Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in Prince Edward Island: An Economic – Hydrologic Modelling Approach

by

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ABSTRACT

Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in PEI: An Economic – Hydrologic Modelling

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Nitrate, a residual of intensive potato farming systems and a diffused contaminant, has contributed to the degradation of groundwater and surface water quality in Prince Edward Island causing ecologically destructive eutrophication in estuaries and residential groundwater wells exceeding Health Canada’s drinking water standard. The economic–hydrologic optimization model estimates the groundwater nitrate leachate marginal abatement costs resulting from the adoption of non-traditional beneficial management practices within potato farming systems with spatial heterogeneity. Prospect potato variety adoption is cost-effective in nitrate leachate abatement with a marginal abatement cost of $47 per kg NO$_3$-N. However, at greater nitrate abatement targets marginal abatement costs are heterogeneous between producers, which illuminate the value of tailoring incentive instruments to recognize heterogeneity. This research output supports holistic approaches to estimate nitrate leachate abatement targets by integrating economic and hydrogeological modelling to improve groundwater quality.
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Chapter 1: Introduction to Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in Prince Edward Island

1.0 Introduction

Chapter 1 provides an overview of the environmental problem occurring in Prince Edward Island (PEI) resultant of intensive agricultural production, particularly potato (*Solanum tuberosum* L.) production. Agriculture is prominent in the lives of Islanders as well as the concern for agriculture’s residual diffused pollutant, nitrate leachate in groundwater and surface water. The background of this research is presented with a brief review of literature specializing in economic-hydrologic modelling and policy instruments to improve water quality related to agriculture. The economic problem and economic research problem is discussed followed by the purpose and objectives of my thesis research. Finally, an outline of how this thesis progresses is presented.

1.1 Background

The Canadian province of Prince Edward Island (PEI) has a unique ecological and economic dependence on water quality, which is affected directly by the agricultural systems used. PEI residents rely solely on groundwater as its source of drinking water and groundwater contributes approximately 70% to surface waters such as streams, rivers, and estuaries (Benson *et al.* 2007; Jiang and Somers 2009). These groundwater and surface waters on the Island have been contaminated with Nitrate (NO$_3^-$) and subsequently Nitrate-Nitrogen (nitrate-N, NO$_3^-$-N); for the remainder of this thesis the term, “nitrate” refers to nitrate-nitrogen. Approximately 54% of PEI residents are served by private well systems with the remainder served by municipal distribution
systems, both sourced from groundwater (Council of Canadian Academies 2009a). Of these residential wells within intensive farming watersheds, 20% exceed Health Canada’s maximum acceptable nitrate-N concentration of 10 milligrams per litre (mg/L), or 45 mg/L as nitrate (Jiang and Somers 2009; Health Canada 2012). Additionally, surface water nitrate-N concentrations have increased steadily since 1966 (PEI Dept. of Environment, Labour and Justice 2014).

Nitrate contaminated groundwater is of concern because of its ability to deteriorate surface and aquatic ecosystems’ quality due to nutrient enrichment leading to algae blooms and hypoxic and anoxic events. Such events can cause fish kills and other aquatic deaths that cause economic losses to the sport fishing tourism sector as well as commercial fishing and shellfish industries (Government of PEI 2008). Additionally, nitrate contaminated drinking water in excess of Health Canada’s maximum acceptable concentration poses serious threats to human health as it can block the oxygen carrying capacity of haemoglobin, causing methaemoglobinaemia also known as “blue baby syndrome” (Camargo et al. 2005; Davidson et al. 2012; Council of Canadian Academies 2009b). It also has a potential role in developing cancers of the digestive tract (Camargo et al. 2005; Davidson et al. 2012).

The reliance on the quality of groundwater in PEI by ecosystems and residents coexists within an intensive agricultural sector that is economically important to the province. Potatoes (Solanum tuberosum L.) are grown on over 40% of the 1.4 million acre land base and the crop generates over 75% of the total cash receipts from this cropland (PEI Dept. of Agriculture and Forestry 2014c; Statistics Canada 2012; 2014a; 2014b). The heavy reliance of nitrogen for this high-value crop grown on the sandy soils of PEI has resulted in significant groundwater nitrate contamination (Rourke 1985).
The concern surrounding groundwater and surface water nitrate contamination and the role of potato farming systems in the increasing contamination rates was highlighted by the Government of PEI’s *The Report of the Commission on Nitrates in Groundwater* (Government of PEI 2008). *The Report of the Commission on Nitrates in Groundwater* identified six of 30 recommendations that were absolutely essential including: improving public education on protecting water quality; reducing nutrient loading from sewage treatment systems; supporting watershed-based water management planning; mandatory three-year crop rotations; agricultural nutrient management planning; and identifying high nitrate susceptible areas (Government of Prince Edward Island 2008). A consequence of the report was the implementation of the *Agricultural Crop Rotation Act (2013a)*, in following years that restricted potatoes to be grown no more frequently than once in three years and not on land with a slope greater than 9% (PEI Dept. of Agriculture and Forestry 2013a). Other beneficial management practices (BMPs) that reduce nitrate leachate and soil erosion have been identified and efforts made to encourage adoption but little is known on their cost-effectiveness (Lantz et al. 2009).

The problem of excess nitrate in groundwater has economic and environmental implications. The economic implications are that in order to reduce nitrate leachate from producers must modify their production practices at the least cost to their production budget. The environmental implications are with BMPs adopted by producers, nitrate concentrations in groundwater and surface water from nitrate contamination, and resulting aquatic ecosystems, are mitigated.
1.2 A Review of Economic – Hydrologic Modelling Literature with Respect to Nitrate Leachate

The concern of nitrate leachate in surface water and groundwater has attracted the attention of physical scientists such as hydrogeologists and agronomists to research the impact of agricultural land management practices on nitrate leachate using hydrologic modelling techniques (Benson et al. 2006, 2007; Jiang and Somers 2009). Yet, the economic analyses of the adoption of BMPs and how to incentivize these practices in PEI have become secondary to hydrologic modelling as the confidence and reliance on the method has strengthened. Literature that integrates hydrologic modelling with economics using linear programming to assess agricultural land management practices on nitrate leachate in PEI has studied potato crop rotations, tillage treatment, and surface residue post potato harvest (Jatoe 2008). For non-PEI focused studies, the effect on nitrate leachate from the adoption of tillage treatment and crop rotations for potatoes and non-potato crops have been modelled through linear programming (Amon-Armah et al. 2013), as well as nitrification inhibitors for dairy systems using non-linear programming (Doole and Paragahawewa 2011). Alternatively, the value of the benefits resulting from a reduction of nitrates in groundwater resulting from decreased nitrogen fertilizer applications for Southern Ontario was estimated by Giraldez and Fox (1995). Partial budget analysis using net present value and break-even analyses have also been used to evaluate buffer strips, nutrient management planning, cover crops, and controlled drainage to reduce nitrate-N pollution for tobacco rotations (Wossink and Osmond 2002). A recent advancement in integrated hydrologic – economic modelling techniques is the use of evolutionary algorithms. Simulation-optimization framework to solve for cost-efficient and spatial allocations of nitrogen abatement BMPs such as
conservation tillage, buffer strips, grassed waterways, reduced fertilizer, and agricultural land retirement in Iowa (Rabotyagov et al. 2010).

Although there have been varied methods to address beneficial management practice (BMP) adoption to reduce nitrate leachate in the literature, there lacks integrated economic–hydrologic optimization models that consider the cost of adopting non-traditional BMPs such as potato varieties, spring tillage, combined with nutrient management planning, sensitive land retirement and crop rotations as well as the means to incentivize such adoption.

1.3 Economic Problem of Nitrate in Prince Edward Island

The environmental issue facing the collaborative partners for this project, Prince Edward Island Department of Agriculture and Forestry (PEI Dept. of Agriculture and Forestry), Canadian Water Network, and Agriculture and Agri-Food Canada, is nitrate contaminated groundwater results from residual nitrate within the soil profile that leaches through the subsurface into the aquifer as well as agricultural runoff into surface water (Benson et al. 2007; Jiang and Somers 2009). Contamination causes drinking water nitrate concentrations above Health Canada’s maximum acceptable concentration threshold as well as hypoxic and anoxic events in surface water, which causes economic damages to the Island’s tourism and fishing industries.

The economic problem arises from the project partners’ interest in potential methods to reduce nitrate leachate in sedimentary bedrock groundwater in PEI. The economic problem is, “What are the benefits and costs of the technically-feasible agricultural BMPs for adoption by Island potato producers to reduce nitrate leachate?”
1.4 Economic Research Problems of Nitrate in Prince Edward Island

The first economic research question of nitrate leachate in groundwater in PEI is, “What are the gross margin maximizing sets of technically-feasible BMPs for PEI potato producers to adopt to achieve nitrate abatement targets?” The second economic research question is, “What are the resulting marginal nitrate leachate abatement costs for the adoption of such gross margin maximizing sets of technically feasible BMPs?” The third economic research question is, “How can the adoption of such gross margin maximizing sets of technically-feasible BMPs be incentivized?” These economic research questions are currently unknown by the PEI Dept. of Agriculture and Forestry as well as Island watershed associations, and with further knowledge these organizations will be better equipped with the marginal abatement costs of BMPs effective in abating nitrate leachate on the Island that may be utilized within BMP incentive programs.

The scope of the problem is within three sub-watersheds of the upper watersheds of the Southwest River – Tuplin Creek, Southwest River, and Durant Creek. These sub-watersheds are within the Kensington North Watershed Association (Jiang 2013).

1.5 Purpose and Objectives

The purpose of this research is to evaluate the gross margin associated with the adoption of agricultural BMPs and the resultant nitrate leachate reduction in sedimentary bedrock groundwater in PEI. The specific objectives of the study are as follows:

I. To identify agricultural land management practices that have been empirically tested to affect nitrate leachate abatement by connecting with agronomists, field extension specialists, hydrogeologists, and watershed associations in PEI.
The outcome of Objective I in *Chapter 2* as well as Chapter 4 identifies why PEI is a unique research area for nitrate contaminated groundwater given its soil characteristics, hydrologic features, and intensive agricultural production. Additionally, in *Chapter 2* agricultural land management practices that abate nitrate leachate in groundwater and measures taken by the PEI Dept. of Agriculture and Forestry are addressed.

II. To develop the conceptual model the producer’s production decision to adopt nitrate leachate abating BMPs and its impact on gross margin by graphical and algebraic representation.

To achieve Objective II is to develop an interdisciplinary conceptual model combining economic and hydrologic factors to demonstrate the reduction of nitrate leachate in groundwater from the adoption of BMPs. This is achieved through a conceptual model that optimizes gross margin and nitrate leachate abatement, which creates the marginal abatement cost curves for two producers with differing land quality. *Chapter 3* discusses this conceptual model while *Chapter 4* presents the empirical economic – hydrologic optimization model of this conceptual model.

III. To populate the empirical model with the costs and revenues of a representative potato producer and the hydrologic nitrate leachate abatement data for high and low quality land by connecting with Island specialists.
The results from Objective III will populate the economic and hydrologic variables within the empirical model; *Chapter 4* addresses Objective III.

**IV.** To estimate the representative potato producer’s gross margin and corresponding nitrate leachate abatement on low and high quality land by the use of linear programming to optimize gross margin constrained by nitrate leachate abatement targets.

The empirical economic – hydrologic optimization model simulates the producer’s production choices given no abatement targets, the situation where she does not consider her externality of nitrate leachate, as well as at a variety of successive abatement targets. *Chapter 4* addresses Objective IV.

**V.** To estimate the marginal nitrate abatement costs of adopting BMPs to achieve nitrate leachate abatement targets on low and high quality land by creating a trade-off frontier of gross margin -nitrate leachate abatement sets.

The trade-off frontier is derived from the results of Objective IV from the change in gross margin resultant of an increased nitrate leachate abatement target. The marginal abatement cost is derived from the change in gross margin associated with adopting BMPs to achieve the target. Objective V is addressed in *Chapter 5.*
1.6 Outline of Chapters

This thesis proceeds with a background on agriculture and nitrate leachate as well as the occurrence of nitrate in PEI, Chapter 2: Agriculture and Nitrate Leachate in Prince Edward Island. Chapter 2 also discusses nitrate leachate abating BMPs and abatement programs that are encouraged to reduce nitrate leachate in groundwater and surface water on the Island. Chapter 3: Conceptual Model of Nitrate Leachate Abatement includes the individually and socially optimal as well as the cost-effective allocation of nitrate leachate abatement. Chapter 4: Empirical Economic – Hydrologic Optimization Model presents the empirical economic – hydrologic optimization model, results, and discussion. Chapter 5: Concluding Remarks and Implications for Incentive Instruments reviews significant results, contributions of this research to practice and literature, as well as limitations and pathways of potential future research.
Chapter 2: Agricultural Production and Nitrate Leachate in Prince Edward Island

2.0 Introduction to Chapter
Nitrogen is the base molecule used to build proteins for humans and animals. A change in the nitrogen (N) cycle occurs as the global population consuming agricultural and energy-produced products continues to grow (Cunningham et al. 2005). The consequence of this is an increase in available nitrogen in the atmosphere and terrestrial systems. This excess nitrogen may affect ecosystems and human health negatively. This chapter proceeds to discuss the nitrogen cycle and cascade, sources and effects of nitrate in the environment, nitrate in Prince Edward Island, and beneficial management practices that abate nitrate leachate.

2.1 The Nitrogen Cycle
From primary producers to humans rely on nitrogen; we cannot exist without nitrogen-containing amino acids, proteins, peptides, and nucleic acids (Cunningham et al. 2005). Although approximately 78% of the atmosphere is nitrogen (N$_2$), photosynthesizing organisms cannot retain this nitrogen and instead uptake nitrogen from a gaseous cycle, the nitrogen cycle (Cunningham et al. 2005). Nitrogen (N) is separated into two categories, nonreactive or atmospheric nitrogen (N$_2$) and reactive nitrogen (Nr). Reactive nitrogen includes highly active compounds in the atmosphere and biosphere such as nitrogen oxides, ammonia (NH$_3$), ammonium (NH$_4^+$), nitrous oxide (N$_2$O), nitrate (NO$_3^-$), urea, and organic nitrogen compounds (Galloway et al. 2003).

The Nitrogen Cycle, as discussed by Cunningham et al. (2005), may begin with atmospheric nitrogen from lightning, agricultural nitrogen fixation, volcano eruption, and fossil
fuel burning that is fixed within the soil by nitrogen fixing bacteria that convert N\textsubscript{2} into ammonia (NH\textsubscript{3}). Bacteria combine this ammonia with oxygen (NO\textsubscript{3}) to form nitrite, which is then transformed into nitrate (NO\textsubscript{3}) by nitrifying bacteria. There is rivalrous competition for nitrate between plant uptake, nitrate leaching into groundwater, and denitrification within the cycle (Cunningham et al. 2005). Plants may uptake nitrate that reduce into ammonium (NH\textsubscript{4}\textsuperscript{+}) to build amino acids and other proteins that may be consumed by humans and animals. Or, nitrate may leach from the soil profile into groundwater. Or, nitrate may be denitrified from bacteria that convert nitrate back into the atmosphere as atmospheric nitrogen or nitrous oxide (N\textsubscript{2}O), a greenhouse gas. The Cycle continues as nitrogen returns to the system through the decomposition of organisms, exoskeletons, animal hair, and urinary wastes that release ammonia and ammonium ions that are used once again to form nitrate (Cunningham et al. 2005). Figure 2.1 illustrates this Nitrogen Cycle (Ontario Ministry of Agriculture, Food and Rural Affairs 2005).
2.2 Sources of Nitrate in the Environment

Reactive nitrogen is produced by both natural and anthropogenic processes. On a global scale, natural processes such as lightening and volcano eruptions contribute approximately 10 million metric tonnes N per year whereas anthropogenic sources such as fossil fuel combustion,
commercial and agricultural nitrogen fixation contribute approximately 140 million metric tonnes N per year (Cunningham et al. 2005). Anthropogenic creation of reactive nitrogen is introduced to the environment through two means. The first is cultivation-induced biological nitrogen fixation, and the second is the Haber – Bosch process of extracting atmospheric nitrogen and hydrogen and converting it to ammonia (Doering et al. 2011). Ammonia is used in synthetic nitrogen fertilizers that are used in agricultural production. In the United States, for agricultural purposes 10.9 million metric tonnes Nr per year is attributable to the Haber – Bosch fertilizers and 7.7 million metric tonnes Nr per year to cultivation-induced biological nitrogen fixation, compared to only 6.4 million metric tonnes Nr per year attributable to natural biological nitrogen fixation (Doering et al. 2011).

2.2.1 Sources of Nitrate in the Environment from Agricultural Systems

In agricultural crop production systems, synthetic nitrogen – based fertilizers are used to supplement biological nitrogen fixation to sustain crop fertility demands. The crop agroecosystem receives 170 metric tonnes of synthetically created reactive nitrogen per year, of which 121 million metric tonnes of is lost to the atmosphere, water sources, or reintroduced to crop systems during the next cycle (Galloway et al. 2003). Agricultural livestock production systems also contribute nitrate to the environment. In livestock production systems reactive nitrogen is introduced through proteins in grain feed but lost through manure and urine (Galloway et al. 2003). Reactive nitrogen from manure is lost through three channels: air emissions including greenhouse gases, agricultural runoff into surface water, and nitrate leached into groundwater (Galloway et al. 2003).
If Agricultural producers consider their external cost on the environment, a trade-off exists between greenhouse gas emissions, and surface water and groundwater. Synthetic fertilizers and organic manure applied to agricultural land emits nitrate into surface water and groundwater, but if stored and treated manure releases methane (CH$_4$), a greenhouse gas (IPCC 2006). Greenhouse gas emission directly related to crop and livestock production accounted for 8% of total greenhouse gas emissions for Canada in 2010 (Environment Canada 2012). For total emissions of methane (CH$_4$) and nitrous oxide (N$_2$O) in Canada, agriculture accounted for 24% and 72%, respectively (Environment Canada 2012). The main drivers of emissions from agriculture are from beef cattle and swine populations and the use of synthetic nitrogen fertilizers for crop production (Environment Canada 2012).

