-case' climate scenario. The BMP scenarios chosen to be simulated in SWAT+ were (1) buffer strips (60 m, 30 m), (2) delayed tillage of forage crop from fall to spring, and (3) alternative crop rotation of Potato-Soybean-Barley (PSB) from the default PBC rotation used for other SWAT+ runs.

Buffer strips refer to narrow strips of dense grass surrounding waterways on agricultural land (Helmerts et al., 2006). They are known to slow down runoff velocity to control field erosion and trap particulate pollutants and have been shown to facilitate NO₃-N removal from shallow groundwater (Simpkins et al., 2002). A spatial analysis revealed that most agricultural fields in the watershed have a grassed buffer of 30 m between the field and waterways, which is double the provincially mandated width of 15 m. A scenario incorporating a 60 m buffer was simulated, which would be considered an extreme measure. The removal of NO₃-N in vegetative filter strips in SWAT+ is predicted based on the ratio between field area and filter strip area. It should be noted that the decrease in cropland associated with an increase in buffer size was not included in this simulation to isolate the effect of the buffer, thus, the total effect of an increased buffer width would be underestimated in these results.

Typically, on PEI, a forage crop (i.e., clover, timothy, rye) is grown in the year prior to potato planting. By delaying tillage of forage from fall to spring, just before planting, NO₃-N leaching in the winter months is reduced, and there is residual NO₃-N left in the

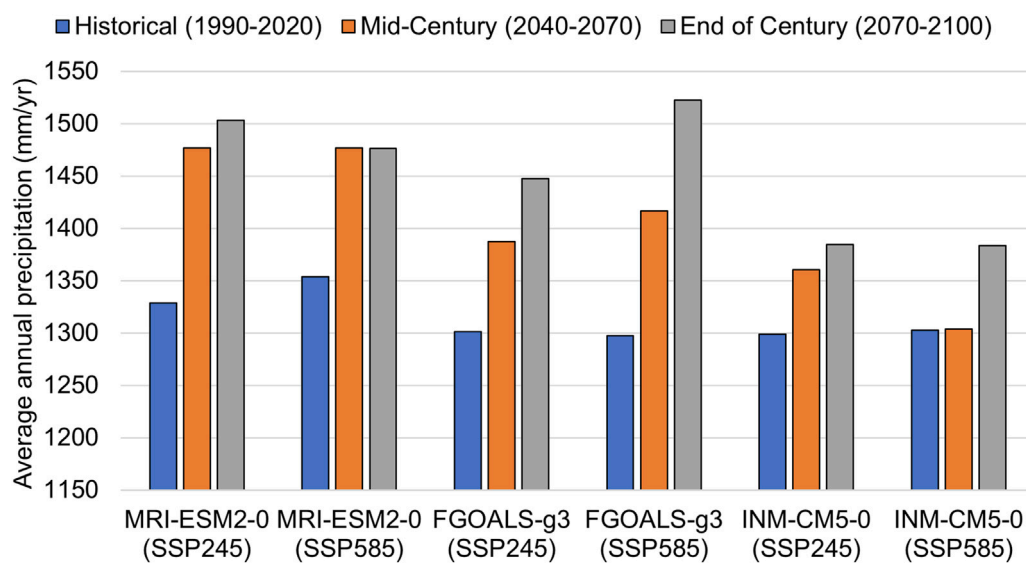


FIGURE 2

Representative climate models chosen based on average annual precipitation values for each modeled period. Distributions of the mean annual precipitation and air temperature for each scenario are presented in [Supplementary Figures S8, S9](#).

soil in spring, reducing the need for fertilizer (Stuart, 2017). This effect was modeled in SWAT+ by editing the agricultural operations such that clover was plowed May 15th, prior to planting of potatoes, instead of on September 15th and by reducing fertilizer application by 25% (Stuart, 2017).

PBC is a representative crop rotation for PEI; however, recent studies have suggested that incorporating legumes may improve soil health, increase potato yields and reduce $\text{NO}_3\text{-N}$ surplus leading to leaching due to the N fixing characteristics of legumes (Liang et al., 2019; Whittaker et al., 2023). A PSB crop rotation was modeled in SWAT+ (Supplementary Table S7) to test this hypothesis under the three periods, for which fertilizer application was reduced by 50% to account for the N fixing characteristics of soybeans. This reduction amount was chosen arbitrarily based on the results of Liang et al. (2019) that showed N efficiency (i.e., how well plants utilize available N) of PSB crop rotations were 1.6 times that of PBC rotations.

