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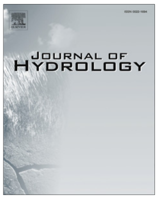

# Modeling land-based nitrogen loads from groundwater-dominated agricultural watersheds to estuaries to inform nutrient reduction planning

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## SUMMARY

Excessive nitrate loads from intensive potato production have been linked to the reoccurring anoxic events in many estuaries in Prince Edward Island (PEI), Canada. Community-led watershed-based nutrient reduction planning has been promoted as a strategy for water quality restoration and initial nitrate load criteria have been proposed for the impacted estuaries. An integrated modeling approach was developed to predict base flow nitrate loads to inform the planning activities in the groundwater-dominated agricultural watersheds. Nitrate load is calculated as base flow multiplied by the average of nitrate concentration at the receiving watershed outlet. The average of nitrate concentration is estimated as the integration of nitrate leaching concentration over the watershed area minus a nitrate loss coefficient that accounts for long-term nitrate storage in the aquifer and losses from the recharge to the discharge zones. Nitrate leaching concentrations from potato rotation systems were estimated with a LEACHN model and the land use areas were determined from satellite image data (2006–2009) using GIS. The simulated average nitrate concentrations are compared with the arithmetic average of nitrate concentration measurements in each of the 27 watersheds for model calibration and in 138 watersheds for model verifications during 2006–2009. Sensitivity of the model to the variations of land use mapping errors, nitrate leaching concentrations from key sources, and nitrate loss coefficient was tested. The calibration and verification statistics and sensitivity analysis show that the model can provide accurate nitrate concentration predictions for watersheds with drainage areas more than 5 $\mathrm{km}^2$ and nitrate concentration over 2 $\mathrm{mg\,N\,L^{-1}}$, while the model resolution for watersheds with drainage areas below 5 $\mathrm{km}^2$ and/or nitrate concentration below 2 $\mathrm{mg\,N\,L^{-1}}$ may not be sufficient for nitrate load management purposes. Comparisons of normalized daily stream discharges among the active hydrometric stations indicated that stream base flow could be prorated for nitrate load calculation from the nearest gauging station in the absence of discharge measurements. Annual nitrate losses, including aquifer long-term storage, denitrification, and riparian plant uptake were estimated to be 0.8 $\mathrm{mg\,N\,L^{-1}}$, corresponding to 3.4 $\mathrm{kg\,N\,ha^{-1}}$. The maximum and median base flow nitrate loads to the estuaries from among the 27 calibration watersheds were predicted to be 28.4 and 8.7 $\mathrm{kg\,N\,ha^{-1}}$ respectively with a root mean square error (RMSE) as 2.3 $\mathrm{kg\,N\,ha^{-1}}$. From among the 75 watersheds selected for model verification, the maximum and median base flow nitrate loads to the estuaries were estimated to be 29 and 5.5 $\mathrm{kg\,N\,ha^{-1}}$ respectively with RMSE as 2.6 $\mathrm{kg\,N\,ha^{-1}}$. At the estuaries with nitrate loads above the medians, the predominant nitrate sources (75–98%) were derived from the potato rotation lands, highlighting the importance of N use management with potato production for water quality restoration; nitrate load derived from atmospheric N deposits was estimated to account for 3.6–13% of annual nitrate loads in watersheds with nitrate loads exceeding the median values. The application of the model to nutrient reduction planning in the Southwest River

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watershed implies that a significant change on cropping practices has to be made in order to mitigate the anoxic events in this highly impacted agricultural watershed.

## 1. Introduction

Excessive nitrogen (N) losses from anthropogenic activity contribute to eutrophication and impairment of estuarine ecosystems world-wide (NRC, 2000; Voss et al., 2011; Ahtiainen et al., 2014). Nitrogen has been identified as the limiting factor for the growth of most primary producers in estuarine environment (Howarth and Marino, 2006). Excessive N loads can spur the growth of algae in the estuaries and when the algae die, the decay can create undesirable hypoxic or anoxic conditions (NRC, 2000). In many cases, elevated N loads in estuarine environment were linked to a greater farming intensity in the upland areas (Burkart and James, 1999), although inputs from other sources are also important (Bachman et al., 1998; Wade et al., 2005). Nitrogen is the nutrient required in the largest quantities for crop growth and almost all non-leguminous crops need N inputs for optimal production. Agricultural production systems are, however, inherently "leaky", and a certain amount of N within the system is lost due to leaching. Nitrate leaching below the soil profile is a major pathway for N loss from cropping systems in humid regions (Jemison and Fox, 1994; Baker, 2001). Nitrate is generally mobile in groundwater, but can be lost via denitrification under anaerobic conditions, plant uptake and groundwater extractions; however, any remaining nitrate mass will be discharged with base flow and seepage into associated surface waters (Chen and MacQuarrie, 2004). Base flow and/or seepage could carry significant nitrate loads into estuaries and/or coastal water (Valiela et al., 2002; Bowen et al., 2007; Danielescu and MacQuarrie, 2011).