2.3 Effects of Nitrate in the Environment

As discussed in the previous section, humans are more efficient at reactive nitrogen creation through the Haber – Bosch process than nature. Increasing demand for agricultural inputs for the production of food and alternative energy sources results in losses to the environment through the nitrogen cascade. The nitrogen cascade is the movement of reactive nitrogen across three natural systems: the atmosphere, terrestrial and aquatic ecosystems, and the connected impacts on air, water, and soil quality, and subsequently human health (Galloway et al. 2003). Nitrate contamination of groundwater is diffused pollution; diffused or nonpoint-source pollution is considered as not having a direct discharge source, such as an outfall pipe, at which the pollution can be measured or monitored before it enters the ambient environment (Russell and Shogren 1993).
As a result of synthetic fertilizers and organic manures used in agricultural production, the loss of nitrate to the environment through leachate, agricultural runoff, and soil erosion into surface water is of serious concern. A prominent concern in agricultural watersheds are excess nitrates not absorbed by plants nor denitrified that remain in the soil and leach through the water table into the saturated zone where they mix with waters recharging the aquifer (Benson et al. 2007). The aquifer discharges into streams, lakes, estuaries, and into well water for human consumption (Benson et al. 2007). When concentrated levels of nitrates in surface water and groundwater are present, damages to ecological areas and human health result (Benson et al. 2007; Davidson et al. 2011; Doering et al. 2011).

2.3.1 Environmental and Ecological Effects

Surface water and groundwater contamination in agricultural landscapes results from both point and diffused pollutions. Point source pollution is a confined discharge to surface water and groundwater from observable sources such as feedlots, chemical spills, manure piles, and septic (Bianchi and Harter 2002). Although originally from a single source, diffused pollution is dispersed throughout the natural environment assisted by climatic conditions and human activities (Bianchi and Harter 2002). Diffused pollution is associated with agricultural production, and includes agricultural runoff in surface water, pollution of lakes from septic leaks, and nitrate leachate groundwater from fertilizer use (Bianchi and Harter 2002).

A cascade of ecological events ensues as contaminated groundwater discharges to rivers, streams, lakes, and estuaries and costal waters resulting in surface water contamination. Eutrophication is the result of excess nutrients in an aquatic system mediated by biotic and abiotic processes (Cunningham et al. 2005). These nutrients stimulate algae growth and
reproduction, which depletes nutrients necessary for plant and animal survival. As algae die and decompose, oxygen is removed from the water. This reduction in available oxygen can kill fish and other organisms, manifesting into aquatic dead zones (Camargo et al. 2005; Davidson et al. 2012). Contaminated surface water becomes a cloudy, green, yellow, brown or red, which may decrease the value of surface water bodies for commercial, recreational, and amenity purposes.

2.3.2 Human Health Effects
Elevated concentrations about Health Canada’s maximum acceptable nitrate-N concentration of 10 milligrams per litre (mg/L), or 45 mg/L as nitrate of nitrate in drinking water pose serious risks for human health (Camargo et al. 2005; Davidson et al. 2005; Health Canada 2012). Once ingested, anaerobic conditions within the body convert nitrates into nitrites and subsequently block the oxygen carrying capacity of haemoglobin, which causes methaemoglobinaemia also known as “blue baby syndrome”. Bottle-fed infants are at particular risk for this disorder (Camargo et al. 2005; Davidson et al. 2012; Council of Canadian Academies 2009b). Additionally, nitrites are potentially responsible for developing cancers of the digestive tract, prostate, bladder, and colon (Camargo et al. 2005; Davidson et al. 2012).

2.4 Occurrence of Nitrate in Prince Edward Island
PEI residents rely solely on groundwater as their source of drinking water and groundwater contributes approximately 70% to the surface water of streams, rivers, and estuaries (Benson et al. 2007; Jiang and Somers 2009). PEI has a total population of 145,273 of which approximately 54% of residents are served by private wells, with the remainder served by groundwater-sourced municipal distribution systems (Council of Canadian Academies 2009b; PEI Statistics Bureau
This dependence on groundwater by the residents and ecosystems of the Island coexists within a dominant, fertilizer intensive, agricultural industry.

PEI has the smallest land area in Canada yet provides about one quarter of domestic potato production (Agriculture and Agri-Food Canada 2014); PEI has a total land area of 1.4 million acres with 594,000 acres for agricultural purposes, of which in the 2014 season 90,500 acres were used for the cultivation of a single commodity, potatoes (PEI Dept. of Agriculture and Forestry 2014c). The heavy reliance of nitrogen for this high-value crop grown on the sandy soils of PEI has resulted in significant groundwater nitrate contamination (Rourke 1985).

2.4.1 Magnitude of the Nitrate Problem in Prince Edward Island

Contaminated surface water and groundwater in Prince Edward Island with nitrate and nitrate-N concentrations above capacity for aquatic health and human consumption are prominent concerns for individuals in Prince Edward Island (PEI Watershed Alliance 2010; Wheatley River Improvement Group 2013). Approximately 20% of residential wells within intensive farming watersheds exceed Health Canada’s maximum acceptable nitrate-N concentration of 10 milligrams per litre (mg/L), or 45 mg/L as nitrate (Jiang and Somers 2009; Health Canada 2012). In Figure 2.2 below, watersheds in the south central and the northwestern portion of the Island had the highest groundwater nitrate concentrations with samples from private wells across the Island within the nitrate concentration ranges of 3 –10 increased from 1995 to 2007 (Council of Canadian Academies 2009a).
From a sample of ten rivers across the Island, surface water nitrate concentrations (NO$_3^-$-N milligram per litre), along with potato acreage have increased over the past 40 years (PEI Dept. of Environment, Labour and Justice 2014). Both potato area and nitrate concentration exhibit a sharp incline post-1990, although potato area peaks then falls prior to nitrate concentrations suggesting residual nitrate from potato production remains within the ecosystem.
As discussed in Section 2.3.1 Environmental and Ecological Effects, alterations in aquatic ecosystems are a consequence of nitrate contaminated surface water and groundwater. Figure 2.4 illustrates the locations of anoxic events from 2008 to 2012 in PEI. The PEI Dept. of Environment, Labour and Justice define an anoxic event if two of the following three criteria have been observed: milky white or green discoloration of the water, hydrogen sulphide (H₂S) or
rotten turnip odour, and/or near zero dissolved oxygen readings (PEI Dept. of Environment, Labour and Justice 2013). Reported and classified anoxic events between 2002 and 2012 varied from 12 to 25 per year; the number of anoxic events per year is illustrated in Figure 2.5; 2003, 2010, and 2012 reported the greatest number of anoxic (PEI Dept. of Environment, Labour and Justice 2013).

Figure 2.4: Anoxic Events in Prince Edward Island from 2008 to 2012 (PEI Dept. of Environment, Labour and Justice 2013)
Figure 2.5: Observed and Reported Anoxic Events in Prince Edward Island from 2002 to 2012 (Data adapted from PEI Dept. of Environment, Labour and Justice 2013).

There have been 50 documented fish kills since 1962 on PEI (Macphail Woods – Ecological Forestry Project 2013). Fish kills may result from low oxygen levels in the water due to eutrophication, but more frequently are resultant of pesticide runoff washed into surface waters by heavy rain (PEI Dept. of Agriculture and Forestry 2014d). Fish kills are becoming a regular event, for the past three years the Trout River, in western Prince Edward Island, has documented a fish kill per year (CBC News 2013). Figure 2.7 illustrates the location of fish kills from 1962 to 2011, which if visually compared to Figure 2.2 appear to have correlated high groundwater nitrate concentration as well as fish kills (PEI Dept. of Agriculture and Forestry 2014d)
With the presence of nitrate contaminated groundwater, surface water, anoxic events, and fish kills exists the fishing industry and sport fishing tourism. When anoxic events and fish kills occur as consequence of agricultural production, the fishing industry and sport fishing industries are negatively impacted. PEI estuaries, rivers, and shallow bays provide the habitat for fish desired by the fishing and tourism industry. The fishing industry catches lobster, Bluefin tuna, scallops, oysters, mussels, eels, sea plants, ground fish, crabs, and herring (PEI Dept. of Fisheries and Aquaculture n.d.). Sport fishing draws tourism for both fresh and saltwater angling offering
brook speckled and rainbow trout, Atlantic salmon, mackerel, shark, and Bluefin tuna (PEI Dept. of Agriculture and Forestry 2014f). Aquaculture accounts for approximately $34 million of gross output in Prince Edward Island, and $7.6 million worth of wages and salaries to Islanders (Statistics Canada 2013).

2.5 Nitrate Leachate Abatement Practices in Prince Edward Island

Beneficial Management Practices (BMPs) are agricultural land management practices that reduce negative externalities such as erosion, sediment runoff, nitrate leaching, and soil degradation stemming from agricultural production. Agronomists and hydrogeologists have empirically tested adoption of the following BMPs to affect nitrate leachate abatement: sensitive land retirement, minimum three-year crop rotations, Prospect versus Russet Burbank potato variety, nutrient management planning, and spring tillage (Jiang 2013). Reforestation of sensitive land and improving on-farm septic systems are additional BMPs producers may adopt (Jiang 2013). Education and awareness of nitrate leachate issues, solutions, and innovations in technologies have also been noted as potential strategies that go beyond the on-field practices to improve water quality in Prince Edward Island (Jiang 2013; Government of Prince Edward Island 2008).

2.5.1 Sensitive Land Retirement

Sensitive land retirement (SLR) is a key feature of the Alternative Land Use Services 2 in PEI, discussed in Section 2.6.3 and Table 2.2. SLR is land sensitive to ecological degradation such as land adjacent to riparian buffers, grassed headlands near watercourses or bufferable wetlands, or high sloped agricultural land (PEI Dept. of Agriculture and Forestry 2013b). The retirement of these lands from agricultural produce increases nitrate leachate abatement.
Estimated farmland values increased an average of 5.7% in the second half of 2012, with 3.1% and 1.5% changes in the first half of 2012 and last half of 2011 in PEI, respectively, according to Farm Credit Canada (2013). Stable or positive changes in farmland values were attributed to favourable moisture and sunshine throughout the crop season, which led to profitable potato yields to fund growers’ purchases of more land. These higher farmland prices exhibit the general consensus of confidence in the potato industry (Farm Credit Canada 2013). Given recent positive farmland values, adoption of beneficial management practices that retire sensitive land have a high opportunity cost for potato producers in Prince Edward Island.

Chapter 4 Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in PEI: An Economic – Hydrologic Modelling Approach discusses the cost and revenues associated with SLR used within the empirical model.

2.5.2 Crop Rotation and Prince Edward Island Agricultural Crop Rotation Act

The Prince Edward Island Agricultural Crop Rotation Act (PEI ACRA) was implemented as result of the Commission of Nitrates in Groundwater’s recommendations. Its purposes are to maintain and improve groundwater and surface water quality, improve soil quality, and to preserve soil productivity (PEI Dept. of Agriculture and Forestry 2013a). Potatoes are grown on no more than one-third of the land base due to the restriction and/or on a slope greater than 9% imposed by the PEI ACRA (Government of Prince Edward Island 2012; PEI Dept. of Agriculture and Forestry 2013a). Potatoes may be grown more frequent than 1-in-3 years if they do not exceed the 7.4 MT per hectare per year soil erosion (PEI Dept. of Agriculture and Forestry 2015c); the Revised Universal Soil Loss Equation considers spatial and hydrologic factors along
with land management practices implemented by the producer to determine if 2-in-5 rotations are eligible under \textit{PEI ACRA} (PEI Dept. of Agriculture and Forestry 2015c).

If a producer fails to abide to the regulations is liable to a fine of $1,000 per hectare of land planted in violation (PEI Dept. of Agriculture and Forestry 2013a; Government of Prince Edward Island 2012). Although, non-compliance with \textit{PEI ACRA} by some producers has been documented (MacLean 2014). Additionally, in PEI land rentals between producer types, complicate monitoring, and enforcement is difficult due to informal land trades between potato and livestock producers (PEI Dept. of Agriculture and Forestry 2013f; Wright 2013).

A crop rotation sets a fixed amount of arable land planted in crops year-over-year for the complete rotation. Aside from potato, rotation crops include soybean, barley, barley underseeded with hay, and/or hay are within rotations that are considered typical for PEI based on discussions with provincial field staff (PEI Dept. of Agriculture and Forestry 2014g). \textit{Chapter 4 Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in PEI: An Economic – Hydrologic Modelling Approach} discusses the terminology of crop rotation with respect to the empirical model. Approximately 60 – 65% of current potato land is on the 1-in-3 year crop rotation of potato-small cereals underseeded with forage-forage (Wright 2013). Occasionally some producers implement potatoes followed by two years of forage (PEI Dept. of Agriculture and Forestry 2014g; Wright 2013). Approximately 25% - 30% of potato is in 2-in-5 year rotation of potato-small cereal-potato-small cereal-forage (Wright 2013).

The choice of crop within a crop rotation can influence nitrate leachate. Winter cover crops on early harvested potatoes, and crops such as buckwheat, tillage radish and oilseed radish take up leftover nutrients, but they are not a common rotational crop in PEI (Wright 2013). Cereals may be underseeded with forages, with forages remaining after the harvest of the cereal.
Although underseeding aids in nutrient retention, forages and cereals compete for nutrients, water, and sunlight. Successful underseeds are red clover, timothy, and ryegrasses rather than alfalfa and most other grasses (Forage and Corn Variety Evaluation Task Group, n.d.). The inclusion of hay within a rotation increases the soil organic matter by adding carbon and nitrogen as well as breaking pest cycles thereby positively contributing to potato yields (Jiang 2014; Watts 2015a).

2.5.3 Potato Variety

Historically, there have been two french fry processors located in Prince Edward Island, McCain Foods Limited and Cavendish Farms, who negotiate contracts with Island producers for potato varieties through the Processing Committee of the PEI Potato Board (PEI Potato n.d.). Announced in August of 2014, McCain announced it would be closing its french fry facility located Borden-Carleton, which accounts for approximately four percent of the Island’s potato production; which translates into $7 million worth of potatoes grown in Prince Edward Island by 23 Island producers contracts (CBC 2014). McCain, the producer of one in three French fries eaten globally, purchases Russet Burbank along with Shepody, Pentland Dell, and Bintje for their potato products – mainly French fries for McDonalds (McCain Foods Limited 2011).

The potato variety Russet Burbank is the traditional choice potato for french fries as it is high in starch with netted brown skin and white flesh that is light and fluffy when cooked and ideal for frying (Cavendish Produce n.d.). In addition to Russet Burbank, a producer on the Island may the Prospect potato variety, which is a proprietary variety of Cavendish Farms (CBC News 2010); Cavendish Farms also sells Russet Burbank and Shepody seed potato varieties to producers in Prince Edward Island. The Prospect is a high yielding plant that sets five large
tubers with a few small tubers, matures earlier than Russets, requires much less fertilizer, and no soil fumigation because of the variety’s resistance to most field diseases (Cavendish Farms 2012). The Prospect variety has good drought tolerance, very good storability quality, medium specific gravity and medium dormancy period (Washington State University 2013). Cavendish Farms provides Wendy’s with potatoes for french fries, and Wendy’s was the first major customer to buy the Prospect variety (CBC News 2010).

Russet Burbank requires a greater nitrogen fertilizer rate than Prospect, and consequently Prospect is a nitrate leachate abating variety (PEI Dept. of Agriculture and Forestry 2014j).

2.5.4 Nutrient Management Planning

Nutrient Management Planning (NMP) ensures that crop and livestock nutrient requirements are met without unnecessary over application of nutrients. The goal of nutrient management planning is to optimize crop yield and quality, minimize input costs, ensure cost-effectiveness, and protect soil and water quality (Lantz et al. 2009). This is achieved by ensuring the application of additive nutrients equal the difference between nutrients required to meet targeted yields and organic nutrients already in the soil (Lantz et al. 2009; PEI Dept. of Agriculture and Forestry 2013e; Government of Prince Edward Island 2008). Nutrient management planning in PEI was implemented to reduce on-farm nutrient use, excess nutrients in the environment, fertilizer costs as well as maintain and increase soil capacity, utilize organic manure nutrients, and prevent excessive nutrient buildup (PEI Dept. of Agriculture and Forestry 2013e).

The Report from the Commission on Nitrates in Groundwater recommended nutrient management planning as a key management practice to reduce the amount of nutrients applied to crops, particularly potatoes (Government of Prince Edward Island 2008). The Commission on
Nitrates in Groundwater concluded Prince Edward Island potato and crop producers applied nitrogen-based fertilizers in excess of crop nutrient requirements, which contributed to groundwater nitrate contamination (Government of Prince Edward Island 2008).

2.5.5 Tillage Timing

Typically, arable land is tilled after the forage crop is harvested in the fall but an alternative is to delay tillage until the spring. Spring tillage eliminates bare fields over the winter, which reduces soil erosion as well as retains soil nitrogen from the preceding crop, which may reduce the nitrogen fertilizer input required for the following crop and therefore reduce nitrate leaching during the potato phase (Jiang et al. 2014; Lantz et al. 2009).

2.6 Nitrate Leachate Abatement Programs in Prince Edward Island

The province of Prince Edward Island has implemented nitrate leachate abatement programs to try to reduce the negative impacts from intensive agricultural practices on the Island. In 1999, amendments to the Environmental Protection Act mandated a handful of beneficial management practices: a 10-meter buffer zone and 50-meter conservation zone, restrictions limiting row crops on slopes greater than 9%, and some crop rotations (Council of Canadian Academies 2012). Officials had trouble enforcing the laws because of lack of resources to monitor (Council of Canadian Academies 2012). As regulatory approaches were unsuccessful officials shifted to voluntary incentive programs, which have resulted in 200 to 250 applicants per year to the Agricultural Stewardship Program (Council of Canadian Academies 2012). This incentive based approach that includes support for beneficial management practices, cross-compliance
mechanisms, and advocacy has been more effective in bringing about positive environmental changes from farming practices (Council of Canadian Academies 2012).

2.6.1 Agriculture Stewardship Program

The Agriculture Stewardship Program, first introduced in 2006, is a cost-share program that offers technical and financial support to encourage Prince Edward Island producers to voluntarily adopt beneficial management practices that reduce environmental damage (PEI Dept. of Agriculture and Forestry 2014b). The Agriculture Stewardship Program is mandated under Growing Forward 2, and funded by both federal and provincial governments, to ensure that the agricultural sector contributes to society’s priorities of clean soil, water and air, and biodiversity (PEI Dept. of Agriculture and Forestry 2014b). There are six program categories with just over twenty approved beneficial management practices eligible for adoption. The categories are soil management, storage management, water management, nutrient management, energy management, and buffer zone and riparian management. To participate in the Program producers are required to have a current, or within the past five years, Environmental Farm Plan (PEI Dept. of Agriculture and Forestry 2013f; PEI Dept. of Agriculture and Forestry 2014b). Financial assistance per farm operation is maxed at $75,000 until the Program expires in 2018, which operates through cost-share and per land unit funding schemes. Technical assistance includes development and implementation of soil conservation structures, storage facilities, livestock watering and fencing, stream crossings, water management and efficiencies, nutrient management, and energy efficiencies (PEI Dept. of Agriculture and Forestry 2014b).