Results and discussion

Sampling results and model calibration

73 water samples from the Basin Head tributaries were analyzed for $\text{NO}_3\text{-N}$, of which 24 (33%) exceeded the Canadian Council of Ministers of the Environment (CCME) guideline for the protection of aquatic life in freshwater (3 mg L^{-1} , CCME, 2012). $\text{NO}_3\text{-N}$ concentrations range from 0 to 6.2 mg/L, with tributary 1 having the highest average concentration (4.2 mg/L) compared to the other tributaries (1.3–1.9 mg/L). TSS concentrations ranged from 0 to 44.0 mg/L, with tributary 2 and 3 being higher on average (11.3–12.3 mg/L) than tributary 1 and 2 (6.1–7.2 mg/L). All grab sample measurements are summarized in [Supplementary Table S3](#).

All sensitive model parameters for hydrology (Supplementary Table S8) were manually calibrated to the measured streamflow

(Supplementary Figure S5) until the goodness of fit was satisfactory from April 1st to 1 September 2022, to represent hydrology in the growing season (Table 2). It should be noted that model results from winter months are not calibrated, thus one must take caution when drawing conclusions during these months. Also, snowmelt_min, snowmelt_max, and snowmelt_tmp are climate-related parameters, and would most likely be spatially uniform for a small watershed; they were manually changed to improve streamflow calibration. The sensitivity analysis revealed that simulated $\text{NO}_3\text{-N}$ concentrations were sensitive to only six out of eight parameters: hlif_n, the half-life of nitrate in the shallow aquifer, nperco, the nitrate percolation coefficient, sdnco, the denitrification threshold water content, cdn, denitrification exponential rate coefficient, cmn, the rate factor for humus mineralization of active organic nutrients and n_updis, the nitrogen uptake distribution parameter. $\text{NO}_3\text{-N}$ and TSS were calibrated from 11 November 2021, to 5 July 2023, and from 27 July 2022, to 5 July 2023, respectively. The graphical representation of $\text{NO}_3\text{-N}$ calibration and RMSE (Equation 4) values between measured to simulated concentration are found in [Supplementary Figure S6](#). Six parameters were calibrated for $\text{NO}_3\text{-N}$: hlif_n (600 for tributary 1, 200 for tributaries 2–4), nperco (0.15 for tributaries 1–3, 0.05 for tributary 4), sdnco (0.66), cdn (0.07), cmn (0.0029) and n_updis (66.7). RMSE (Equation 4) between measured $\text{NO}_3\text{-N}$ load (i.e., concentration multiplied by flow) and simulated load were calculated to be 2.7, 7.6, 4.5 and 1.0 kg/day for tributaries 1 through 4.

The sediment calibration process in this study closely followed a previous SWAT study (Sinclair, 2014) by choosing sensitive starting parameters for calibration with a focus on in-channel processes. SWAT+ uses the Modified Universal Soil Loss Equation (MUSLE) to generate the landscape erosion contribution to channel TSS values. MUSLE is a function of several factors, which were entered into SWAT+ as default values, except for the soil erodibility factor, which was calculated to be 0.49 based on soil

TABLE 2 Manually calibrated goodness of fit parameters for streamflow, NO₃-N and TSS for each tributary (trib, Figure 1B) for the calibration period April 1st to 1 September 2022.

	Goodness of fit parameter	Tributary 1	Tributary 2	Tributary 3	Tributary 4
Streamflow	NSE (Equation 1)	0.6	0.8	0.8	0.8
	RSR (Equation 2)	0.7	0.5	0.5	0.5
	PBIAS (Equation 3)	2.5	0.04	-20	-14
NO ₃ -N	RMSE (mg/L) (Equation 4)	2.1	1.1	1.3	1.3
TSS	RMSE (mg/L) (Equation 4)	9	19	21	15

information. High sediment loads in several PEI rivers have been documented, mainly citing sediment deposition resulting from intensive agricultural practices (Sirabahenda et al., 2020). Supplementary Figure S7 presents a graphical representation of TSS calibration and RMSE values between measured and simulated concentrations. Four parameters were calibrated for TSS: spexp (1), spcon (0.0001), cov fact (0.02 for tributaries 2 and 3, 0.005 for tributaries 1 and 4), and erod_fact (0.25 for tributaries 1 and 4, 0.75 for tributary 2 and 0.5 for tributary 3). RMSE between measured TSS load (i.e., concentration multiplied by flow) and simulated load were calculated to be 6.7, 34.7, 36.5, and 1.1 kg/day for tributaries 1 through 4. Final calibrated RSME values for NO₃-N, TSS, and streamflow for each tributary are found in Table 2. NO₃-N was successfully calibrated; however, RMSE values for TSS are significantly higher than 1–2 mg/L, indicating that it is only preliminarily calibrated for sediment transport.