There has been growing interest in estuarine remediation through reducing N loads (Mitsch et al., 1999; European Parliament, 2008; Howden et al., 2011). Estuarine water quality is the product of a large spatial and temporal scale integration of land use in the watershed and the associated physical, chemical and biological interactions occurring therein (Jorgensen, 2002; Bowen et al., 2007) and as a result, reducing N loads requires integrated land use management. Measuring the effects of the management scenarios through experiments may often not be feasible and thus the influence of land use on N load is often predicted using N loading models to support management decision making (Valiela et al., 2002; Volf et al., 2013; Dunn et al., 2013). Distributed or semi-distributed and integrated models have been developed for predicting land-based N loads to estuaries (Krysanova et al., 1998; Wade et al., 2005; Howden et al., 2011). While distributed models such as surface water-focused SWAT (Arnold and Fohrer, 2005) and groundwater-focused MT3D (Zheng and Wang, 1999) can represent the physical systems in detail, the intensive data and resources required to run these models can be a barrier for model applications. Where data and resources are not sufficient to justify a distributed model, the less data intensive integrated models could be an alternative (Weiskel and Howes, 1991; Valiela et al., 2002).

While fewer parameters are required to run an integrated model, defining these parameters can be challenging because one parameter may represent the integrated effect of multiple processes. Thus, the model predictions may significantly deviate from actual loadings if the integrated parameters do not adequately represent these processes. For example, N loads from septic systems, fertilizer use and atmospheric deposition for specific land use parcels are commonly calculated separately with integrated nitrate loading models (Valiela et al., 2002; Howden et al., 2011), and loss (or export) coefficients for fertilizer N use are applied to relate N losses from agricultural sources (e.g., Jones, 1996; Volf et al., 2013; Alvarez-Romero et al., 2014). N losses from crop production systems are a function of soil carbon (C) and N dynamics, management practices and weather (including the composition and quality of soil organic matter, fertilizer N rate, format and application approach, manure applications, rotation length, crop residue management, crop varieties, and tillage practices) (Johnsson et al., 1987; Rodriguez et al., 2005; Zebarth et al., 2012). While a loss coefficient may oversimplify the processes governing N losses from the crop production system, the data required for defining a loss coefficient for each crop land category or assessing the spatiotemporal effects of all these factors are usually not fully available. Coupling a process-based soil C and N model such as LEACHN (Hutson, 2003) and SOILN (Johnsson et al., 1987) to an N loading model could help evaluate the effects of these factors on the input parameters for an integrated nitrate load model in an agricultural watershed. A model has to be customized for specific objectives, data availability and biophysical conditions, and calibrated and verified against field measurements before it is used for prediction purposes (Weiskel and Howes, 1991; Alvarez-Romero et al., 2014).

Prince Edward Island (PEI) is the smallest province in Canada (5750 km$^2$), yet it is the largest producer of potatoes in the country, accounting for about 25% of the Canadian potato crop (Statistics Canada, 2012). Intensive potato production has been conducted on sandy soils underlain by a fractured-porous sandstone aquifer, which also provides all the drinking water in PEI (Jiang et al., 2012). The potato crop usually receives high fertilizer N inputs in order to meet industry tuber yield and size requirements, whereas apparent recovery of applied fertilizer N in the potato crop commonly ranges from as low as 40% to 60% (Zebarth and Rosen, 2007; Vos, 2009). This biophysical configuration in combined with a humid maritime climate creates a favorable situation for nitrate leaching. High levels of nitrate losses from the production systems have been linked to the contamination of the drinking water (Benson et al., 2006). Nitrate-enriched groundwater discharges to the local streams and associated estuaries, leading to reoccurring anoxic events in many estuaries in PEI (Raymond et al., 2002; Schein et al., 2012). A commission on nitrates in groundwater made some recommendations for nitrate mitigation in PEI in 2007 (Commission on Nitrates in Groundwater in PEI, 2008). In response to the Commission's report, community-led watershed-based planning for nitrate reduction was promoted as a strategy for nitrate mitigation. These kinds of planning activities have been underway and initial N load criteria for estuaries in PEI have been developed (Bugden et al., 2014). The objective of this work is to develop an integrated modeling approach for predicting land-derived N loads to estuaries in PEI and prove the credibility and applicability of the model via model calibration, verifications, sensitivity analysis, and a pilot application. The model is intended to inform the planning processes by predicting whether the N load criteria would be met if nitrate reduction land-use adjustments, such as increasing potato rotation length, growing low N input potato varieties, and reducing potato growing areas, are implemented. The modeling approach should work for the local physical conditions, be relatively simple for the community groups to use, and provide N load estimates and source breakdowns using readily available data. Nitrogen loads are considered equal to nitrate loads