Table 2.1 illustrates the Agriculture Stewardship Program’s finer details. The six categories are refined into specific BMPs with the cost-share percentage and funding cap.
With respect to the empirical model in Chapter 5, BMPs payments within the Nutrient Management category are not considered as eligibility requirements and payments target fixed costs or do not align with rotational assumptions.

<table>
<thead>
<tr>
<th>BMP Category</th>
<th>Cost-Share</th>
<th>Eligible Best Management Practices</th>
<th>Category Funding Cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Soil Management</td>
<td>66%</td>
<td>1.1 Erosion Control Structures</td>
<td>$50,000</td>
</tr>
<tr>
<td></td>
<td>$25 per acre up to $3,000 per year</td>
<td>1.2 Crop residue management - 25% cover immediately after planting</td>
<td>$6,000</td>
</tr>
<tr>
<td></td>
<td>$15 per acre up to $2,500 per year</td>
<td>1.3 Primary Residue Tillage-spring of fall 20% coverage</td>
<td>$5,000</td>
</tr>
<tr>
<td></td>
<td>$15 per acre up to $3,000 per year</td>
<td>1.4 Furrow damming</td>
<td>$5,000</td>
</tr>
<tr>
<td></td>
<td>$20 per acre</td>
<td>1.5 Strip Cropping</td>
<td>$2,000</td>
</tr>
<tr>
<td>2. Storage Management</td>
<td>50%</td>
<td>2.1 On-farm fuel storage; double walled tanks only</td>
<td>$7,000</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>2.2 On-farm pesticide storage</td>
<td>$8,000</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>2.3 On-farm silage storage</td>
<td>$25,000</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>2.4 Improved manure storage</td>
<td>$50,000</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>2.5 Covered feedlot - impermeable base and roof for minimizing livestock runoff</td>
<td>$30,000</td>
</tr>
<tr>
<td>3. Buffer Riparian Zone</td>
<td>50%</td>
<td>3.1 Alternate watering systems</td>
<td>$8,000</td>
</tr>
<tr>
<td>Management</td>
<td>50%</td>
<td>3.2 Improved stream crossings for farm machinery</td>
<td>$25,000</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>3.3 Power to remote sites for alternate watering systems</td>
<td>$4,500</td>
</tr>
<tr>
<td></td>
<td>66%</td>
<td>3.4 Fencing and livestock stream crossings</td>
<td>$15,000</td>
</tr>
<tr>
<td>4. Water Management</td>
<td>50%</td>
<td>4.1 Agricultural water quality</td>
<td>$15,000</td>
</tr>
<tr>
<td></td>
<td>4.2 On-farm water use efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>4.3 Improved irrigation efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>4.4 Sustainable agricultural water supply</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>4.5 Well water management</td>
<td>$6,000</td>
</tr>
<tr>
<td>5. Nutrient Management</td>
<td>50%</td>
<td>5.1 Nutrient management planning</td>
<td>$3,000</td>
</tr>
<tr>
<td></td>
<td>$25 per acre up to maximum $500 per</td>
<td>5.2 Rotational Crops for Pest Management and Nutrient Reduction Loss</td>
<td>$3,000</td>
</tr>
<tr>
<td>6. Energy Management</td>
<td>30%</td>
<td>6.1 On-farm energy management</td>
<td>$10,000</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----</td>
<td>-----------------------------</td>
<td>--------</td>
</tr>
</tbody>
</table>

Source: Adapted from PEI Dept. of Agriculture and Forestry (2014)

2.6.2 Environmental Farm Plan

To participate in the Agriculture Stewardship Program a producer must obtain an Environmental Farm Plan through the Prince Edward Island Federation of Agriculture (PEI Dept. of Agriculture and Forestry 2013d). Producers attend a one-day workshop to complete an environmental assessment and create a plan to address environmental issues resultant from their production practices (PEI Dept. of Agriculture and Forestry 2013d). The process helps producers identify and address environmental risks and opportunities by maintaining water, soil and air quality, and biodiversity. The Environmental Farm Plan effectively manages agricultural inputs like herbicides, insecticides and fertilizers, to demonstrate to the public, government, and investors that producers are managing their environmental risks (PEI Federation of Agriculture n.d.). Additional goals of the Environmental Farm Plan are to increase the producers’ understanding of legal requirements related to environmental issues and identify what producers are already doing well and pinpoint where improvements can be made (PEI Federation of Agriculture n.d.; PEI Dept. of Agriculture and Forestry 2013f).

2.6.3 Alternative Land-Use Services 2 Program

The Alternative Land-Use Services 2 in PEI is a voluntary, incentive – based ecological goods and services program that administers annual payments to producers to compensate the cost of implementing beneficial management practices to encourage alternative land use practices (PEI Dept. of Agriculture and Forestry 2013b). The goals of the program are to improve water quality,
reduce erosion, improve wildlife habitat, and reduce the impacts of climate change (PEI Dept. of Agriculture and Forestry 2013b). Alternative Land-Use Services 2 operates through voluntary participation of Prince Edward Island producers, where producers have the financial incentive to enrol up to 20% of their cultivated land. Priority is to take marginal, unproductive, inefficient or environmentally sensitive lands out of agricultural production. Lands of particular focus are along waterways, steep sloped cropland, erodible fields, and small unusable patches. Producers receive from 50% to 100% of initial capital costs, and a potential annual performance or maintenance incentive for continual service (PEI Dept. of Agriculture and Forestry 2013b).

Table 2.2 illustrates eligible practices and associated subsidies for each practice by area per year. Approximately 70% of agricultural producers in Prince Edward Island have participated in the Alternative Land Use Services 2 program (PEI Dept. of Agriculture and Forestry 2013f).

Currently, out of the beneficial management practices considered within this research, only NMP can retrieve a payment from incentive programs on the Island, although it is only a fixed cost for consultant feeds exist to aid the adoption of NMP. Additional environmental programs and services in Prince Edward Island are crop insurance discounts, watercourse buffer zones, environmentally significant class of land holdings, and the environmental property tax credit program (PEI Dept. of Agriculture and Forestry 2013d).
Table 2.2: Alternative Land Use Services 2 – Eligible Categories

<table>
<thead>
<tr>
<th>Eligible Practice</th>
<th>Subsidy (hectare per year)</th>
<th>Subsidy (acre per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Buffer Zone Tree Planting</td>
<td>$185</td>
<td>$74.87</td>
</tr>
<tr>
<td>2. Sensitive Land Retirement: Expanded Buffer Zone</td>
<td>$185</td>
<td>$74.87</td>
</tr>
<tr>
<td>3. Sensitive Land Retirement: Non Regulated Grassed Headlands</td>
<td>$185</td>
<td>$74.87</td>
</tr>
<tr>
<td>4. Sensitive Land Retirement: High Sloped Land</td>
<td>$150</td>
<td>$60.70</td>
</tr>
<tr>
<td>5. Land Under Soil Conservation Structures</td>
<td>$250</td>
<td>$101.17</td>
</tr>
<tr>
<td>6. Maintaining Livestock Fences Adjacent to Watercourses and Wetlands</td>
<td>$0.30/meter/year</td>
<td>$0.30/meter/year</td>
</tr>
</tbody>
</table>

Source: PEI Department of Agriculture and Forestry (2013b)

2.6 Summary

Chapter 2 has progressed from an explanation of the nitrogen cycle, to nitrate sources and impacts on the environment and human health, and the occurrence of nitrate in Prince Edward Island. The extent of nitrate concentrations in excess of Health Canada’s maximum acceptable concentration is of concern to Island residents for community and ecosystem health. Five BMPs that effectively abate nitrate leachate in groundwater and surface waters have been discussed. These BMPs are: SLR, crop rotation, potato variety, NMP, and spring tillage. PEI Dept. of Agriculture and Forestry offer a variety of incentive-based BMP programs including Agriculture Stewardship Program, Alternative Land Use Services 2, and the Environmental Farm Plan.
Chapter 3: Conceptual Model of Nitrate Leachate Abatement

3.0 Introduction of Chapter

Within potato farming systems the producer may adjust her land management choices at the intensive and extensive margins. Modifying the rate of nitrogen fertilizer application is an intensive land management choice whereas potato variety choice, crop rotation, tillage timing, and sensitive land retirement are extensive land management choices. Nitrogen fertilizer application influences potato crop production, and consequently gross margin, but it also contributes to nitrate leachate, a prominent agricultural diffused pollutant (Yiridoe and Weersink 1998; Zebarth and Rosen 2007). If a target that reduces nitrate leachate from potato farming systems is set, the producer may reallocate her land management choices.

The conceptual framework, illustrated by Figure 3.1, shows the impact of nitrate leachate targets on nitrogen fertilizer application, which follows the structure of Yiridoe and Weersink (1998). Two agricultural producers are differentiated by land quality within the framework; one producer farms on high quality land (HQ) and one producer farms on low quality land (LQ). The HQ producer has a wide selection of crop rotations to produce with on his arable land as opposed to the LQ producer but hydrogeological characteristics between the producers do not differ. Subsequent figures illustrate the individual and social marginal abatement cost and marginal environmental damage functions, as well as cost-effective nitrate leachate abatement between two producers on heterogeneous land.
3.1 Impact on HQ and LQ Producers’ Gross Margins from Nitrate Leachate Regulation

3.1.1 Panel I: Gross Margin ($\pi$) vs. Fertilizer N Rate ($F$)

Potato crop production ($Y$) is a function of the applied fertilizer nitrogen rates, $F$, where $Y = f(F)$ is a production function twice continuously differentiable. Each HQ and LQ producer maximizes gross margin by optimizing the intensive choice of fertilizer N rate subject to the cost of fertilizer nitrogen, $c(F)$, and all other cropping costs, $C$:

$$\pi = \max_F f(F) - c(F) - C$$  \hspace{1cm} (eq. 3.1)

Figure 3.1, illustrates four panels; Panel I illustrates the gross margin function maximized for both HQ and LQ producers. The vertical axis is gross margin in Canadian dollars and the horizontal axis is fertilizer N rate, which increases from left to right. Producer HQ’s optimized gross margin ($\pi^*_\text{HQ}$) is greater than producer LQ’s ($\pi^*_\text{LQ}$) optimized gross margin for all fertilizer N rates. The optimized fertilizer nitrogen rate for HQ producer ($F^*_\text{HQ}$) is greater than producer LQ’s ($F^*_\text{LQ}$).

3.1.2 Panel II: Nitrate Leachate ($N$) vs. Fertilizer Nitrogen Rate ($F$)

In Panel II the vertical axis is nitrate leachate [$N$, (kg NO$_3$-N per hectare)] and the horizontal axis is the fertilizer nitrogen rate ($F$). The fertilizer nitrogen rate applied to potatoes is positively correlated to nitrate leachate, where $N = N(F)$. When nitrate leachate is unregulated and no property rights exist for groundwater, the producer does not consider her nitrate leachate contamination to groundwater as a production cost within her gross margin maximization (eq.3.1). Due to similar hydrogeological characteristics between HQ and LQ producers it is assumed that nitrate leachate is homogeneous, even with differing topographical land quality, the
producers will have the same nitrate leachate production function. The fertilizer nitrogen rate that maximizes gross margin for HQ and LQ producers may be substituted into each producers’ nitrate leachate production function, such as $N_{HQ}^* = N(F_{HQ}^*)$. Given optimized gross margin within Panel I, the associated optimized nitrate leachate for HQ and LQ producers is determined by the nitrate leachate function. The optimized fertilizer nitrogen rate for HQ producer ($F_{HQ}^*$) generates $N_{HQ}^*$ nitrate leachate; the optimized fertilizer nitrogen rate for LQ producer ($F_{LQ}^*$) generates $N_{LQ}^*$ nitrate leachate.

3.1.3 Panel III: HQ Nitrate Leachate ($N_{HQ}$) vs. LQ Nitrate Leachate ($N_{LQ}$)
In Panel III, nitrate leachate for HQ and LQ producers are plotted along a 45-degree line to illustrate the relativity of HQ and LQ producers’ nitrate leachate with and without regulation.

3.1.4 Panel IV: Nitrate Leachate (N) vs. Gross Margin ($\pi$)
Panel IV illustrates gross margin as a function of nitrate leachate. The vertical axis is gross margin ($\pi$) the horizontal axis is nitrate leachate (N). The nitrate leachate production function peaks at each producer’s optimal gross margin, $\pi_{HQ}^*$ and $\pi_{LQ}^*$. This is because potato production as a function of applied fertilizer nitrogen increases, maximizes, and then decreases (Zebarth and Rosen 2007). As the fertilizer nitrogen rate influences the quantity of nitrate leached, this concave pattern is translated to the nitrate leachate production function therefore gross margin along the y-axis increases, maximizes, and then decreases. A rational producer should not apply a fertilizer nitrogen rate greater or less than the gross margin-maximizing rate, $F_{HQ}^*$ and $F_{LQ}^*$. This fertilizer nitrogen rate translates into the gross margin maximizing nitrate leachate for HQ and LQ producers, $N_{HQ}^*$ and $N_{LQ}^*$. HQ producer has greater gross margin and nitrate leachate into groundwater ($\pi_{HQ}^*, N_{HQ}^*$) than LQ producer ($\pi_{LQ}^*, N_{LQ}^*$).
3.1.5 Regulation on Nitrate Leachate ($N^R$)

Regulation may be implemented that restricts the amount of nitrate leachate. If so, HQ and LQ producers must modify the fertilizer nitrogen rate to comply with the regulation. In the unregulated scenario producers will determine fertilizer nitrogen rate to maximize gross margin. Therefore, any regulation that sets a nitrate leachate target, or conversely a nitrate leachate
abatement target, is associated with lower gross margin. With nitrate leachate regulation, each HQ and LQ producer optimizes gross margin:

\[ \pi^R = \text{Max}_F f(F) - c(F) - C + \lambda(N^R - N^*) \]  

(eq. 3.2)

Where \( \lambda \) is the marginal abatement cost of a unit reduction in nitrate leachate. \( N^R \) is the nitrate leachate standard set by regulation and \( N^* \) is the nitrate leachate associated with maximized gross margin, either \( N^*_{HQ} \) or \( N^*_{LQ} \) respective to each producer. The gross margin maximizing fertilizer nitrogen rate \( (F^*_{HQ}, F^*_{LQ}) \) are now a function of nitrate leachate due to the regulation. The fertilizer nitrogen rates are determined by the nitrate leachate function, which is the same for each producer, \( N=N(F) \) in Panel II. Solving the first order conditions of (eq. 3.2) results in the marginal abatement cost function, \( \lambda=\lambda(c(F), N^R) \) (Yiridoe and Weersink 1998).

Regulation \( (N^R) \) reduces nitrate leachate, and consequently fertilizer nitrogen rate, below HQ and LQ producers’ optimal nitrate leachate and reduces optimal gross margins given the regulation, \( \pi^R_{HQ} \) and \( \pi^R_{LQ} \). The difference between unregulated and regulated gross margin maximization \( \pi^*_{HQ} \) and \( \pi^R_{HQ} \) and \( \pi^*_{LQ} \) and \( \pi^R_{LQ} \) are the marginal abatement costs (MAC_{HQ} and MAC_{LQ}). The HQ producer’s gross margins are greater impacted by regulation than those of the LQ producer, \( (\pi^*_{HQ} - \pi^R_{HQ}) > (\pi^*_{LQ} - \pi^R_{LQ}) \) or \( \text{MAC}_{HQ} > \text{MAC}_{LQ} \).

3.2 Nitrate Leachate Marginal Abatement Cost and Marginal Environmental Damage

The marginal abatement cost function can be derived for each producer from the difference between the unregulated and regulated optimized gross margin for each infinite nitrate leachate target, MAC_{HQ} and MAC_{LQ}. Figure 3.2 has two panels illustrating the marginal
abatement cost (MAC\text{HQ} and MAC\text{LQ}) and marginal environmental damage (MED\text{HQ} and MED\text{LQ}) functions of nitrate leachate for each HQ and LQ producer. Within each panel, the vertical axes measure the value of an additional unit of output in Canadian dollars; the horizontal axes have two interconnected measurements. The primary interpretation is the level of nitrate leachate (N\text{LOW}, N\text{HIGH}), which is read low to high from left to right. The second measurement is the level of nitrate leachate abatement (A\text{LOW}, A\text{HIGH}), which is read high to low from left to right.

The marginal abatement cost functions represent the cost of reducing a kilogram nitrate per hectare (kg NO\text{\textsubscript{3}}-N per hectare) from entering groundwater given gross margin optimization. The HQ and LQ producers marginal abatement cost functions (MAC\text{HQ} and MAC\text{LQ}) have an exponential slope because at first costs rise modestly at high levels of nitrate leachate and low levels of abatement (N\text{HIGH}, A\text{LOW}) as producers begin to adopt beneficial management practices but as nitrate leachate is reduced to lower levels the cost of abatement rises rapidly (Field and Olewiler 1995). As topographical land quality is heterogeneous between the HQ and LQ producers, there is heterogeneity between their MACs. The HQ producer’s marginal abatement cost function (MAC\text{HQ}) is greater than the LQ producer (MAC\text{LQ}), which illustrates that the HQ producer will face greater challenges to abate nitrate leachate because the cost of abating one unit of nitrate leachate is greater than the LQ producer.

The marginal environmental damage functions (MED\text{HQ} and MED\text{LQ}) illustrate the relationship between a unit change in nitrate leachate abatement and the resulting change in damages from nitrate leachate. MED\text{HQ} and MED\text{LQ increase only modestly at levels of low nitrate leachate and high abatement (N\text{LOW}, A\text{HIGH}) and more rapidly as the level of nitrate leachate increases, or conversely as the level of nitrate abatement decreases (Field and Olewiler}}
1995). As discussed above in Section 3.1.2 Panel II: Nitrate Leachate (N) vs. Fertilizer Nitrogen Rate (F) it is assumed that nitrate leachate is homogeneous between the HQ and LQ producers, and therefore \( \text{MED}_{\text{HQ}} \) and \( \text{MED}_{\text{LQ}} \) have the same characteristics.