Modelled conditions using MRI-ESM2-0 SSP5-8.5 from the historical period (1990–2020) generally aligned with expected water balance for PEI where an annual average of 1,100 mm of precipitation is partitioned into 440 mm evapotranspiration, 260 mm surface water runoff and 400 mm is groundwater flow (PEI Department of Fisheries and Environment, 1996). During this period SWAT+ simulates the average annual NO₃-N transported via surface runoff as 1 kg/ha, while average annual NO₃-N transported through groundwater is 6 kg/ha, which aligns with other PEI studies such as Grizard. (2013) that simulated an average NO₃-N load of 12 kg-N/ha watershed/yr for the period 1996–2012. Average annual sediment load via overland erosion was modelled to be 0.96 t/ha/yr, which aligns with a nearby previous study in Souris River, PEI that found overland erosion to occur at a rate of 1.5–1.8 t/ha/yr, attributing this high sediment load to row crop agriculture which is common across PEI (Alberto et al., 2016). SWAT+ models deposition of sediment in all tributaries in the watershed, meaning that all TSS at the channel outlets are originated from overland erosion.

Projected climate change impacts

Changes to moisture conditions and seasonality of precipitation events due to climate change could result in changes to the ratio of baseflow and surface runoff contributions in streamflow. The monthly averaged BFI was analyzed for each period in SWAT+, revealing shifts in the partitioning of streamflow over time (Figure 4B). Average BFI in the months of January to May increased from 0.39 in the historical (1990–2020) period to

0.74 and 0.78 in the mid-century (2020–2070) and end-of-century (2070–2100) periods. The largest BFI change occurred in February where monthly average BFI increased from 0.12 in the historical period to 0.63 and 0.68 in the two future periods (>five-fold increase). Average annual simulated BFI increased 22% from historical (1990–2020) to mid-century (2040–2070) periods, and only increased 1% between mid-century and end of century (2070–2100) periods. These baseflow changes could be attributed to increased precipitation as rainfall, more mid-winter thaws, and an earlier spring melt period, inducing recharge and subsequent flow through the shallow aquifer during the winter season.

The SWAT+ model projections also show suppressed summer flow, particularly in April and May, and increased winter flow between historical (1990–2020) and both future periods (2040–2070 and 2070–2100) and illustrate that projected changes in nitrate loading and streamflow follow similar seasonal patterns (Figures 4A, C). During the historical period in the months of January and February, the standard deviation in flow is much lower than the end-of-century period (average decrease of 74%). However, in the months of April to May, the standard deviations of the flow values in the end-of-century period are much lower than in the historical period (–72% on average). This indicates that in the winter months (January and February), there is more variance in flow in the end-of-century period, while in the spring months (April and May) there is more variance during the historical period. Standard deviations of flow between historical and both future periods were within 50% of each other from June to November and were highest from December to May. Increased flow variability in winter and early spring could reflect uncertainty in the effects of climate change on snowmelt processes. The historical period T50 (March 19), a measure of streamflow timing, was shifted earlier by 73 and 78 days respectively for the mid-century (January 7) and end of century (January 1) periods. Some studies (Mukundan et al., 2020; Shrestha et al., 2012) have proposed that earlier snowpack melt and an increase to annual rainfall due to climate change, both of which were modeled in this study, will increase the magnitude and shift the timing of nutrient loading. Average annual streamflow is simulated to increase 5% between historical (1990–2020) and mid-century (2040–2070) periods, and increase 4% between mid-century and end of century (2070–2100) periods. This could be attributed to increased precipitation expected in a future climate, or increased snowmelt due to higher temperatures. Higher streamflows with on average higher baseflow influence in future years (2040–2100) could result in a higher flux of NO₃-N to coastal waters.