The individual efficient level of nitrate leachate (nitrate abatement) for the HQ and LQ producer occurs where each producer’s marginal environmental damage and marginal abatement cost functions equate; there exists no further mutually beneficial trades to occur (Field and Olewiler 1995). The HQ producer’s efficient nitrate leachate is greater than the LQ producer’s efficient nitrate leachate, \( N^{**}_{\text{HQ}} > N^{**}_{\text{LQ}} \). Conversely, the HQ producer achieves lower abatement than the LQ producer \( A^{**}_{\text{HQ}} < A^{**}_{\text{LQ}} \). At these efficient nitrate leachate and abatement levels marginal environmental damages and marginal abatement costs exactly offset each other and are equal to the prices, \( p(N^{**}_{\text{HQ}}) \) and \( p(N^{**}_{\text{LQ}}) \).

Figure 3.2: HQ and LQ Producers’ Individually Efficient Nitrate Leachate and Nitrate Leachate Abatement
3.3 Total Nitrate Leachate Marginal Abatement Cost and Marginal Environmental Damage

Assuming the HQ and LQ producer are the only producers within the watershed market, Figure 3.3 illustrates the aggregate marginal abatement cost (MAC) and aggregate marginal environmental damage (MED) functions of nitrate leachate and conversely nitrate abatement. The aggregate MAC and MED are derived from the horizontally summed MAC_{HQ} and MAC_{LQ} as well as the MED_{HQ} and MED_{LQ}. The vertical axis measures the value of an additional unit of output in Canadian dollars. The horizontal axis has two interconnected measurements. The primary interpretation is the level of nitrate leachate (N_{LOW}, N_{HIGH}), which has been summed across HQ and LQ producers’ nitrate leachate; this is read low to high from left to right. The second measurement is the nitrate leachate abatement, which has been summed across HQ and LQ producers; this read high to low from left to right (A_{HIGH}, A_{LOW}).

When property rights for groundwater or regulation to protect groundwater are absent producers have no incentive to adopt abatement practices; this is N_{HIGH} within Figure 3.3 where producers have very high MEDs and zero MACs. When full property rights exist for groundwater to ensure producers internalize all production costs, including the external cost of nitrate leachate, the socially efficient level of nitrate leachate (nitrate abatement) will occur.

The socially efficient level of nitrate leachate (N^{**}) and consequently nitrate abatement (A^{**}) occurs where aggregate marginal environmental damages equate to aggregate marginal abatement costs. At this socially efficient equilibrium, neither the marginal abatement cost nor the marginal environmental damage from an additional unit of nitrate leachate exposed to Prince Edward Island residents has greater value for ecosystem or human health.
When the value of nitrate leachate damage to the environment cannot be estimated, a cost-effective analysis of nitrate leachate and nitrate leachate abatement level is an alternative method. Nitrate leachate abatement is deemed cost-effective when the producer, or producers, achieve a given environmental quality target, nitrate leachate abatement, at the least cost (Field 1994a; Field and Olewiler 2005b).

To achieve cost-effective nitrate leachate abatement between two producers, the equimarginal principle may be applied. The equimarginal principle states that given a nitrate leachate or nitrate leachate abatement target production will be distributed such that marginal abatement costs are equalized between producers to minimize total abatement cost (Field 1994b). Therefore, nitrate leachate abatement allocation will be distributed between the HQ and LQ.
producers such that their marginal abatement costs equate to minimize total abatement cost (Field and Olewiler 2005a; 2005c).

Figure 3.4 illustrates the heterogeneity between the HQ and LQ producers’ marginal abatement cost functions. The vertical axes are the value of an additional unit of output in Canadian dollars. The primary interpretation of the horizontal axis is nitrate leachate abatement. For the HQ producer, nitrate abatement is read high to low from left to right. For the LQ producer, nitrate abatement is read low to high from left to right.

Marginal abatement costs equate between HQ and LQ producers at $A^{C_{HQ}}$ and $A^{C_{LQ}}$ where the HQ producer abates from $[A^{LOW}_{HQ}]$ to $A^{C_{HQ}}$ and the LQ producer abates from $[A^{LOW}_{LQ}]$ to $A^{C_{LQ}}$. Given the LQ producer’s lower MAC function, she abates a greater amount of nitrate leachate when the equimarginal principle is applied. Additionally, Figure 3.4 is helpful in illustrating regulations that impose homogenous versus heterogeneous nitrate abatement targets on HQ and LQ producers. If regulators suggest the HQ and LQ producers abate a homogenous amount of nitrate leachate ($A^{U_{HQ}}$ and $A^{U_{LQ}}$) then the HQ producer will have higher total abatement costs than the LQ producer (Field and Olewiler 2005a; 2005c). If regulators recognize that producers do not have the homogenous MACs then heterogeneous abatement is more efficient and less costly by abating at the equimarginal principle allocation, $A^{C_{HQ}}$ and $A^{C_{LQ}}$ (Field and Olewiler 2005a; 2005c).
Figure 3.4: Nitrate Leachate Abatement for Two Producers with Heterogeneous MACs

Figure 3.5 also illustrates cost-effect abatement with two different nitrate leachate abatement targets, Abatement Target 1 and Abatement Target 2, as well as the marginal abatement costs for the producer on high quality land and the producer on low quality land, MAC_{HQ} and MAC_{LQ}. Abatement Target 1 intersects both the MAC_{HQ} and MAC_{LQ}, therefore there are potato farming systems that are feasible for the producers to adopt. Neither the producer on high quality nor low quality land would select the potato farming system at any point other than where Abatement Target 1 intersects MAC_{HQ} or MAC_{LQ}, either triangle. The potato farming system represented by the black square has a higher marginal abatement cost compared to either potato farming system represented by the triangles. The producer on low quality land can achieve Abatement Target 1 at a lower cost than the producer on high quality land. Abatement Target 2 intersects neither
MAC_{HQ} nor MAC_{LQ}. Therefore, Abatement Target 2 is unfeasible for producers on high and low quality land.

![Diagram showing cost-effective nitrate leachate abatement for two producers with heterogeneous MACs]

**Figure 3.5: Cost-effective Nitrate Leachate Abatement for Two Producers with Heterogeneous MACs**

### 3.5 Incentive Instruments for Heterogeneous Marginal Abatement Costs

Given heterogeneous factors, a potentially beneficial abatement regulation would be to implement a water quality market, such as a reverse emission reduction credit auction or an abatement action points trading system, that capitalizes on the heterogeneous nature of producers’ marginal abatement costs as opposed to uniform schemes such as voluntary adoption programs that pay for beneficial management practice adoption (Kling 2011; Shortle 2012).

Literature has identified that, as opposed to traditional policy instruments, water quality markets
encourage the reallocation of nitrate reduction to agricultural producers who have greater abatement cost-efficiency (Horan and Shortle 2011). Three fundamental design pillars of water quality markets are suggested: the commodity to be traded, rules of exchange, and the environmental target (Horan and Shortle 2011). Yet, analyses of water quality markets in practice identify that regardless of how closely a market’s design resembles a free-market, the most successful in achieving water quality targets have been markets that capitalize on the characteristics of the agricultural community (Shortle 2013). Notable characteristics have been trust and communication between the implementing agency and participants as a result of historical beneficial management practice adoption programs.

The significant potential of an implementable water quality market in Prince Edward Island is notably due to three prominent characteristics of its agricultural community. Firstly, farm sizes are constrained by the scarcity of land in Prince Edward Island, and therefore agricultural producers are familiar with other producers in their community due to the close proximity of neighbouring farms. Secondly, through a variety of cost-share and direct payment programs for beneficial management practice adoption the Prince Edward Island Department of Agriculture and Forestry has developed trust and communication with many producers on the Island. Lastly, the issue of nitrate in groundwater is magnified due to agricultural production and residents co-existing on constrained land, which results in heightened public concern and awareness. Given this, producers may be willing to participate in water quality markets to mitigate negative public perceptions of their production practices. Therefore, given these three factors, the transaction costs to implement a water quality market on the Island for potato producers may have low transaction costs.
3.6 Summary

This chapter discusses the conceptual model of nitrate leachate applicable to Prince Edward Island potato farming systems by first looking at the intensive choice of fertilizer nitrogen application to the potato crop and its affect on gross margin as well as nitrate leachate. The impact of regulation or nitrate leachate targets is applied to illustrate marginal abatement costs. This foundation of knowledge that illustrates a producer’s internal farming system choice, is then applied to a two-producer model, one with HQ land and the other with LQ land, and their marginal abatement cost and marginal environmental damage functions of nitrate leachate and conversely nitrate leachate abatement. This two-producer watershed model illustrates the socially optimal allocation of nitrate leachate and nitrate leachate abatement. Although, when the ability to estimate marginal environmental damages is insufficient, cost-effective analysis using the equimarginal principle is applied.

The significant take away that motivates subsequent chapters and economic-hydrologic modeling of nitrate leachate abatement is that given differences in land quality, heterogeneous marginal abatement costs result. Therefore, the cost-effective allocation of nitrate leachate and conversely abatement will also differ. This suggests abatement regulation and policy instruments will be more efficient if heterogeneity is considered as opposed to uniform abatement regulations.
Chapter 4: Incentivizing Beneficial Management Practice Adoption to Improve Groundwater Quality in PEI: An Economic – Hydrologic Modelling Approach

4.1 Introduction

The Canadian province of Prince Edward Island (PEI) has a unique ecological and economic dependence on water quality, which is affected directly by the agricultural systems used. PEI residents rely solely on groundwater as their source of drinking water and groundwater contributes approximately 70% to the surface water of streams, rivers, and estuaries (Benson et al. 2007; Jiang and Somers 2009). Approximately 54% of PEI residents are served by private well systems with the remainder served by municipal distribution systems, both sourced from groundwater (Council of Canadian Academies 2009a). These groundwater and surface waters on the Island have been contaminated with Nitrate (NO$_3^-$) and subsequently Nitrate-Nitrogen (nitrate-N, NO$_3^-$-N). Of these residential wells within intensive farming watersheds, 20% exceed Health Canada’s maximum acceptable nitrate-N concentration of 10 milligrams per litre (mg/L NO$_3^-$-N), or 45 mg/L as nitrate (mg/L NO$_3^-$) (Jiang and Somers 2009; Health Canada 2012). Additionally, surface water nitrate-N concentrations have increased steadily since 1966 (PEI Dept. of Environment, Labour and Justice 2014).

Nitrate contaminated groundwater is of concern because of its ability to deteriorate surface and aquatic ecosystems’ quality due to nutrient enrichment leading to algae blooms and hypoxic and anoxic events. Such events can cause fish kills and other aquatic deaths that cause economic losses to the sport fishing tourism sector as well as commercial fishing and shellfish industries (Government of PEI 2008). Additionally, nitrate contaminated drinking water poses serious threats to human health as it can block the oxygen carrying capacity of haemoglobin, causing methaemoglobinaemia also known as “blue baby syndrome” (Camargo et al. 2005;
Davidson et al. 2012; Council of Canadian Academies 2009b). It also has a potential role in developing cancers of the digestive tract (Camargo et al. 2005; Davidson et al. 2012).

The reliance on the quality of groundwater in PEI by ecosystems and residents coexists within an intensive agricultural sector that is economically important to the province. Potatoes (Solanum tuberosum L.) are grown on over 15% of the 1.4 million acre land base and the crop generates over three-quarters of the total cash receipts from this cropland (PEI Dept. of Agriculture and Forestry 2014c; Statistics Canada 2012; 2014a; 2014b). The heavy reliance of nitrogen for this high-value crop grown on the sandy soils of PEI has resulted in significant groundwater nitrate contamination (Rourke 1985).

The concern surrounding groundwater and surface water nitrate contamination and the role of potato farming systems in the increasing contamination rates was highlighted by the Government of PEI’s The Report of the Commission on Nitrates in Groundwater (Government of PEI 2008). A consequence of the report was the implementation of the Agricultural Crop Rotation Act, which restricted potatoes to be grown no more frequently than once in three years and not on land with a slope greater than 9% (PEI Dept. of Agriculture and Forestry 2013a). Other beneficial management practices (BMPs) that reduce nitrate leachate and soil erosion have been identified and efforts made to encourage adoption but little is known on their cost-effectiveness (Lantz et al. 2009).

The concern of nitrate leachate in surface water and groundwater has attracted the attention of physical scientists such as hydrogeologists and agronomists to research the impact of agricultural land management practices on nitrate leachate using hydrologic modelling techniques (Benson et al. 2006, 2007; Jiang and Somers 2009). Yet, the economic analyses of the adoption of BMPs and how to incentivize these practices in PEI have become secondary to
hydrologic modelling as the confidence and reliance on the method has strengthened. Literature that integrates hydrologic modelling with economics using linear programming to assess agricultural land management practices on nitrate leachate in PEI has studied potato crop rotations, tillage treatment, and surface residue post potato harvest (Jatoe 2008). For non-PEI focused studies, the effect on nitrate leachate from the adoption of tillage treatment and crop rotations for potatoes and non-potato crops have been modelled through linear programming (Amon-Armah *et al.* 2013), as well as nitrification inhibitors for dairy systems using non-linear programming (Doole and Paragahawewa 2011). Alternatively, the value of the benefits resulting from a reduction of nitrates in groundwater resulting from decreased nitrogen fertilizer applications for Southern Ontario was estimated by Giraldez and Fox (1995). Partial budget analysis using net present value and break-even analyses have also been used to evaluate buffer strips, nutrient management planning, cover crops, and controlled drainage to reduce nitrate-N pollution for tobacco rotations (Wossink and Osmond 2002). A recent advancement in integrated hydrologic–economic modelling techniques is the use of evolutionary algorithms. Simulation-optimization framework to solve for cost-efficient and spatial allocations of nitrogen abatement BMPs such as conservation tillage, buffer strips, grassed waterways, reduced fertilizer, and agricultural land retirement in Iowa (Rabotyagov *et al.* 2010).

Although there have been varied methods to address beneficial management practice (BMP) adoption to reduce nitrate leachate in the literature, there lacks integrated economic–hydrologic optimization models that consider non-traditional BMPs such as potato varieties, spring tillage, combined with nutrient management planning, sensitive land retirement and crop rotations. The economic–hydrologic model featured in this thesis provides a unique analytical perspective on groundwater nitrate contamination abatement in PEI potato systems. This chapter
continues with a description of the research site, materials and methods of the economic–hydrologic optimization model followed by the results, discussion, and concluding remarks.

4.2 Materials and Methods

4.2.1 Land Quality within the Research Area

The coastline of PEI is about 1,000 miles with bays and the outlets of streams mixing to estuaries. The surface of the Island is flat to moderately undulating with the highest above sea level point at 500 feet (Whiteside 1965). The bedrock from which most soils on the Island are derived is composed of mostly sandstone, and these soils are typically a deep red colour due to the presence of iron compounds (Whiteside 1965). Alberry and Charlottetown are the soil series that overlay the bedrock in the study area. Both soils are of moderately coarse texture, strongly acidic, with good surface drainage and imperfect subsoil drainage, and susceptible to erosion (Soil Research Institute 1966). Although the fertility level of these soils is low, both respond well to good management and applications of fertilizer (Whiteside 1965). However, the high permeability due to the porous nature of the overburden combined with high horizontal and vertical fracture frequencies as well as high fracture permeability of the upper portion of the aquifer in PEI, leads to a greater probability of contaminants quickly moving from the surface into the bedrock and into the upper aquifer (Francis 1981 via O’Connor 2014). The high permeability of the soil and bedrock combined with intensive fertilizer use for agriculture makes Prince Edward Island’s groundwater very susceptible to nitrate contamination.

There are two types of arable land that a potato farming system may be produced on, high quality (HQ) and low quality (LQ) land, which are considered within this research. The PEI
Agricultural Crop Rotation Act (PEI ACRA) affects which potato crop rotations high and low quality land producers may adopt.

4.2.2 Prince Edward Island Agricultural Crop Rotation Act

The Prince Edward Island Agricultural Crop Rotation Act (PEI ACRA) was implemented to reduce soil erosion and indirectly nitrate leachate, as discussed in Chapter 2 Section 2.5.2 Crop Rotation and Prince Edward Island Agricultural Crop Rotation Act. Previous to implementation an Island producer could adopt any potato crop rotation she desired that maximized gross margin. PEI Agricultural Crop Rotation Act (PEI ACRA) ensures maintenance of ecological goods and services by restricting crop rotations, specifically potato crop rotations, to 1-in-3 potato crop rotations or to any crop rotation on land with spatial factors that generate annual soil erosion no greater than 7.4 metric tonnes (MT) per hectare, which is determined by the Revised Universal Soil Loss Equation by the PEI Dept. of Agriculture and Forestry and the PEI Dept. of Environment, Labour and Justice (PEI Dept. of Agriculture and Forestry 2015c). The Revised Universal Soil Loss Equation considers spatial factors such as slope incline, slope length, and soil quality in addition to the land management practices adopted by the producer (PEI Dept. of Agriculture and Forestry 2015c).

Within the economic – hydrologic model, for producers on high quality land, it is assumed the implementation of the PEI ACRA restricts the adoption of the 1-in-2 potato crop rotation potato-barley (P,B) due to spatial factors that generate soil erosion greater than 7.4 MT per hectare. It is assumed for producers on low quality land, the PEI ACRA restricts the adoption of the 1-in-2 potato crop rotation potato-barley (P,B) as well as the 2-in-5 potato crop rotations potato-barley-potato-soybean-barley (P,BP,SB) and potato-barley-potato-barley underseeded...
with hay-hay (P,BP,BH) due to spatial factors that generate soil erosion greater than 7.4 MT per hectare.

Heterogeneous land quality combined with the PEI ACRA affects the adoption of crop rotations, which causes marginal nitrate leachate abatement costs to be heterogeneous between producers within the economic – hydrologic optimization model. There are three conditions that are successively applied to the economic – hydrologic optimization model that affect gross margin and nitrate leachate abatement: Base Potato Farming System, PEI ACRA, and Nitrate Leachate Abatement Targets under PEI ACRA.

4.2.2.1 Base Potato Farming System Conditions
For both producers on high quality and low quality land, in the absence of the PEI ACRA, gross margin is optimized subject to structural constraints, as discussed in Section 4.2.8 Empirical Economic – Hydrologic Optimization Model. There are no restrictions on the crop rotations available for adoption, which the PEI ACRA condition imposes. For both high and low quality land producers, the Base Potato Farming System is optimized from nine crop rotations and 72 potato farming systems. The economic – hydrologic optimization model given the Base Potato Farming System conditions has greatest number of potato farming systems and therefore can achieve the highest gross margin.

4.2.2.2 Prince Edward Island Agricultural Crop Rotation Act Conditions
The PEI ACRA condition imposes the potato crop rotation restrictions assuming the PEI ACRA is implemented, as discussed in Section 4.2.2 Prince Edward Island Agricultural Crop Rotation Act. The PEI ACRA conditions reduce the set of potato crop rotations available for adoption by
high and low quality land producers. For the producer on high quality land, the *PEI ACRA* restricts the adoption of the potato-barley (P,B) crop rotation; the number of potato farming systems falls from 72 to 64. For the producer on low quality land, the *PEI ACRA* restricts the adoption of the potato-barley (P,B) crop rotation as well as the 2-in-5 potato crop rotations; the number of potato farming systems falls from 72 to 48.

4.2.2.3 *Nitrate Leachate Abatement Targets under PEI ACRA Conditions*  
Assuming the *PEI ACRA* conditions are imposed on both high and low quality land producers, further nitrate leachate abatement targets are constrained within the economic – hydrologic optimization model to estimate the nitrate leachate marginal abatement costs for adopting beneficial management practices such as crop rotation, Prospect potato variety, nutrient management planning, spring tillage, and sensitive land retirement.

4.2.3 *Nitrate Leachate within the Research Area*  
Nitrate (NO$_3^-$) and subsequently nitrate-N (NO$_3^-$-N) are the dominant species of nitrogen in the water environment. For simplicity, for the remainder of this thesis the term “nitrate” refers to nitrate-nitrogen (NO$_3^-$-N) unless explicitly stated otherwise. Nitrate (NO$_3^-$-N) may be measured by mass in kg per hectare (kg NO$_3^-$-N per ha) or concentration in milligrams per Litre (mg/L NO$_3^-$-N). When discussing drinking water thresholds and human consumption, mass is translated to concentration by volume in milligrams per Litre; this is convention that aligns with Health Canada’s maximum acceptable nitrate concentration drinking water threshold of 10 mg/L NO$_3^-$-N.
The Kensington North Watersheds Associations’ *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River* (Jiang 2013) is the source of nitrate leachate abatement and nitrate leachate data used within the economic – hydrologic model in this research. Specialists at Agriculture and Agri-Food Canada, PEI Department of Environment, Labour & Justice, and the PEI Department of Agriculture and Forestry contributed to the estimation of this data (Jiang 2013). The research area is a 157 hectare potato farm within the Kensington North Watersheds area, which is on the northern side of the Island (Figure 4.1). The nitrate leachate abatement data was estimated for three sub-watersheds within the Kensington North Watersheds area: Southwest River, Tuplin Creek and Durant Creek (Jiang 2013). The total land area of the three sub-watersheds is 3,865 hectares of which 2,937 hectares is agriculture with the remaining land in forest, developed, or wetland area (Jiang 2013).

Within the three sub-watersheds of the Kensington North Watersheds area average nitrate concentrations in private residential wells average from 4.62 to 5.45 mg/L NO$_3^-$-N. Yet, concentrations range between 7.5 and 13.2 mg/L NO$_3^-$-N illustrating residential wells do indeed exceed Health Canada’s drinking water threshold of 10 mg/L NO$_3^-$-N causing concern for health risks associated with ingesting high concentrated nitrate water (Jiang 2013). See *Chapter 2 Section 2.3 Effects of Nitrate in the Environment* for further discussion of the effects of nitrate in groundwater, surface water, and drinking water.

The current annual nitrate loading that aligns with the Base Potato Farming System optimization is 22.5 kg NO$_3^-$-N per hectare or translated to a nitrate concentration of 5.63 mg/L NO$_3^-$-N. This current nitrate loading aligns with four to five anoxic events every five years and 14% of residential wells exceeding Health Canada’s drinking water threshold of 10 mg/L NO$_3^-$-N (Jiang 2013). The Kensington North Watersheds Association’s annual target load is 16.34 kg
NO₃⁻-N per hectare or translated to a nitrate concentration 4.09 mg/L NO₃⁻-N (Jiang 2013). Physical specialists on the Island who contributed to the Kensington North Watersheds Associations’ *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River* determined this annual target nitrate leachate load. It was set to achieve a reduction in anoxic events to 2.4 anoxic events every five years and a reduction to only 4.7% of residential groundwater wells exceeding 10 mg/L NO₃⁻-N (Jiang 2013).

For the research area of 157 hectares of arable land, the economic – hydrologic model optimizes gross margin and nitrate leachate abatement for farming system $i$ from the current nitrate leachate load for producers on low quality and high quality land. The economic – hydrologic optimization model uses the beneficial management practices and their nitrate leachate abatement coefficients presented within the Kensington North Watersheds Associations’ *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River* to estimate gross margin given varying nitrate abatement targets. Given this, I am able to compare the target nitrate leachate load, or conversely the nitrate leachate abatement required to achieve the target nitrate leachate load, to feasible potato farming systems estimated by the economic – hydrologic model.
4.2.4 Specification of Potato Farming Systems

Nitrate contamination of groundwater is assumed to be influenced primarily by five land management choices available to a potato producer on high and low quality land: (1) total arable land in crop production (2) crop rotation, (3) potato variety, (4) nutrient application rates, and (5) tillage. Each of the five land management choices has an option to adopt the beneficial management practice (BMP) that effectively abates nitrate leachate. To optimize gross margin, the producer proceeds through the decision framework by first selecting to allocate land to crop production or sensitive land retirement, and if crop production then a potato crop rotation is selected. Within the potato crop rotation Russet Burbank (P_{RB}) and/or Prospect (P_{P}) potato
variety is selected. Once the potato variety is selected, the producer selects the fertilizer nitrogen rate, Grower Standard Program (GSP) and/or Nutrient Management Planning (NMP). Finally, fall tillage ($T_F$) and/or spring tillage ($T_S$) for the potato variety is selected. Table 4.1 lists the prices, variable production costs, and yields by crop rotation that are discussed in subsequent sections.

The total amount of arable land can be allocated to either crop production or retired as sensitive land. The *Alternative Land Use Services 2* (PEI Dept. of Agriculture and Forestry 2013b, 2013c) land management payment program classifies three types of agricultural land as eligible for sensitive land retirement: grassed headlands greater than 200 meters from watercourses or bufferable wetlands, agricultural land adjacent to riparian buffers, and land greater than one hectare with a slope 9% or larger (PEI Dept. of Agriculture and Forestry 2013b, 2013c). A producer can receive a fixed value of $150 per hectare per year for the latter and $185 per hectare per year for the former two types of sensitive land, an average of $173 per hectare per year (PEI Dept. of Agriculture and Forestry 2013b). In addition to improving wildlife habitat and reducing soil erosion, the set aside of ecologically fragile land may improve water quality through reduced nitrate leaching and runoff (Jiang 2013).

Within the empirical model, only one year of the crop rotation is estimated but it is assumed that a producer’s crop rotation choice remains constant over the entirety of the crop rotation. Therefore, total arable land is divided equitably to each crop given their relative share within the crop rotation. Herein after the term “crop rotation” is used to represent this one-year snapshot. On the Island potatoes may be grown in rotation with field crops such as barley, grasses, legumes, wheat, oats, or corn (PEI Dept. of Agriculture and Forestry 2014h). Within the economic – hydrologic optimization model in addition to potatoes rotation crops include
soybean, barley, barley underseeded with hay, and hay (PEI Dept. of Agriculture and Forestry 2014g); these rotations are considered typical for potato farming systems on the Island based on discussions with specialists (PEI Dept. of Agriculture and Forestry 2014g).

Nine crop rotations, all of which include potatoes on 25% to 50% of total arable land in crop production, are considered and listed in Table 4.1. As discussed in Section 4.2.2 Prince Edward Island Agricultural Crop Rotation Act (PEI ACRA), potatoes are regulated to a 1-in-3 crop rotation to achieve a maximum of 7.4 MT per hectare per year of soil erosion. The potato producer may adopt a crop rotation with greater potato frequency if the land’s spatial factors do not let soil erosion exceed the 7.4 MT per hectare per year (PEI Dept. of Agriculture and Forestry 2013a; PEI Dept. of Agriculture and Forestry 2015c).

The inclusion of hay within a rotation increases the soil organic matter by adding carbon and nitrogen as well as breaking pest cycles thereby positively contributing to potato yields (Jiang 2014; Watts 2015a). Soybeans fix nitrogen but provide little organic matter back into the soil, which consequently reduces soil organic matter, leaving soils dry and decreasing yields of other crops within a rotation (Jiang 2014; Watts 2015a). Crop rotations are ranked by considering non-potato crops’ affects on potato yields (Watts 2015c). Table 4.1 illustrates the available potato crop rotations within the economic – hydrologic model under the Base Potato Farming System conditions and their associated yields.

Within each of the nine crop rotations, two potato varieties are available for a producer to select: Russet Burbank (P_{RB}) and Prospect (P_{P}). The Russet Burbank is the traditional variety grown in PEI due to its processing characteristics and makes up approximately 60% of all potatoes grown (Coffin 2014; PEI Potato Board 2014c). Prospect is a proprietary variety of Cavendish Farms that provides similar desired characteristics for processing as the Russet
Burbank (Cavendish Farms 2012; Coffin 2014). The Prospect matures earlier as well as has lower susceptibility to sugar ends and Verticillium, which are favourable characteristics for processing (Coffin 2014).

Both Russet Burbank and Prospect potato varieties are applied with nitrogen (N) fertilizer. The producer may select the standard N fertilizer rates, grower standard practice (GSP) or the rates from a Nutrient Management Plan (NMP). Under NMP, applied fertilizer fills the difference between organic soil nutrients and crop fertility requirements based upon crop uptake, nutrient supply within the soil, risks of nutrient loss, and field operation logistics (Canadian Fertilizer Institute n.d. (a)). The GSP rates are assumed to be higher than those under NMP as many farmers apply more than the recommended rate as a risk insurance measure (Rajsic and Weersink 2008). Although some NMP trials in PEI have maintained comparable or exceeded potato yields under GSP (Canadian Fertilizer Institute n.d. (b)), Rajsic and Weersink (2008) find this over-application strategy under GSP to pay off over time. In years with favourable climatic conditions, the benefits of enhanced yields are greater than the cost of the excess fertilizer applied in the other years (Rajsic and Weersink 2008). Yields are adjusted to reflect the difference between GSP and NMP management systems and discussed below in Section 4.2.5 Estimation of Land Management Practices on Potato Farming Systems.

The final management practice influencing nitrate contamination levels is tillage timing. Typically, arable land is tilled after the forage crop is harvested in the fall but an alternative is to delay tillage until the spring. Spring tillage eliminates bare fields over the winter and retains soil nitrogen from the preceding crop, which may reduce the nitrogen fertilizer input required for the following crop and therefore reduce nitrate leaching during the potato phase (Jiang et al. 2014; Lantz et al. 2009). Climatic conditions across years may also affect tillage systems. While potato
and soybean crop yields are similar under fall and spring tillage in good growing conditions (Jiang et al. 2014), the advantage of fall tillage is that it reduces the amount of time required to prepare the seedbed in the spring and lowers the probability of diseases such as wireworm (PEI Dept. of Agriculture and Forestry 2014i). If a late spring delays the seed planting past the first week of June the majority of producers are likely to recapture yield loss by pushing their growing season and delaying harvest till early November (PEI Dept. of Agriculture and Forestry 2014i). Consequently, a late spring is only a small annoyance to producers who can extend their season. A yield penalty is applied to proxy for the inconvenience and higher probability of disease due to spring tillage.

Figure 4.2. Economic Decision Framework of a PEI Potato Producer. Where Russet Burbank (P_RB), Prospect (P_P), Grower Standard Program (GSP), Nutrient Management Planning (NMP), Fall Tillage (T_F), Spring Tillage (T_S).

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Table 4.1: Prices, Variable Production Costs, and Yields by Crop Rotation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Russet Burbank (P_{RB})</th>
<th>Prospect (P_{Pr})</th>
<th>Barley (B)</th>
<th>Barley underseeded Hay (B_{H})</th>
<th>Soybean (S)</th>
<th>Clover-Timothy Hay (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price ($/MT)</td>
<td>$227</td>
<td>$198</td>
<td>$226</td>
<td>$226</td>
<td>$488</td>
<td>$0</td>
</tr>
<tr>
<td>Variable Cost ($/ha)</td>
<td>$3,961</td>
<td>$4,401</td>
<td>$615</td>
<td>$583</td>
<td>$855</td>
<td>$544</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yields by Crop Rotation (MT per hectare)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Yields</td>
</tr>
<tr>
<td>P_{RB}HH</td>
</tr>
<tr>
<td>P_{RB}BH</td>
</tr>
<tr>
<td>P_{RB}BPBH</td>
</tr>
<tr>
<td>P_{RB}BSBH</td>
</tr>
<tr>
<td>P_{RB}SB</td>
</tr>
<tr>
<td>P_{RB}SH</td>
</tr>
<tr>
<td>P_{RB}BB</td>
</tr>
<tr>
<td>P_{RB}B</td>
</tr>
<tr>
<td>P_{RB}SB</td>
</tr>
</tbody>
</table>

Notes:
(1) If a crop is not within the crop rotation specified it is not assigned a yield, therefore yield is 0.

4.2.5 Estimation of Land Management Practices on Potato Farming Systems

A total of 72 farming systems are considered for land that is cropped: nine rotations multiplied by two potato varieties multiplied by two fertilizer application rates multiplied by two tillage systems. Figure 4.2 illustrates the decision framework for the producer of potato systems.

Crop rotations are ranked by considering non-potato rotation crops’ affects on potato yields and soil quality, and listed within Table 4.1 (Watts 2015c). The inclusion of hay increases soil organic matter and yields, while soybeans have the opposite effect (Watts 2015a). Base yields are set to the predominant potato farming system in PEI, potato-hay-hay (P_{RB}HH). A cumulative and linear 1% reduction is applied to crop yield as the crop appears within the potato crop rotation ranking. From the potato crop rotations considered within the model, potato-hay-
hay (P,HH) produces the highest yields while potato-soybean-barley (P,SB) produces the lowest yields (Watts 2015c).

The Russet Burbank base yield is the 2005 to 2012 average (PEI Dept. of Agriculture and Forestry 2014j), while the Prospect base yield is based upon producers’ budget figures from the PEI Potato Board (2015). The barley base yield is the 3-year average yield from a Harrington, PEI research site whereas the barley underseeded with hay base yield is from the PEI Dept. of Agriculture and Forestry (2014a; 2015a). The soybean base yield is from AgriAlliance’s and PEI Dept. of Agriculture and Forestry’s Cost of Production for Rotational Crops (PEI Dept. of Agriculture and Forestry 2012). Hay, a clover-timothy forage mix, base yield is from Agriculture and Agri-Food Canada (2002) via PEI Dept. of Agriculture and Forestry (2014k) although the crop is not harvested to be sold but plowed down to enhance soil organic matter through nitrogen additions.

The two varieties of potatoes, Russet Burbank and Prospect, differ in terms of price, yield, nitrogen fertility requirement, and seed cost. Russet Burbank receives a greater price ($227/MT vs. $198/MT) but is lower yielding (29.5 vs. 33.3 MT/hectare) than Prospects (PEI Potato Board 2014b, 2015; PEI Dept. of Agriculture and Forestry 2014j). Prospect requires less nitrogen (151 vs. 207 kg N/hectare) and therefore a lower fertilizer expense (PEI Dept. of Agriculture and Forestry 2014j). However, Prospect has a higher seed cost than Russet Burbank (PEI Potato Board 2015a). For comparison, the revenue from Russet Burbank and Prospect potatoes given the base yields are $6,702 and $6,605 per hectare, respectively.

In addition to crop rotation, yields are further adjusted to reflect the amount of nitrogen fertilizer applied. NMP recommends rates sufficient to meet the requirements of the crop given soil nutrients. However, as discussed above in Section 4.2.4 Specification of Potato Farming
Systems, producers may apply greater than recommended rates of fertilizer as a risk insurance measure (Rajsic and Weersink 2008). The GSP fertilizer rates for Russet Burbank and Prospect are 225 and 179 kg N per hectare (Watts 2015b). The PEI Dept. of Agriculture and Forestry (PEI Dept. of Agriculture and Forestry 2014j) NMP program recommends 207 and 151 kg N per hectare for Russet Burbank and Prospect, respectively. The NMP rate for Russet Burbank and Prospect involves 17.8% and 15.6% less fertilizer than the GSP and decreases yields by 20% based on the results of Rajsic and Weersink (2008) for corn. Potato fertilizer cost is estimated using two factors: the first is a 13-20-20 fertilizer mix applied at 1,233 kg per hectare (Cavendish Farms 2015), which translates into 160 kg N per hectare application rate at a cost of $641 per MT. To fill the remaining N required by GSP and NMP a 34-0-0 ammonium nitrate fertilizer cost of $1.52 per kg N cost is used (Dept. of Agriculture and Forestry 2015b). For the Prospect NMP cost, a per unit fertilizer cost was calculated and applied to Prospect’s recommended nutrient rate. Table 4.2 illustrates the GSP and NMP rate production costs.

The mechanical cost of tillage remains the same between spring and fall but to proxy for the inconvenience cost of spring tillage and higher probability of disease that threatens the potato crop, a yield penalty of 5 MT per hectare is applied to potato crops under the spring tillage system (PEI Potato Board 2014a). The yield penalty represents a 17% and 15% decline in yields for Russet Burbank and Prospect, respectively. The yield penalty was estimated using the lost yield per week if a delayed spring was to occur, given the growing season is fixed from year to year (PEI Potato Board 2014a). Although it is unlikely a producer faces this yield loss, as they tend to extend their growing season in the fall, it provides an estimate to proxy for spring tillage.

When both applied fertilizer and tillage treatments are considered within the model, the combined yield affect is the summation of percentage reductions given the treatment. For
example, if the model selects GSP and spring tillage for Russet Burbank the associated yield will have 0% reduction from GSP and 17% reduction on yield per hectare from spring tillage, for a total reduction on Russet Burbank yield within the respective crop rotation of 17%.