Based on the SWAT+ simulations of future climate change impacts and the corresponding ANOVA analysis, only the

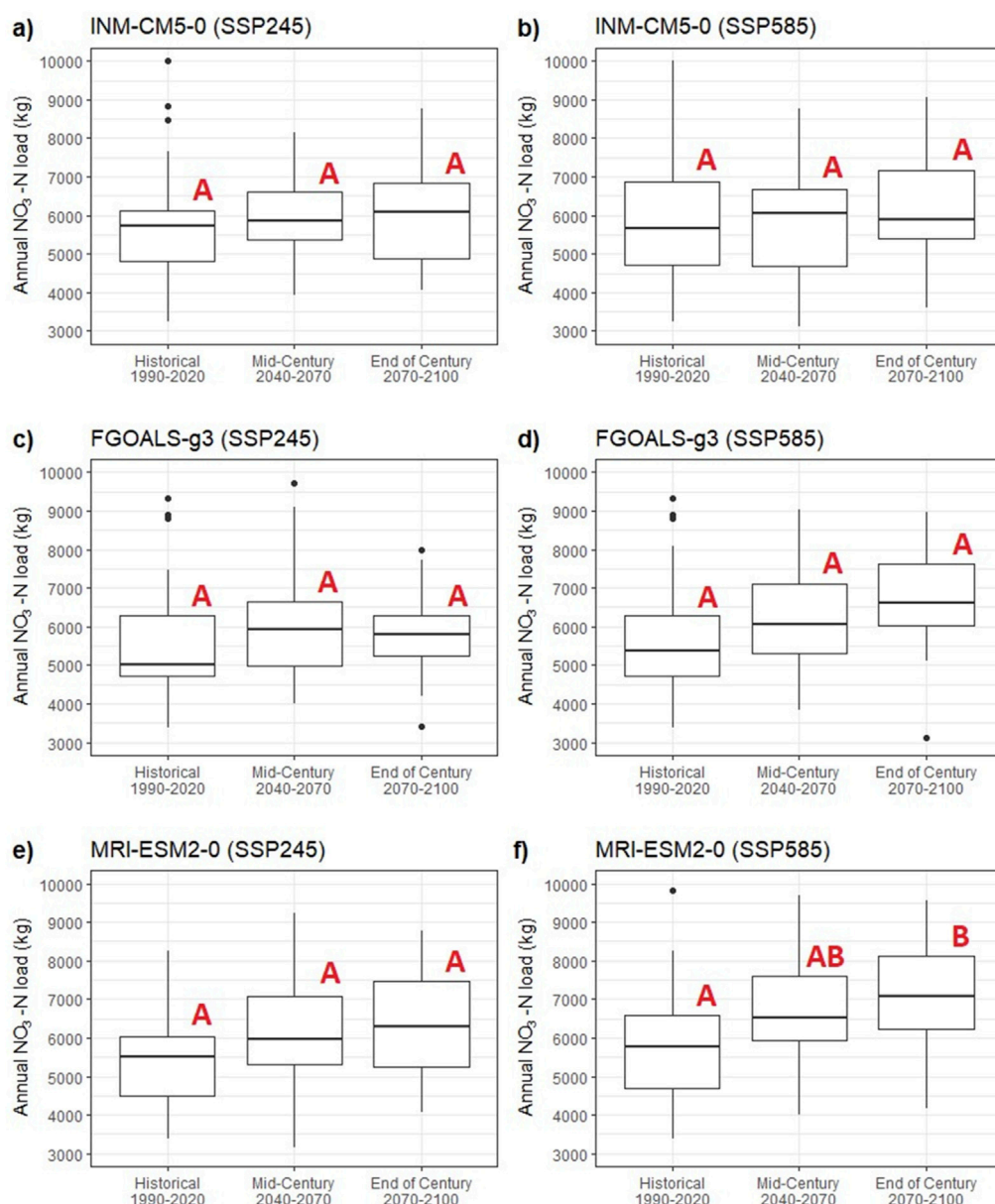


FIGURE 3 Annual NO₃-N load (box and whisker plots showing mean and quartiles) to lagoon from the four main tributaries (Figure 1B) for each climate model scenario (Figure 2), (A) INM-CM5-0 SSP2-4.5, (B) INM-CM5-0 SSP5-8.5, (C) FGOALS-g3 SSP2-4.5, (D) FGOALS-g3 SSP5-8.5, (E) MRI-ESM2-0 SSP2-4.5, (F) MRI-ESM2-0 SSP5-8.5. Distributions that do not share a letter are significantly statistically different.

scenario with the highest cumulative precipitation (MRI-ESM2-0 SSP5-8.5) resulted in statistically significant ($p < 0.05$) changes in NO₃-N loading to the lagoon, and only when comparing historical to end-of-century (1990-2020 to 2070-2100) time periods (Figure 3). Under this scenario, the median annual NO₃-N load increased from 5,752 to 7,239 kg (+26%). Among all climate scenarios considered, this scenario produced both the highest mean annual precipitation and the highest mean annual air temperature at the end of century (Supplementary Figures S8, S9).