Table 4.2: Effects of Fertilizer and Tillage Timing on Rotation

<table>
<thead>
<tr>
<th>Fertilizer Rate</th>
<th>Nutrient Management Planning (NMP)</th>
<th>Tillage Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grower Standard Program (GSP)</td>
<td>Fall</td>
<td>Spring</td>
</tr>
<tr>
<td>PRB</td>
<td>PP</td>
<td>PRB</td>
</tr>
<tr>
<td>Fertilizer N Rate</td>
<td>252</td>
<td>179</td>
</tr>
<tr>
<td>Yield Reduction</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Variable Cost</td>
<td>$930</td>
<td>$820</td>
</tr>
</tbody>
</table>

4.2.6 Prices and Costs of Production for Potato Farming Systems

Individual crop prices and production costs are listed in Table 4.1. The price received by contracted producers for potatoes graded as number ones varies depending on whether the potatoes are delivered straight to processing plants from the field for Fall contracts, or from grower storages for Winter contracts (PEI Potato Board 2014b). Producers of Russet Burbank and Prospect potatoes receive a higher price for winter contracts as opposed to fall. The prices for Russet Burbank and Prospect potatoes are the average of fall and winter contract prices for the 2013-growing year (PEI Potato Board 2014b). The price of barley and soybeans is the average 2013 price from Statistics Canada Farm Product Prices Survey (Statistics Canada 2014c). As noted earlier, there is no price given for hay, as it is not sold in these systems.

For the all crops, the variable cost of production is used within the economic – hydrologic optimization model. For the two potato varieties, Russet Burbank and Prospect, variable
production costs are the same except the seed and fertilizer costs differ (Cavendish Farms 2015; PEI Potato Board 2015b). For barley and soybean the variable production cost is sourced from AgriAlliance and PEI Dept. of Agriculture and Forestry Cost of Production for Rotational Crops (PEI Dept. of Agriculture and Forestry 2012). For barley underseeded with hay as well as hay, the variable production costs are estimates from PEI Dept. of Agriculture and Forestry (2015a).

Under the Alternative Land Use Services 2 program, the producer can receive an average payment of $173 per hectare if one of the three following types of sensitive land retirement are adopted: expanded buffer zone, non-regulated grassed headlands, or high sloped land (PEI Dept. of Agriculture and Forestry 2013b). The median cost of sensitive land retirement is $371 per hectare. The cost of sensitive land retirement is equal to its opportunity cost of renting it to another potato producer, similarly the rental rate received by the producer. The rental rate per hectare depends on the quality of land, terms of contract, and the last time the land was limed (PEI Potato Board 2014b; PEI Dept. of Agriculture and Forestry 2015b). The price may range from free to $82 to $741 per hectare with the lower bound rented for a full rotation and upper bound rented for “in and out” potato production where the landowner manages the land for the rotation crops (PEI Potato Board 2014).

4.2.7 Nitrate Leachate Abatement Calibration of Potato Farming Systems

As discussed in Section 4.2.3 Nitrate Leachate Abatement within the Research Area, the economic – hydrologic model estimates nitrate leachate abatement, in kg NO$_3$-N per hectare, associated with each land management practice as opposed to absolute nitrate leachate. Therefore, improvements in groundwater quality are achieved by increasing nitrate leachate abatement. The Kensington North Watersheds Association’s An Adaptive Management Plan to
Reduce Nitrates in the Upper Watersheds of the Southwest River (Jiang 2013) is the source of nitrate leachate abatement coefficients for each beneficial management practice within the economic – hydrologic model. Physical specialists at Agriculture and Agri-Food Canada, PEI Department of Environment, Labour & Justice, and the PEI Department of Agriculture and Forestry contributed to the estimation of this data (Jiang 2013).

Nitrate leachate abatement is expressed as kg NO₃⁻-N per hectare, although it could also be expressed as kg N per hectare as nitrate (NO₃⁻) and nitrate-N (NO₃⁻-N) are the dominant species of nitrogen (N) in the environment. Total nitrate leachate abatement (kg NO₃⁻-N) estimated by the economic – hydrologic model is translated into per hectare abatement (kg N per hectare), and then translated into the final nitrate concentration in residential groundwater wells (mg per litre NO₃⁻-N, mg/L NO₃⁻-N). Hereinafter, nitrate leachate abatement may be referred to as nitrate abatement, and nitrate leachate abatement target may be referred to as nitrate abatement target or abatement target.

Below, Table 4.3 lists the land management practices and their associated nitrate leachate abatement coefficients used within the economic – hydrologic optimization model. Sensitive land retirement withdraws land from crop production, thereby reducing the applied nitrogen and consequently nitrate leachate. Sensitive land retirement and turning it into pasture or forest abates nitrate leachate by 0.41 kg NO₃⁻-N per hectare. Within the economic – hydrologic model, for each crop within a potato crop rotation is assigned a nitrate leachate abatement coefficient of 0.2 kg NO₃⁻-N per hectare. This per crop coefficient value was derived from the nitrate leachate abatement of 0.6 kg NO₃⁻-N per hectare from adopting a potato-barley underseeded with clover-clover crop rotation from two and two and a half year potato rotations (Jiang 2013). For potatoes, the applied nitrogen recovery of ranges between 40 and 60%, therefore leaving excess nitrogen
within the soil profile to leach into groundwater (Zebarth and Rosen 2007). The nitrate leachate abatement for the two potato varieties is as follows: adoption of the Prospect variety has a 9 kg NO$_3^-$-N per hectare abatement and Russet Burbank has 0.2 kg NO$_3^-$-N per hectare only from its per crop abatement within the crop rotation. The adoption of NMP abates nitrate leachate by 3.2 kg NO$_3^-$-N per hectare while GSP does not abate nitrate leachate. With regards to spring tillage, a field study by Jiang et al. (2014) finds that delaying tillage until the spring reduces nitrate leaching in groundwater by 20 – 61% during the forage phase. The adoption of the spring tillage on the forage preceding the potato crop abates nitrate leachate by 0.08 kg NO$_3^-$-N per hectare whereas fall tillage does not abate nitrate leachate.

| Table 4.3: Nitrate Leachate Abatement by Land Management Practice (kg NO$_3^-$-N per hectare) |
|------------------------------------------|---------------------|---------------------|---------------------|---------------------|
| Fertilizer Rate                          | Tillage Timing      | Potato Variety      | Per Crop w/i Crop Rotation | SLR                |
| Grower Standard Program (GSP)            | Nutrient Management Planning (NMP) | Fall | Spring | P$_{RB}$ | P$_{P}$ | n/a | n/a |
| Potato Variety                           | 0                   | 3.2                 | 0                   | 0.08               | 0.2             | 9.0  | 0.2           | 0.41           |

Notes:  
1 Nitrate leachate abatement coefficient values for NMP and spring tillage when adopted with Prospect abate an additional 9 kg N/ha from the adoption of the Potato variety. For example, if NMP, spring tillage, and Prospect are adopted nitrate leachate abatement is 3.2+0.08+9 kg NO$_3^-$-N per ha=12.28 plus the per crop w/i crop rotation abatement.

4.2.8 Empirical Economic – Hydrologic Optimization Model

The choice among alternative farming systems is determined through an economic – hydrological model that uses mathematical programming to optimize gross margin subject to the
amount of arable and sensitive land, minimum crop allocations within rotations, fertilizer rates, and nitrate leachate abatement target. The gross margin-maximizing problem for the producer is:

\[ \max_{\mathbf{X}} \sum_{i=1}^{n} \pi_i X_i \quad (eq. 2.7.1) \]

Where,

- \( i \) is the set land management practices such as potato variety, crop rotation, fertilizer N rate, and tillage timing that are selected to be the potato farming system
- \( n \) is the total number of potato farming systems available
- \( X_i \) is the land allocated to potato farming system \( i \)
- \( \pi_i \) is gross margin, revenue minus variable production costs, for potato farming system \( i \) for \( X_i \)

The economic – hydrologic optimization model maximizes gross margin for the land allocated \( X_i \) to potato farming system \( i \) which is summed over the total number of potato farming systems available. There are two different producers, one on high quality land and one on low quality land. For producers on both high and low quality, \( n=72 \) in the Base Potato Farming System condition that demonstrates gross margin if \( PEI\ ACRA \) was not implemented. When \( PEI\ ACRA \) and subsequent abatement targets are implemented the number of total farming systems falls to \( n=64 \) for the producer on high quality land and \( n=48 \) for the producer on low quality land. \( X_i \) is only assigned a positive non-zero value for the optimized potato farming system \( i \) whereas all other potato farming systems are assigned a zero value.
Subject to:

\[ \sum_{i=1}^{n} d_{ij}X_i \leq b_j \ (j = 1, 2, \ldots, m) \quad (eq.\ 2.7.2) \]

Where,

\( j \) is the individual constraints on \( eq.\ 2.7.1 \) such as land allocation within a crop rotation, total available rented and owned arable land, fertilizer nitrogen rate, and other transfers

\( m \) is the total number of constraints on \( eq.\ 2.7.1 \)

\( d_{ij} \) is the technical coefficient for potato farming system \( i \) and constraint type \( j \)

\( b_j \) is the resource endowment or minimum condition value for constraint type \( j \)

\( Eq.\ 2.7.2 \) represents the general form of the structural constraints that the objective function (\( eq.\ 2.7.1 \)) is subject to. \( Eq.\ 2.7.2 \) is interpreted as the technical coefficient for potato farming system \( i \) and constraint \( j \) applied to the land allocated to potato farming system, \( X_i \), must be less than or equal to the resource endowment or minimum condition within constraint type \( j \) and summed across \( n \) potato farming systems. Like in the objective function, \( X_i \) is only assigned a positive non-zero value for the optimized potato farming system \( i \) whereas all other potato farming systems are assigned a zero value.

\[ \sum_{i=1}^{n} a_iX_i \geq A \quad (eq.\ 2.7.3) \]

Where,

\( a_i \) is the level of nitrate leachate abatement effort from potato farming system \( i \)

\( A \) is the nitrate leachate abatement target
Structural constraint (eq. 2.7.3) incorporates the hydrologic factor of nitrate leachate abatement from potato farming system $i$ into the optimization model.

The Base Potato Farming System conditions, emulates the absence of the *PEI ACRA* regulation, which does not restrict the potato crop rotation a producer may adopt. Therefore the producer maximizes gross margin given no concern for her nitrate leachate in groundwater from her potato production practices and therefore does not internalize the cost of her externality; the nitrate leachate abatement target is set $A = 0$ for $n = 72$. In successive conditions on the economic – hydrologic optimization model, the affects of the *PEI ACRA* on gross margin and nitrate leachate abatement are estimated by setting $A \geq 0$ for $n=64$ and $n=48$ for the producers on high and low quality lands, respectively. Nitrate leachate abatement is constrained by successive levels to determine farming system $i$ that achieves the nitrate leachate abatement target, $A \geq 0$, at the least cost. By setting successive nitrate leachate abatement targets, $A$, the marginal nitrate leachate abatement costs may be estimated. These marginal nitrate abatement costs are heterogeneous between producers on high quality land versus low quality land for the same nitrate leachate abatement target, $A$.

$$X_i \geq 0 \quad (eq.2.7.4)$$

Where, the final constraint is the non-negativity constraint is interpreted as the decision variable, $X_i$, is non-negative within the economic – hydrologic optimization model.
4.3 Results and Discussion

4.3.1 Potato Farming Systems’ Gross Margin, Nitrate Leachate Abatement, Residential Groundwater Well Nitrate Concentration

The gross margin and nitrate leachate abatement per hectare as well as the residential groundwater well nitrate concentration are listed in Table 4.4. From the total 72-potato farming systems considered within the economic – hydrologic optimization model only the profitable potato farming systems are listed. There tends to be a negative correlation between the nitrate leachate abatement from the adoption of beneficial management practices and gross margins.

The system that adopts all available beneficial management practices, excluding sensitive land retirement, has the greatest nitrate leachate abatement; this is the system that adopts NMP fertilizer nitrogen rate, Prospect potato variety, spring tillage, along with a crop rotation. The Prospect variety yields the greatest nitrate leachate abatement so much so that two Prospect systems paired with GSP and both tillage treatments have greater nitrate abatement than the NMP systems with Russet Burbank and both tillage treatments. Given the crop rotations that have positive gross margins, the crop rotations P₇BP₇SB and P₇BB have greatest nitrate leachate abatement.
Table 4.4: Potato Farming Systems’ Gross Margin, Nitrate Leachate Abatement, and Residential Groundwater Well Nitrate Concentration

<table>
<thead>
<tr>
<th>Rotation &amp; Potato Variety</th>
<th>Fertilizer</th>
<th>Tillage Timing</th>
<th>Gross Margin ($ per hectare)</th>
<th>Nitrate Leachate Reduction (kg NO₃-N per ha)</th>
<th>Residential Groundwater Well Nitrate Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pоборот B</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$691</td>
<td>0</td>
<td>5.6</td>
</tr>
<tr>
<td>Pоборот BPоборот Bоборот H</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$674</td>
<td>1.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Pоборот B</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$541</td>
<td>1.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$534</td>
<td>0.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Pоборот PSоборот Bоборот H</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$505</td>
<td>10.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Pоборот SB</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$479</td>
<td>0.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$395</td>
<td>9.6</td>
<td>3.2</td>
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<tr>
<td>Pоборот BPоборот Bоборот H</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$372</td>
<td>10.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Pоборот SB</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$341</td>
<td>9.6</td>
<td>3.2</td>
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<td>Pоборот Bоборот H</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$338</td>
<td>0.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Pоборот SH</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$290</td>
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<td>5.5</td>
</tr>
<tr>
<td>Pоборот Bоборот H</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$261</td>
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<td>Pоборот BPоборот Bоборот HS</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$234</td>
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<td>5.4</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$198</td>
<td>9.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Pоборот PSоборот HS</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$187</td>
<td>4.2</td>
<td>4.6</td>
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<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$178</td>
<td>0.7</td>
<td>5.5</td>
</tr>
<tr>
<td>Pоборот SH</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$155</td>
<td>9.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$151</td>
<td>9.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$143</td>
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<td>5.5</td>
</tr>
<tr>
<td>Pоборот HS</td>
<td>NMP</td>
<td>Tₚ</td>
<td>$141</td>
<td>3.8</td>
<td>4.7</td>
</tr>
<tr>
<td>Pоборот SB</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$131</td>
<td>0.7</td>
<td>5.5</td>
</tr>
<tr>
<td>Pоборот PSоборот Bоборот H</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$121</td>
<td>10.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>NMP</td>
<td>Tₚ</td>
<td>$94</td>
<td>3.8</td>
<td>4.7</td>
</tr>
<tr>
<td>Pоборот BPоборот Bоборот HS</td>
<td>GSP</td>
<td>Tₛ</td>
<td>$92</td>
<td>1.1</td>
<td>5.4</td>
</tr>
<tr>
<td>Pоборот BSSERT</td>
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<td>Tₛ</td>
<td>$85</td>
<td>9.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Pоборот BPоборот H</td>
<td>NMP</td>
<td>Tₚ</td>
<td>$43</td>
<td>4.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>NMP</td>
<td>Tₛ</td>
<td>$37</td>
<td>9.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>NMP</td>
<td>Tₚ</td>
<td>$28</td>
<td>13.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Pоборот BB</td>
<td>NMP</td>
<td>Tₛ</td>
<td>$10</td>
<td>12.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Pоборот HH</td>
<td>GSP</td>
<td>Tₚ</td>
<td>$3</td>
<td>9.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>

4.3.2 Gross Margin Optimization for High Quality (HQ) Land Producer

4.3.2.1 Base Potato Farming System for HQ Land Producer

Table 4.4 illustrates the results from the economic – hydrologic optimization model for the producer farming on high quality land. As discussed in Section 4.2.2.1 Base Potato Farming
System Conditions and Section 4.2.8 Empirical Economic – Hydrologic Optimization Model, there are no restrictions on the crop rotations available for adoption by the producer under the Base Potato Farming System conditions. The producer on high quality land optimizes from all available potato crop rotations within the economic – hydrologic model, from 72 potato farming systems.

The high quality land producer’s Base Potato Farming System is the following: the crop rotation potato-barley (P,B) optimizes the high quality land producer’s gross margin given nitrate leachate abatement, A=0, with Russet Burbank, GSP fertilizer, and fall tillage. Russet Burbank (P_RB) and barley are both allocated 78.7 hectares. In terms of quantity Russet Burbank and barley produce 2,158 and 296 MT, respectively. The total gross margin is $108,821 and the producer does not adopt any beneficial management practices so there is zero nitrate leachate abatement resultant from the Base Potato Farming System for the producer on high quality land; the residential groundwater well nitrate concentration is 5.63 mg/L NO$_3^-$ N. The producer will exhaust her ability to rent land, as well as all owned hectares, and allocate 157 hectares to potato crop production. The shadow value of owned land is greater than that of rented land by $371, which may be interpreted as the value of owning an additional hectare has a greater impact on gross margin than rented land.

4.3.2.2 Nitrate Leachate Abatement under PEI ACRA for HQ Land Producer

As discussed in Section 4.2.2 Prince Edward Island Agricultural Crop Rotation Act and Section 4.2.2.2 Prince Edward Island Agricultural Crop Rotation Act Conditions, the PEI ACRA restricts the adoption of the 1-in-2 potato crop rotation potato-barley (P,B) due to spatial factors that generate annual soil erosion greater than 7.4 MT per hectare. Consequently, the economic
hydrologic optimization model now has $n = 64$ and $A \geq 0$ given the restrictions on crop rotation imposed by the \textit{PEI ACRA} regulation. For the producer on high quality land, the nitrate leachate marginal abatement cost due to the conditions imposed by the \textit{PEI ACRA} is $85$ per kg NO$_3^-$-N up until $31.48$ kg NO$_3^-$-N.

The crop rotation potato-barley-potato-soybean-barley (P$_i$BP$_i$SB) optimizes the high quality land producer’s gross margin with Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage. The constraint required a minimum of $40\%$ of land to be allocated to potato, $40\%$ allocated to barley, and $20\%$ to be allocated to soybean. Russet Burbank and barley were both allocated $63$ hectares with soybean receiving $31.5$ hectares. In terms of quantity Russet Burbank, barley, and soybean produce $1,782$, $244$, and $71$ MT, respectively. Given the \textit{PEI ACRA} regulation, the 2-in-5 rotation P$_i$BP$_i$SB is assumed to emit less than $7.4$ MT of soil erosion per hectare per year (PEI Dept. of Agriculture and Forestry 2015c).

The total gross margin is $106,153$ where the producer does not adopt a beneficial management practice besides crop rotation. The total nitrate leachate reduction for the total land area of $157$ hectares is $31.48$ kg NO$_3^-$-N, which translates to a nitrate leachate concentration in residential groundwater of $5.58$ mg/L NO$_3^-$-N. This is only slightly lower than the current nitrate concentration of $5.63$ mg/L NO$_3^-$-N. The producer will exhaust her ability to rent land, as well as all owned hectares. The shadow value of owned land is greater than that of rented land by $371$, which may be interpreted as the value of owning an additional hectare has a greater impact on gross margin than rented land.