The GCM scenarios with the lowest cumulative precipitation (INM-CM5-0 SSP2-4.5 and INM-CM5-0 SSP5-8.5) saw small changes in median NO₃-N load of less than 7% between consecutive model periods. The mid-range cumulative precipitation

GCM scenario, FGOALS-g3 SSP2-4.5, yielded interesting results, as annual median NO₃-N load increased by 13% between historical (1990-2020) and mid-century (2040-2070) periods but decreased by 2% from mid-century (2040-2070) to end of century (2070-2100). The FGOALS-g3 SSP5-8.5 GCM yielded a 5% and 10% increase in annual median NO₃-N load between the same periods. In general, the simulations with higher cumulative precipitation resulted in larger increases in annual NO₃-N load (Figure 2). Between each subsequent modeled period, the MRI-ESM2-0 SSP2-4.5 GCM resulted in a 9% and 6% increase to median annual NO₃-N load, while MRI-ESM2-0 SSP5-8.5 resulted in an increase of 13% and 11%, respectively.

These NO₃-N load trends generally correspond to trends in cumulative precipitation (Figure 2) and suggest that the projected

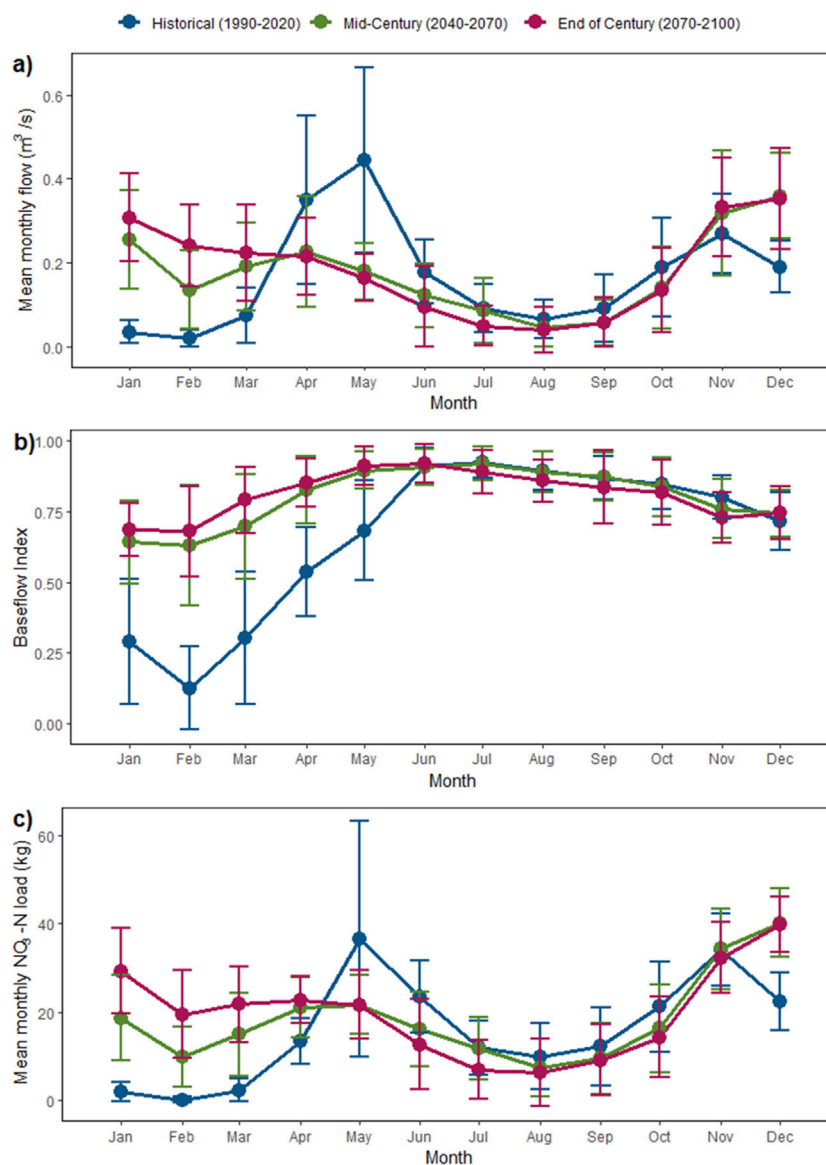


FIGURE 4 (A) Average monthly flow from all four tributaries for each 30-year period simulated in SWAT+, (B) Monthly average baseflow index at all four tributaries for each 30-year period simulated in SWAT+, (C) NO₃-N load (kg/day) averaged on monthly basis from all four tributaries for each 30-year period simulated in SWAT+. Error bars represent standard deviation of average annual values in each simulated period. The GCM plotted is the highest cumulative precipitation climate scenario MRI-ESM2-0 SSP5-8.5.

increased NO₃-N loading could be attributed to increased water yield and/or enhanced biogeochemical cycling of N (e.g., greater mineralization of organic N and nitrification of ammonia-N) (Pesce et al., 2018; Rabalais et al., 2009). The similarity in pattern of seasonal streamflow and NO₃-N (Figures 4A, C) indicates that increased water yield, rather than elevated concentration, is predominantly responsible for the projected increase in NO₃-N loading.

The effects of NO₃-N leaching through surface and groundwater pathways under future climate change scenarios is presently not well understood. However, it is known that climate change impacts groundwater recharge and discharge (Kurylyk et al., 2014), sea levels, soil conditions (i.e., soil moisture, organic carbon, alkalinity) and agricultural productivity (Stuart et al., 2011), all of

which could impact nutrient loading and transport dynamics in coastal watersheds. Some studies investigating the effects of climate change on nutrient loading highlight the uncertainty of climate change models on a regional scale (Bürger et al., 2013; El-Khoury et al., 2015; Jeppesen et al., 2011). These have suggested that the use of different downscaling methods for GCMs can result in conflicting trends in directions and magnitudes of nutrient loading, which is likely partly related to the uncertainty in future trend directions and magnitudes for precipitation and groundwater recharge (Kurylyk and MacQuarrie, 2013). A few studies (e.g., Luo et al., 2020; Qi et al., 2009; Tong and Liu, 2006) have suggested that changes to hydrology have more influence on nutrient loading dynamics than changes in land use, while a local PEI study (De Jong et al., 2008) suggests land use is the more important factor. Pulido-Velazquez et al. (2015)

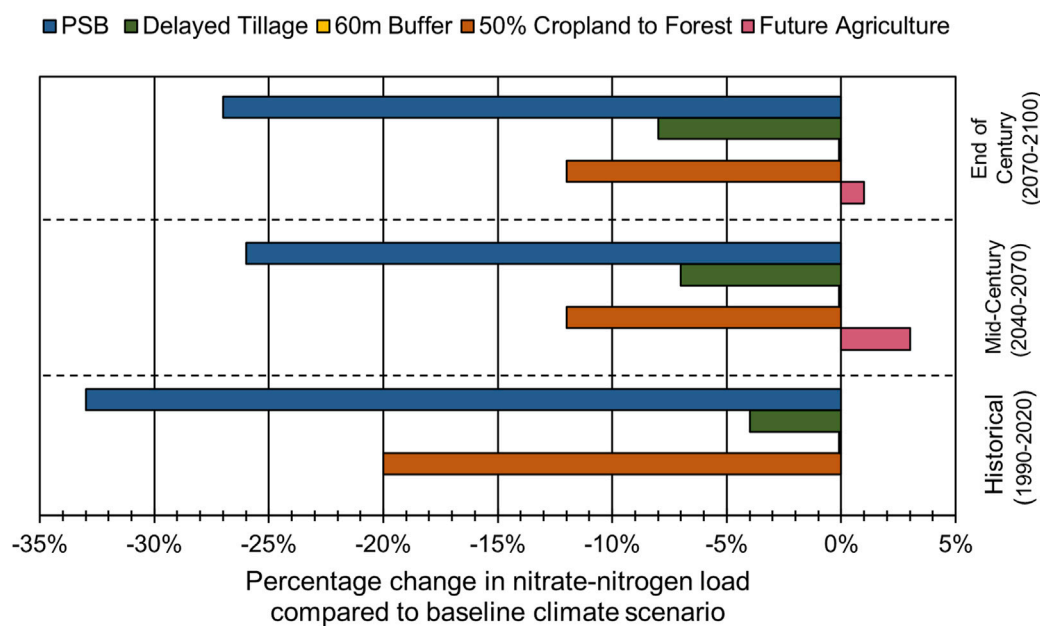


FIGURE 5
Percentage of $\text{NO}_3\text{-N}$ load compared to baseline climate change scenario from all four modeled tributaries to the lagoon using a future agricultural scenario, altered land-use scenario where 50% of cropland is changed to forest, and BMPs (60 m Buffers, delayed tillage of cover crop from fall to spring, alternative crop rotation of Potato-Soybean-Barley, PSB). The GCM plotted is the highest cumulative precipitation climate scenario MRI-ESM2-0 SSP5-8.5.

noted the importance of analyzing the impacts of land use and hydrologic stressors together when considering nutrient loading patterns. The use of SWAT+ in this study addresses many of these concerns by incorporating future climate data and current land use and agricultural practices, with capability to simulate a wide range of future outcomes.