Given the available crop rotations under the \textit{PEI ACRA} conditions, potatoes are allocated the greatest share of arable land within 2-in-5 rotations, and therefore contribute a greater share to gross margin than 1-in-3 or 1-in-4 crop rotations. Compared to the Base Potato Farming
System for high quality land producers, the producer continues to select the potato farming system with Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage but now the adoption of a crop rotation achieves nitrate leachate abatement. Russet Burbank as opposed to Prospect is adopted with GSP fertilizer nitrogen rate because the higher production cost of GSP does not outweigh the yield penalty against NMP. Fall tillage timing is applied to land in potatoes.

The *PEI ACRA* imposes a marginal abatement cost of $85 per kg NO$_3$-N up until 31.48 kg NO$_3$-N nitrate leachate abatement from the base potato farming system of P_B, Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage.

**4.3.2.3 Nitrate Leachate Abatement Targets under PEI ACRA for HQ Land Producer**

Figure 4.3 illustrates gross margin for the producer on high quality land (HQ Producer) and the producer on low quality land (LQ Producer) for nitrate abatement levels as well as the Kensington North Watersheds Association’s nitrate abatement target of 970 kg NO$_3$-N or 6.16 kg NO$_3$-N per hectare (Abatement Target). The *PEI ACRA* conditions abate nitrate leachate by 31.48 kg NO$_3$-N over 157 hectares of arable land from the Base Potato Farming System for the producer on high quality land. The nitrate leachate marginal abatement costs are derived from the change in gross margin resultant from successive nitrate leachate abatement targets. Table 4.5 illustrates the potato farming systems for prominent abatement targets on high quality land. Figure 4.4 illustrates the nitrate leachate marginal abatement cost curves for both producers on high and low quality lands.

Notably, the gross margin-nitrate abatement curve decreases significantly after 598.2 kg NO$_3$-N of abatement. At nitrate abatement targets up until 598.2 kg NO$_3$-N, a producer allocates land to P_BP_SB with both Russet Burbank and Prospect under GSP fertilizer rates and fall tillage.
with a nitrate leachate marginal abatement cost (MAC\textsubscript{HQ}) of $47 per kg NO\textsubscript{3}^{-}-N to adopt Prospect. As the nitrate abatement target increases, land is gradually allocated from Russet Burbank to Prospect. At targets of 598.2 kg NO\textsubscript{3}^{-}-N and greater, only Prospect is adopted under NMP, GSP, and fall tillage with a MAC\textsubscript{HQ} of $373 per kg NO\textsubscript{3}^{-}-N to adopt Prospect and NMP. At abatement targets of 799.7 kg NO\textsubscript{3}^{-}-N and greater, land is allocated to spring tillage, fall tillage, NMP, and Prospect with a MAC\textsubscript{HQ} of $12,009 per kg NO\textsubscript{3}^{-}-N to adopt spring tillage. Between 800.07 and 800.08 kg NO\textsubscript{3}^{-}-N, gross margin falls to zero due to the nitrate abatement target.

Alternatively, nitrate leachate abatement targets in kg NO\textsubscript{3}^{-}-N may be illustrated by nitrate-N concentration in residential groundwater wells in mg/L NO\textsubscript{3}^{-}-N. The high quality PEI ACRA condition nitrate leachate abatement is 31.48 kg NO\textsubscript{3}^{-}-N, which is translated to a nitrate concentration of 5.58 mg/L NO\textsubscript{3}^{-}-N; at 598.2, 799.7, and 800.07 kg NO\textsubscript{3}^{-}-N, nitrate concentrations are 4.67, 4.355, and 4.355 mg/L NO\textsubscript{3}^{-}-N. From the base concentration of 5.63 mg/L NO\textsubscript{3}^{-}-N, the maximum reduction in residential groundwater wells nitrate concentration is 23% associated with break-even gross margin. All nitrate-N concentrations associated with abatement targets are below Health Canada’s maximum nitrate-N concentration threshold, solely due to average nitrate-N concentration within the research area being 5.62 mg/L NO\textsubscript{3}^{-}-N. Although, it is important to note that some nitrate concentrations within residential groundwater wells are as high as 13.5 mg/L NO\textsubscript{3}^{-}-N in the research area, which exceed Health Canada’s threshold, and are only indirectly considered within the average concentration for the research area used within this thesis.
Figure 4.3: Gross Margin-Nitrate Leachate Abatement (kg NO$_3$-N) for Producers on Low Quality Land (LQ) and High Quality Land (HQ)
Figure 4.4: Nitrate Leachate Marginal Abatement Cost ($ per kg NO₃⁻-N) for Low Quality Land Producer (MAC LQ Producer) and High Quality Land (MAC HQ Producer)

Table 4.5: Potato Farming Systems on High Quality Land

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Base Potato Farming System</th>
<th>PEI ACRA</th>
<th>Nitrate Leachate Abatement Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Nitrate Leachate Abatement (kg NO₃⁻-N)</td>
<td>0</td>
<td>31.48</td>
<td>31.6     598.22    799.71    799.72</td>
</tr>
<tr>
<td>Potato Variety (Pₙ)</td>
<td>Pₚₐ</td>
<td>Pₚₐ</td>
<td>Pₚₐ     Pₚₐ Pₚₐ Pₚₐ Pₚₐ</td>
</tr>
<tr>
<td>Fertilizer N Rate</td>
<td>GSP</td>
<td>GSP</td>
<td>GSP     GSP NMP NMP NMP</td>
</tr>
<tr>
<td>Tillage Timing</td>
<td>F</td>
<td>F</td>
<td>F       F F F S</td>
</tr>
<tr>
<td>Gross Margin ($)</td>
<td>$108,821</td>
<td>$106,153</td>
<td>$106,148 $79,573</td>
</tr>
<tr>
<td>Gross Margin ($/ha)</td>
<td>$691</td>
<td>$674</td>
<td>$674    $505</td>
</tr>
<tr>
<td>Nitrate Leachate Abatement (kg NO₃⁻-N/ha)</td>
<td>0</td>
<td>0.2</td>
<td>0.2     3.8  5.1</td>
</tr>
<tr>
<td>Final Nitrate</td>
<td>$0</td>
<td>5.58</td>
<td>5.57    4.67</td>
</tr>
</tbody>
</table>
### Concentration (mg/L NO$_3^-$-N) Marginal Abatement Cost (MAC, $/kg NO$_3^-$-N)

<table>
<thead>
<tr>
<th>Concentration (mg/L NO$_3^-$-N)</th>
<th>Marginal Abatement Cost (MAC, $/kg NO$_3^-$-N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>$0</td>
<td>$47</td>
</tr>
<tr>
<td>$373</td>
<td>$12,009</td>
</tr>
<tr>
<td>$12,009</td>
<td>$12,009</td>
</tr>
</tbody>
</table>

4.3.3 Gross Margin Optimization for Low Quality (LQ) Land Producer

#### 4.3.3.1 Base Potato Farming System For LQ Land Producer

As discussed in Section 4.2.2.1 Base Potato Farming System Conditions and Section 4.2.8 Empirical Economic – Hydrologic Optimization Model, there are no restrictions on the crop rotations available for adoption by the producer, which the PEI ACRA scenario imposes. The producer on low quality land optimizes from all available potato crop rotations within the economic – hydrologic model, from 72 potato farming systems. Therefore, the Base Potato Farming System for the producer on low quality land has the same results as the producer on high quality land. To review these results, the crop rotation potato-barley (P$_i$B) optimizes the low quality land producer’s gross margin given nitrate leachate abatement, A=0, with Russet Burbank, GSP fertilizer, and fall tillage. The total gross margin is $108,821 and the producer does not adopt any beneficial management practices so there is zero nitrate leachate abatement resultant from the Base Potato Farming System for the producer on low quality land; the residential groundwater well nitrate concentration is 5.63 mg/L NO$_3^-$-N. Table 4.6 illustrates the results from the empirical model for the producer on low quality land.

#### 4.3.3.2 Nitrate Leachate Abatement under PEI ACRA for LQ Land Producer

As discussed in Section 4.2.2 Prince Edward Island Agricultural Crop Rotation Act the 1-in-2 crop rotation P$_i$B and the 2-in-5 rotations P$_i$BP$_i$SB and PBP$_{H1}$H are ineligible under the PEI
ACRA if produced on low quality land generating soil erosion greater than 7.4 MT per hectare. Consequently, the economic hydrologic optimization model now has $n=48$ and $A \geq 0$ given the restrictions on crop rotation imposed by the PEI ACRA regulation.

The crop rotation potato-barley-barley (P,BB) optimizes the low quality land producer’s gross margin with Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage. Optimized gross margin is $85,081$ with a nitrate abatement of $31.48$ kg NO$_3$-N over 157 hectares, equivalent to the nitrate-N concentration of $5.58$ mg/L NO$_3$-N. The producer will exhaust her ability to rent land, as well as produce on all owned hectares. The shadow value of owned land is greater than that of rented land by $371$.

The PEI ACRA imposes a marginal abatement cost of $754$ per kg NO$_3$-N up until $31.48$ kg NO$_3$-N nitrate leachate abatement from the base potato farming system of P, B, Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage.

\textbf{4.3.3.3 Nitrate Leachate Abatement Targets under PEI ACRA for LQ Land Producer}

Figure 4.3 illustrates gross margin for the producer on high quality land (HQ Producer) and the producer on low quality land (LQ Producer) for nitrate abatement levels as well as the Kensington North Watersheds Association’s nitrate abatement target of $970$ kg NO$_3$-N or $6.16$ kg NO$_3$-N per hectare (Abatement Target). Table 4.6 illustrates the potato farming systems for prominent abatement targets on low quality land. Figure 4.4 and Figure 4.5 both illustrate the marginal nitrate abatement cost curves for both producers on high and low quality lands.

Notably, the gross margin-abatement curve decreases significantly at $503.76$ kg NO$_3$-N. At nitrate abatement targets up until $503.76$ kg NO$_3$-N, the producer allocates land to P, BB with both Russet Burbank and Prospect, GSP, and fall tillage with a MAC$_{LQ}$ of $47$ per kg NO$_3$-N.
As abatement targets increase land is gradually allocated from Russet Burbank to Prospect. At abatement targets of 503.76 kg NO$_3^-$-N and greater, the producer adopts only Prospect, GSP and NMP fertilizer nitrogen rates, and fall tillage with a MAC$_{LQ}$ of $365$ per kg NO$_3^-$-N. At an abatement target of 671.67 kg NO$_3^-$-N, the producer adopts only Prospect, NMP, and fall tillage with a MAC$_{LQ}$ of $9,836$ per kg NO$_3^-$-N. At an abatement target of 671.68 kg NO$_3^-$-N, the producer adopts Prospect, NMP, and both fall and spring tillage with a MAC$_{LQ}$ of $11,759$ per kg NO$_3^-$-N.

Alternatively, nitrate leachate abatement targets in kg NO$_3^-$-N may be shown by nitrate-N concentration in residential groundwater wells in mg/L NO$_3^-$-N. The PEI ACRA conditions on low quality land have a nitrate leachate abatement is 31.48 kg NO$_3^-$-N, which is translated to a nitrate concentration of 5.58 mg/L; at 503.76, 671.67 and 671.68 kg NO$_3^-$-N, nitrate-N concentrations are 4.82, 4.56, and 4.56 mg/L NO$_3^-$-N. From the base concentration of 5.63 mg/L NO$_3^-$-N, the maximum reduction in residential groundwater wells nitrate concentration is 19% associated with break-even gross margin.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Base Potato Farming System</th>
<th>PEI ACRA</th>
<th>Nitrate Leachate Abatement Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Nitrate Leachate Abatement (kg N)</td>
<td>0</td>
<td>31.48</td>
<td>31.6  503.75  503.76  671.67  671.68</td>
</tr>
<tr>
<td>Potato Variety (P_i)</td>
<td>P_RB</td>
<td>P_RB</td>
<td>P_RB  P_P  P_P  P_P  P_P  P_P</td>
</tr>
<tr>
<td>Fertilizer N Rate</td>
<td>GSP</td>
<td>GSP</td>
<td>GSP  GSP  GSP  NMP  NMP  NMP</td>
</tr>
<tr>
<td>Tillage Timing</td>
<td>F</td>
<td>F</td>
<td>F  F  F  S  S  S  S</td>
</tr>
<tr>
<td>Gross Margin ($)</td>
<td>$108,821</td>
<td>$85,081</td>
<td>$85,076  $63,034  $63,033  $1,688  $1,629</td>
</tr>
<tr>
<td>Gross Margin ($/ha)</td>
<td>$691</td>
<td>$540.5</td>
<td>$540.4  $400  $400  $11  $10</td>
</tr>
<tr>
<td>Nitrate Leachate Abatement (kg N/ha)</td>
<td>0</td>
<td>0.20</td>
<td>0.20  3.20  3.20  4.27  4.27</td>
</tr>
<tr>
<td>Final Nitrate Concentration (mg/L NO₃⁻-N)</td>
<td>$0</td>
<td>5.58</td>
<td>5.57  4.82  4.82  4.56  4.56</td>
</tr>
<tr>
<td>Marginal Abatement Cost (MAC, $/kg NO₃⁻-N)</td>
<td>$0</td>
<td>$0</td>
<td>$47  $166  $365  $9,836  $11,759</td>
</tr>
</tbody>
</table>

4.3.4 Nitrate Leachate Marginal Abatement Costs for Low and High Quality Land Producers

The nitrate leachate marginal abatement costs between the high and low quality land producers may be compared to illuminate efficiencies in nitrate leachate abatement. Figure 4.4 illustrates the nitrate leachate marginal abatement cost curves for both producers on high and low quality lands, and similarly Figure 4.5 illustrates the nitrate leachate marginal abatement costs plotted
against each other, which contributes to the discussion of the equimarginal principle and cost-effective allocation of abatement.

The nitrate leachate marginal abatement costs from the Base Potato Farming Systems due to the *PEI ACRA* are greater for producers on low quality land because they must reallocate land from 50% potatoes to 33% potatoes within a crop rotation. Comparatively, the producer on low quality land incurs a MAC<sub>LQ</sub> of $794 per kg NO<sub>3</sub>⁻-N whereas the producer on high quality land only incurs a lower MAC<sub>HQ</sub> of $85 per kg NO<sub>3</sub>⁻-N.

After the conditions imposed by the *PEI ACRA* are assumed, the nitrate leachate marginal abatement cost between producers on low and high quality land equate to $47 per kg NO<sub>3</sub>⁻-N up to 503.76 kg NO<sub>3</sub>⁻-N, or 4.67 mg/L NO<sub>3</sub>⁻-N. After this abatement level producers on low quality land must adopt NMP fertilizer nitrogen rates to achieve greater abatement targets while producers on high quality land may maintain the MAC<sub>HQ</sub> of $47 per kg NO<sub>3</sub>⁻-N up to and including 598.21 kg NO<sub>3</sub>⁻-N. Although, it should be noted that once producers on high quality land must adopt NMP and spring tillage to attain greater nitrate leachate abatement targets, their marginal abatement costs for these beneficial management practices are higher than those of the producers on low quality land, which is illustrated by Figure 4.4 and Figure 4.5. For NMP and spring tillage the low quality land producer incurs MAC<sub>LQ</sub> of $365 and $11,759 per kg NO<sub>3</sub>⁻-N whereas the high quality land producer incurs MAC<sub>HQ</sub> $373 and $12,009 per kg NO<sub>3</sub>⁻-N, respectively. Therefore, a trade-off occurs as the producer on high quality land has the ability to achieve a greater nitrate leachate abatement target but her costs are higher for each practice than the incurred by the producer on low quality land.

As discussed in *Chapter 3 Section 3.4 Nitrate Leachate Abatement for Two Producers with Heterogeneous MACs* the equimarginal principle implies that given a nitrate leachate
abatement target, production will be distributed such that marginal abatement costs are equalized between producers to minimize total abatement cost (Field 1994b). Therefore, to achieve cost-effective nitrate abatement, nitrate leachate abatement allocation will be distributed between the high and low quality land producers such that the marginal abatement costs equate to minimize total abatement cost (Field and Olewiler 2005a; 2005c).

Given the MACs equate over a range of nitrate leachate abatement, the cost-effective allocation of nitrate leachate abatement is between 350 and 503.76 and kg NO₃⁻-N for the low quality producer and between 450 and 598.21 kg NO₃⁻-N for the high quality producer. These nitrate leachate abatement levels correspond to nitrate concentrations in residential groundwater wells between 5.07 and 4.82 mg/L NO₃⁻-N for low quality producers and 4.91 and 4.67 mg/L NO₃⁻-N for high quality producers.

![Figure 4.5: Equating Nitrate Leachate Marginal Abatement Cost ($/kg NO₃⁻-N) for Low Quality Land Producer (MAC LQ Producer) and High Quality Land (MAC HQ Producer).](image-url)

Figure 4.5: Equating Nitrate Leachate Marginal Abatement Cost ($/kg NO₃⁻-N) for Low Quality Land Producer (MAC LQ Producer) and High Quality Land (MAC HQ Producer).
4.3.5 Kensington North Watersheds Association Nitrate Target

As discussed in Chapter 3 Section 3.4 Nitrate Leachate Abatement for Two Producers with Heterogeneous MACs, nitrate leachate abatement is deemed cost-effective when the producers achieve a given nitrate leachate abatement target at the least cost (Field 1994a; Field and Olewiler 2005b). When the PEI ACRA conditions are imposed as well as successive abatement targets, the Kensington North Watersheds Association’s nitrate abatement target of 970 kg NO$_3^-$-N (6.16 kg NO$_3^-$-N per hectare), or equally their nitrate load target of 16.34 kg NO$_3^-$-N per hectare, is never feasibly attained by the potato farming systems considered within this economic – hydrologic optimization model. This is exemplified by Figure 4.3 and Figure 4.4, where the gross margin curves as well as the nitrate leachate marginal abatement cost curves for producers on high and low quality land never intersect the abatement target set by the Kensington North Watersheds Association. In Figure 4.4, as the abatement target and nitrate leachate marginal abatement cost curves does not intersect there is no cost-effective allocation between producers with heterogeneous nitrate leachate marginal abatement costs. This indicates the abatement target set by the Kensington North Watersheds Association may need to be reconsidered for nitrate leachate abatement to be realistic.

4.3.6 Discussion of Results and Conclusions

The results from the economic – hydrologic optimization model illuminate that for producers on high and low quality land Russet Burbank with GSP fertilizer nitrogen rate and fall tillage timing are the most profitable potato farming systems, which is validated as these three land management practices are traditionally adopted in PEI in the absence of enforcement or
incentives on nitrate leachate abatement. To achieve successive nitrate leachate abatement targets, a producer on either high or low quality land will adopt beneficial management practices in the following pattern: crop rotation, Prospect potato variety, NMP fertilizer nitrogen rate, and finally spring tillage. The producer will adopt these practices gradually by allocating land away from the land management practice towards the beneficial management practice.