Seasonal trends in $\text{NO}_3\text{-N}$ loading to the lagoon were also analyzed under the highest cumulative precipitation climate scenario, MRI-ESM2-0 SSP5-8.5 (Figure 4C). Simulations during the historical period (1990–2020) indicate that $\text{NO}_3\text{-N}$ loading to the lagoon is highest during the months of May and November. These peaks likely correspond to $\text{NO}_3\text{-N}$ availability due to recent fertilizer application in spring or harvest in fall and corresponding large precipitation events and snowmelt that typically occur in spring and fall in PEI. For the future climate scenarios, the overall average $\text{NO}_3\text{-N}$ load increases, but the magnitudes of the May and November loads are damped. The increase in $\text{NO}_3\text{-N}$ load in spring appears to occur earlier in the season, while the fall peak occurs later into December. The December peak is higher than the fall peak in the future scenarios; however, these are reversed in the historical period.

Impacts of best management practices

Agricultural practices were altered to represent conditions in a future climate by extending the growing season and increasing fertilizer application amounts by 10% and 20% for the mid-century and end-of-century periods respectively. Model outputs indicated only small increases in $\text{NO}_3\text{-N}$ load to the lagoon as a result of these changes. For the mid-century period, $\text{NO}_3\text{-N}$ load was

increased by 3%, and for the end of century period, it was increased 1% from the original climate change simulation. An additional scenario was simulated where 50% of crop land was converted to coniferous forest (Supplementary Table S9). Even with this drastic change in land use, $\text{NO}_3\text{-N}$ load was only reduced by 20% in the historical period and by 12% for 2040 to 2100 when compared to the baseline climate change scenario (Figure 5). These results partially reflect the challenges in managing the ‘legacy’ effects of nitrate as aquifers can continue to pollute surface waters long after land-use practices change at the land surface (Tesoriero et al., 2013).

Model simulations incorporating BMPs revealed a small change (0%–8%) in $\text{NO}_3\text{-N}$ loading when a 60 m buffer and delayed tillage were applied as conservation tools (Figure 5). Some studies in other watersheds have shown more pronounced benefits from the tested BMPs. For example, studies have identified grassed buffer strips as effective tools for reducing N export in surface runoff (Dunn et al., 2011; Heathwaite et al., 1998). Mankin et al. (2007) noted a strong reduction in total N concentration in field runoff and observed that infiltration accounted for >90% of total N removal. It is expected that grassed buffers have more impact on sediment, phosphorus, and pesticide transport where the main mode of transport is through surface runoff and soil erosion (Al-Wadaey et al., 2012; Sweeney and Newbold, 2014) rather than the groundwater-dominated transport in the Basin Head watershed. $\text{NO}_3\text{-N}$ is soluble and once infiltrated into groundwater is generally unable to be reduced using BMPs that target surface water and soil erosion.

The SWAT+ model findings for Basin Head differ from results for other PEI studies. For example, delayed tillage of forage crops from fall to spring under a 3-year potato rotation on PEI has been shown to reduce N availability in soil and related leaching into the subsurface (Stuart, 2017), without negative effects on soil health or

potato yield (Carter et al., 1998). This practice aims to reduce mineralization of forage crops through the winter months to allow for more N carry-over into the growing season. However, in the modeled scenario, this practice should be paired with a reduction in fertilizer application to impact NO₃-N leaching. Sanderson et al. (1999) found that spring tillage improved potato tuber yields even at lower fertilization rates than late fall tillage. Model results did not indicate that this practice would significantly reduce NO₃-N loading over future decades, likely due to the large input of fertilizer still needed to cultivate potatoes and poor N utilization efficiency of the crop. The only appreciable reduction to NO₃-N loading in SWAT+ came from changing the crop rotation to PSB from PBC. Under the historical period, NO₃-N load is reduced by approximately 33% with this BMP; however, during the mid-century and end of century periods, this reduction is lowered to 26% and 27%, respectively (Figure 5). This indicates that crop rotation change for this watershed may yield reduced benefits as climate change intensifies. A future climate may experience competing phenomena where precipitation and hence hydrologic loads increase, yet high temperatures and low soil moisture decrease nutrient loading. These results are consistent with Liang et al. (2019) which found N surplus in soils to be significantly higher under a PBC rotation than a PSB rotation, hence leading to higher levels of N leaching. The N fixing properties of legumes in the PSB scenario allowed for a significant reduction in fertilizer application (50%), which is likely the cause of the reduction in NO₃-N leaching. It should be noted that this is a simplistic approach that does not consider exact N fixing characteristics of crop rotations at the site, and no *in situ* soil data was used to confirm the application rates.

Model limitations

A main limitation of the model results are that the findings cannot be generalized to watersheds outside the province of PEI due to the unique soil, crop and aquifer characteristics. Also, the climate change projections (GCMs) used were chosen solely based on cumulative precipitation, representing low, mid-range and high cumulative precipitation, thus, may not represent the full range of potential future conditions. Another limitation that should be noted is that the surface water watershed modeled map not necessarily align with the watershed of the aquifer. This is an assumption that is commonly employed in such studies (Fan, 2019). Based on validation efforts using additional streamflow records, high uncertainty exists in all modelled values currently produced. This model with a relatively short calibration period is used to simulate long-term climate impact, which enhances measurement uncertainty which affects the model confidence. Based on these limitations, such a model should primarily be used for exploratory purposes (Harmel et al., 2014), as in the present study. Streamflow rating curves may not account for high flow conditions properly due to most *in situ* measurements being collected at low flow (Supplementary Figure S4). Thus, extreme weather events cannot be accurately simulated. This introduces uncertainty in NO₃-N and TSS calibration, which uses streamflow to convert from load to concentration (Supplementary Figures S6, S7). Future work to reduce model uncertainty should include the collection of more flow with a higher range of hydrologic conditions, NO₃-N, and TSS data and watershed properties for model calibration and validation.

Furthermore, it should also be emphasized that there is uncertainty in the prediction of NO₃-N transport because of the unknown secondary effects of climate change such as land use change, and changes to agricultural practices (i.e., fertilization rates and timing, growing season) (Howden et al., 2007; Jeppesen et al., 2011). For this reason, future studies are warranted that consider a broader range of future agricultural scenarios and seasonal shifts in hydrologic forcing.

Conclusion

This study evaluated the impacts of climate change and best management practice scenarios on NO₃-N loading to a threatened coastal lagoon in the Atlantic Canadian province of PEI. Model (SWAT+) results indicate that NO₃-N loading is expected to increase under climate change, further exacerbating eutrophic conditions and the related impacts on the protected ecosystem in this lagoon. However, only the highest cumulative precipitation climate model (MRI-ESM2-0 SSP5-8.5) resulted in statistically different (*p*-value <0.05) NO₃-N loading (+26%) between historical (1990–2020) and end-of-century (2070–2100) periods. Implementing buffer strips and delayed tillage had negligible (0%–8% reduction) effects on NO₃-N loading, while changing the crop rotation from potato-barley-clover to potato-soybean-barley yielded a decline (26%–33%) in NO₃-N loading compared to a climate change scenario without incorporation of best management practices. A future agricultural practice scenario was evaluated for mid-century (2040–2070) and end of century (2070–2100) to consider a longer growing season and higher fertilizer application amount. Simulated NO₃-N loading to the lagoon only increased by 3% and 1% respectively for these future time periods under this additional loading. To explore an extreme scenario where drastic measures were incorporated to limit agricultural contamination, a model scenario was run where 50% of cropland was converted to coniferous forest. This resulted in a reduction in NO₃-N loading of 12%–20%. Model analysis revealed changes to seasonal loading dynamics under climate change for which the effect of high spring and fall precipitation effects were subdued, and streamflow and related NO₃-N loads remained more seasonally consistent. Changes to streamflow partitioning were noted under climate change scenarios. Most notably, baseflow contributions increased in winter and early spring (January–May), with the largest change (5-fold increase) occurring in February. These results demonstrate the severity of nitrogen contamination within PEI aquifers and water bodies and the trajectory of NO₃-N loading to the province's coastal waters in a future climate. Although PEI remains a national leader in the implementation of best management practices and agricultural innovation, decades of agricultural activity and aquifer storage of NO₃-N will facilitate continual groundwater export of leached legacy nitrate to the coast. Extreme changes to land use and reduction to fertilizer application would be needed to appreciably reduce NO₃-N loading to the Basin Head watersheds and other PEI watersheds. Conservation tools such as crop rotation will likely become increasingly important to ensure agricultural practices remain resilient to the effects of climate change.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AO: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft. BK: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing—review and editing, Investigation. LJ: Investigation, Methodology, Writing—review and editing, Data curation. NL: Data curation, Formal Analysis, Methodology, Writing—review and editing. LS: Conceptualization, Methodology, Writing—review and editing. RJ: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2024.1468869/full#supplementary-material>

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