The Base Potato Farming System associated with the absence of PEI ACRA is where producers are able to adopt any of the nine potato crop rotations to optimize from a total of 72 potato farming systems. The Base Potato Farming System of potato-barley (P,B) crop rotation, Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage does not achieve nitrate leachate abatement. When the restrictions on potato crop rotation imposed by the PEI ACRA are imposed on the economic hydrologic model, the high quality land producer incurs a considerably lower nitrate leachate marginal abatement cost than the low quality land producer, $85 per kg NO₃⁻-N and $794 per kg NO₃⁻-N up until 31.48 kg NO₃⁻-N for a total nitrate abatement cost of $13,340 and $118,700, respectively. This initial cost to comply with the PEI ACRA is much greater than the subsequent cost of $47 per kg NO₃⁻-N of achieving up to 503.76 and 598.21 kg NO₃⁻-N, for low and high quality land producers respectively, resultant from the adoption of Prospect potato variety. Additionally, high and low quality land producers’ nitrate leachate marginal abatement costs equate when Prospect potato variety is adopted at $47 per kg NO₃⁻-N. Even more so, the adoption of the Prospect potato variety has the least-cost relative to all feasibly adoptable beneficial management practices considered within the economic – hydrologic optimization model.

Interestingly, Prospect potato variety is not purported by the currently established beneficial management practice incentive programs on the Island such as the Alternative Land
**Use Services 2 or Agriculture Stewardship Program** discussed in *Chapter 2 Section 2.6 Nitrate Leachate Abatement Programs in Prince Edward Island*. It must be noted a factor limiting the adoption of the Prospect potato variety, in addition to the producer’s nitrate leachate marginal abatement cost, is that demand for potato varieties come first from end-use product buyers such as Wendy’s® then from potato processors such as Cavendish Farms or McCain Food Limited. Potato processors translate variety demanded from buyers into producer contracts for the specific varieties demanded. Therefore, for the adoption of the Prospect variety by producers on the Island to occur the processors must increase producer contracts for Prospect variety. This may be incentivized internally by processors to boost social licencing, or through the consumer channel by buyer and end-consumer pressure for potatoes and their processed products to be grown with beneficial management practices.

To achieve nitrate leachate abatement targets greater than 503.76 and 598.21 kg NO₃⁻-N, for low and high quality land producers respectively, producers must adopt NMP and/or spring tillage. NMP fertilizer nitrogen rate is costly requiring a payment of $365 and $373 per kg NO₃⁻-N, to incentivize low and high quality land producers, respectively, when adopted along with GSP fertilizer nitrogen rate. To achieve nitrate leachate abatement targets greater than 671.68 and 799.7 kg NO₃⁻-N, it requires even greater payments of $11,759 and $12,009 per kg NO₃⁻-N. Sensitive land retirement is never adopted as its price is always lower than the cost of taking land out of the potato farming system.

The cost-efficient allocation of nitrate leachate abatement is $47 per kg N between 350 and 503.76 and kg NO₃⁻-N for the low quality producer and between 450 and 598.21 kg NO₃⁻-N for the high quality producer. These nitrate leachate abatement levels correspond to nitrate concentrations in residential groundwater wells between 5.07 and 4.82 mg/L NO₃⁻-N for low
quality producers and 4.91 and 4.67 mg/L NO$_3$-N for high quality producers. These results illustrate the importance of implementing policy instruments that value heterogeneity between producers’ ability to adopt nitrate-abating potato farming systems.

Assuming the PEI ACRA is imposed, given no further regulation to incentivize the producers to internalize their externality of nitrate leachate or achieve a particular abatement target, the producer will select the potato farming system that optimizes gross margin respective of their land quality. The nitrate leachate marginal abatement costs estimated by this research may be utilized within incentive instruments such as traditional pay-the-polluter programs, or although potentially non-palatable politically, polluter-pay programs in the form of taxes paid to government or fines paid to watershed associations. Alternatively, non-traditional instruments to incentivize adoption, such as a water quality market may be implemented by capitalizing on the heterogeneity between marginal abatement costs of producers on high and low quality land as well as the cost-effective range of nitrate leachate abatement; water quality markets such as those proposed by Kling (2011), Shortle (2012; 2013), and Horan and Shortle (2011). Even more alternatively, these nitrate leachate marginal abatement costs may contribute to the development of nongovernmental or watershed association driven incentive instruments. These incentive instruments may be industry or consumer driven standards for potatoes grown using nitrate leachate abating beneficial management practices such as Prospect variety, nutrient management planning, spring tillage, and/or crop rotation.

Finally, as discussed in Section 4.2.3 Nitrate Leachate within the Research Area, the beneficial management practices available within a potato farming system were from the Kensington North Watersheds Association’s An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River (Jiang 2013). When the PEI ACRA conditions
are imposed as well as successive abatement targets, the Kensington North Watersheds Association’s nitrate abatement target of 970 kg NO$_3^-$-N (6.16 kg NO$_3^-$-N per hectare), or equally their nitrate load target of 16.34 kg NO$_3^-$-N per hectare, is too large and never feasibly attainable by the potato farming systems considered within this economic – hydrologic optimization model and hence those purported by the Kensington North Watersheds Association’s *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River*. The hydrologic and ecological benefits of the target were accounted for within the Kensington North Watersheds Association’s *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River*, yet consideration of the economic factors to achieve such target were ignored. If the target incorporated the economic considerations of the feasible and effective nitrate abating potato farming systems within the research area estimated by this research, the nitrate leachate abatement target may be reduced. The incorporation of economic factors with the hydrologic factors offers a more holistic analysis. The results of this research illuminate not only the need for but also the value of interdisciplinary and holistic approaches to setting attainable environmental quality targets, especially with respect to nitrate leachate in groundwater in Prince Edward Island.
Chapter 5: Concluding Remarks and Implications for Incentive Instruments

5.0 Introduction

This chapter discusses the significant research outputs, the contributions and implications for policy development targeted at improving groundwater quality respective to nitrate leachate in Prince Edward Island, and finally limitations faced by this research and potential avenues for future research to build upon the output of this research.

5.1 Summary of Significant Outputs

Given two differing qualities of land, high and low quality, nitrate leachate in groundwater is assumed to be influenced by five land management choices within a potato farming system: total area of cropland, crop rotation, potato variety, fertilizer nitrogen rates, and tillage timing. From these, the producer may select to adopt the nitrate-abating beneficial management practices of sensitive land retirement, crop rotation, Prospect potato, nutrient management planning, and spring tillage. The choice among alternative farming systems is determined through an economic – hydrological model that optimizes gross margin subject to the amount of arable and sensitive land, minimum crop allocations within rotations, fertilizer nitrogen rates, and nitrate leachate abatement targets. For both producers on low and high quality land, the Base Potato Farming Systems are associated with the absence of PEI ACRA, which does not achieve nitrate leachate abatement. To achieve nitrate leachate abatement, regulations on potato crop rotations under the PEI ACRA are imposed as well as greater nitrate leachate abatement targets.

The major findings of this thesis research are the estimation of heterogeneous nitrate leachate marginal abatement costs due to the adoption of beneficial management practices to
achieve nitrate leachate abatement targets in Prince Edward Island on high and low land quality.

Succeeding findings sprout from these heterogeneous nitrate leachate marginal abatement costs and are discussed below in Section 5.2 Contribution of Research Outputs and Incentive Instruments for Improved Water Quality in Prince Edward Island.

The Base Potato Farming System associated with the absence of PEI ACRA where producers are able to adopt any of the nine potato crop rotations to optimize from a total of 72 potato farming systems. The Base Potato Farming System of potato-barley (P,B) potato crop rotation, Russet Burbank, GSP fertilizer nitrogen rate, and fall tillage does not achieve nitrate leachate abatement. When the restrictions on potato crop rotation imposed by the PEI ACRA are imposed on the economic hydrologic model, the high quality land producer incurs a considerably lower nitrate leachate marginal abatement cost than the low quality land producer, $85 per kg NO₃-N and $794 per kg NO₃-N up until 31.48 kg NO₃-N for a total nitrate abatement cost of $13,340 and $118,700, respectively. This initial cost to comply with the PEI ACRA is much greater than the ensuing marginal abatement cost of $47 per kg NO₃-N of achieving up to 503.76 and 598.21 kg NO₃-N, for low and high quality land producers respectively, resulting from the adoption of Prospect potato variety. Additionally, high and low quality land producers’ nitrate leachate marginal abatement costs equate when Prospect potato variety is adopted at $47 per kg NO₃-N. Even more so, the adoption of the Prospect potato variety has the least-cost relative to all feasibly adoptable beneficial management practices considered within the economic – hydrologic optimization model.

To achieve nitrate leachate abatement targets greater than 503.76 and 598.21 kg NO₃-N, for low and high quality land producers respectively, producers must adopt NMP and/or spring tillage. NMP fertilizer nitrogen rate is costly requiring a payment of $365 and $373 per kg NO₃-
N, to incentivize low and high quality land producers, respectively, when adopted along with GSP fertilizer nitrogen rate. To achieve nitrate leachate abatement targets greater than 671.68 and 799.7 kg NO$_3^-$-N, it requires even greater payments of $11,759 and $12,009 per kg NO$_3^-$-N. Sensitive land retirement is never adopted, as its price is always lower than the cost of taking land out of the potato farming system.

The cost-efficient allocation of nitrate leachate abatement is $47 per kg N between 350 and 503.76 and kg NO$_3^-$-N for the low quality producer and between 450 and 598.21 kg NO$_3^-$-N for the high quality producer. These nitrate leachate abatement levels correspond to nitrate concentrations in residential groundwater wells between 5.07 and 4.82 mg/L NO$_3^-$-N for low quality producers and 4.91 and 4.67 mg/L NO$_3^-$-N for high quality producers. These results illustrate the importance of implementing policy instruments that values heterogeneity between producers’ ability to adopt nitrate-abating potato farming systems.

Finally, as discussed in Section 4.3.6 Discussion of Results and Conclusions, the beneficial management practices available within a potato farming system were from the Kensington North Watersheds Association’s *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River* (Jiang 2013). For the PEI ACRA scenario as well as successive abatement targets, the Kensington North Watersheds Association’s nitrate abatement target of 970 kg NO$_3^-$-N (6.16 kg NO$_3^-$-N per hectare), or equally their nitrate load target of 16.34 kg NO$_3^-$-N per hectare, is too large and never feasibly attainable by the potato farming systems considered within this economic – hydrologic optimization model and hence those purported by the Kensington North Watersheds Association’s *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River*. The hydrologic and ecological benefits of the target were accounted for within the Kensington North Watersheds.
Association’s An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River, yet consideration of the economic factors to achieve such target were ignored. If the target incorporated the economic considerations of the feasible and effective nitrate abating potato farming systems within the research area estimated by this research, the nitrate leachate abatement target may be reduced. The incorporation of economic factors with the hydrologic factors offers a more holistic analysis. The results of this research illuminate not only the need for but also the value of interdisciplinary and holistic approaches to setting attainable environmental quality targets, especially with respect to nitrate leachate in groundwater in Prince Edward Island.

5.2 Contribution of Research Outputs and Incentive Instruments for Improved Water Quality in Prince Edward Island

This research contributes to the literature of economic – hydrologic modelling for nitrate leachate and nitrate leachate abatement by estimating the spatially differentiated marginal abatement costs of non-traditional beneficial management practices. Additionally, this research is unique in that it incorporates current policy and applicable incentive payments in Prince Edward Island to estimate, as realistically as possible, the nitrate leachate marginal abatement costs. The nitrate leachate marginal abatement costs estimated by this research are usable within already standing voluntary pay-the-polluter incentive programs on the Island such as the Alternative Land Use Services 2 or Agriculture Stewardship Program by the PEI Dept. of Agriculture and Forestry, or within future polluter-pay programs such as taxes and fines paid to the Government of PEI or local watershed associations.
Alternatively, as discussed in Chapter 3 Section 3.5 Incentive Instruments for Heterogeneous Marginal Abatement Costs, non-traditional instruments to incentivize adoption, such as a water quality market may be implemented by capitalizing on the heterogeneity between marginal abatement costs of producers on high and low quality land as well as the cost-effective range of nitrate leachate abatement. Potential successful water quality markets may resemble those proposed by Horan and Shortle (2011), Kling (2011), and Shortle (2012; 2013). There is significant potential for an implementable water quality market in Prince Edward Island due to three prominent characteristics of its agricultural community. Firstly, farm sizes are constrained by the scarcity of land in Prince Edward Island, and therefore agricultural producers are familiar with other producers in their community due to the close proximity of neighbouring farms that may reduce transaction costs of trading credits. Secondly, through a variety of cost-share and direct payment programs for beneficial management practice adoption the Prince Edward Island Dept. of Agriculture and Forestry has developed trust and communication with many producers on the Island. Lastly, the issue of nitrate in groundwater is magnified due to agricultural production and residents co-existing on constrained land, which results in heightened public concern and awareness. Given this, producers may be willing to participate in water quality markets to mitigate negative public perceptions of their production practices. Given these three factors, the transaction costs to implement a water quality market on the Island for potato producers may be low. Although, it may be noted that there may be distributional impacts between producers on low and high quality land as some may be required to abate more than others due to lower nitrate leachate marginal abatement cost.

In contrast to government implemented incentive programs, the estimated nitrate leachate marginal abatement costs contribute to non-government driven incentive instruments that may be
developed by watershed associations or community groups to support more sustainable and ecologically friendly potato production practices. These groups may be interested in threatening the social licence of Cavendish Farms and McCain Food Limited for contracting with producers who do not adopt beneficial management practices to abate nitrate leachate on the Island.

An additional contribution of this thesis research is the economic – hydrologic model provides a framework that may be transferred to other watersheds within and outside of Prince Edward Island, as long as the economic and hydrologic parameters are calibrated respective to the research area in question. This research contributes to the knowledge and information of beneficial management practice adoption and nitrate leachate abatement by providing the background data that was required by the economic hydrologic model to estimate the nitrate leachate marginal abatement costs – all housed by one resource, which did not exist prior to this research. This background data includes: variable production costs for each rotation crop, potato variety, and fertilizer nitrogen rates; current prices of rotational crops and potato varieties; yield penalties associated between crop rotations, fertilizer rates as well as spring tillage. This data will be useful for stakeholders and project partners for designing incentive instruments.

Last but certainly not least, the nitrate leachate marginal abatement costs as well as the associated potato farming systems to achieve nitrate abatement targets are desired by project partners such as the Water Economics, Policy and Governance Network and the Canadian Water Network Origin, Occurrence and Fate of Nitrate in Sedimentary Bedrock Groundwater in the Maritimes research project. This thesis research output feeds into concurrent interdisciplinary research through these project partners. Furthermore, the interdisciplinary and stakeholder characteristics of this research has enabled the establishment of research relationships and communication between stakeholders early on in the research process; this provides the
foundation to share research outputs for meaningful implementation and positive outcomes on the Island. Such stakeholders are the PEI Dept. of Agriculture and Forestry, the PEI Dept. of Environment, Labour and Justice, Agriculture and Agri-Food Canada – Charlottetown, and the PEI Potato Board.

5.3 Limitations and Future Nitrate Leachate Abatement Research

This research required the integration of economic and hydrologic factors, of which posed difficulties in sourcing and estimating the interrelationships between such factors. A limitation of this research with regards to spring tillage is the monetary benefit of the nitrogen credit from spring tilling a red clover crop for the proceeding potato crop, an estimate of 17 – 22 kg N per hectare, was not accounted for within the GSP or NMP nitrogen fertilizer rate as it may double count the benefit of NMP considered within the model (PEI Dept. of Agriculture and Forestry 2014l). Future research avenues may explicitly account for the soil nitrogen credits from spring tillage.

Potato production is the traditional agricultural industry on the Island; the revenue derived from potato production makes adopting alternative agricultural farming systems unattractive. For the purpose of comparison, the revenue from Russet Burbank and Prospect potatoes given the base yields associated with the crop rotation potato-hay-hay (P,HH) are $6,702 and $6,605 per hectare whereas rotational crops are $883, $697, $1,113 and $0 for barley, barley underseeded with hay, soybean, and hay, respectively. Soybeans are the only crop with revenue remotely close to the lucrative potato. Perhaps there may exist alternative agricultural farming systems that achieve greater nitrate leachate abatement at a lower cost than potato farming systems. Potential future research could address this gap in literature and practice.
A limitation of scaling this research is nitrate leachate abatement values associated with beneficial management practices are not spatially differentiated. The hydrogeologists who performed the hydrologic modelling for the Kensington North Watersheds Association’s *An Adaptive Management Plan to Reduce Nitrates in the Upper Watersheds of the Southwest River* justified this by citing no fundamental hydrogeological differences within this specific research area (Li 2015). If future research is to consider a different watershed in PEI or elsewhere, given heterogeneous marginal abatement costs as well as heterogeneous nitrate leachate abatement, the natural future research avenue may be to analyze a water quality trading market between watersheds with both heterogeneous marginal abatement costs as well as nitrate leachate. This future avenue will rely on hydrologic modelling and geographic information systems to spatially differentiate nitrate leachate abatement given hydrogeological factors and land management practices.

5.4 Concluding Remarks
This thesis research has progressed through an introduction to the groundwater nitrate issue in Prince Edward Island and the purpose and objectives of this research, followed by a review of agricultural production and nitrate leachate in Prince Edward Island, the conceptual as well as empirical model of nitrate leachate abatement for producers on high and low quality land for the Base Potato Farming System assuming no regulation on crop rotations, *PEI ACRA* imposed restrictions on crop rotations, as well as *PEI ACRA* effects on crop rotation and nitrate leachate abatement targets. Finally a discussion of the major findings, contributions of research, limitations and future avenues to build upon this research is presented.
This research illustrates that even within the smallest province in Canada, heterogeneity between nitrate leachate marginal abatement costs resulting from producers on two different qualities of land, high and low quality, must be considered as it influences producers’ ability to abate nitrate leachate and therefore affects nitrate leachate marginal abatement costs. Incentive instruments must value these heterogeneities if the cost-efficient allocation of nitrate leachate abatement is to be achieved. This is regardless of whether incentive instruments are pay-the-polluter, polluter-pay, water quality markets, or a non-governmental driven consumer standard for potatoes grown with beneficial management practices that improve groundwater quality in Prince Edward Island.
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