Quantification of groundwater discharge to two small estuaries in Prince Edward Island

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ABSTRACT
In this contribution the total volumetric discharge of groundwater to two small estuaries in Prince Edward Island is assessed using a unique combination of airborne thermal infrared imaging, direct discharge measurements and numerical simulation of groundwater flow. The results show that direct groundwater discharge is significant, comprising 13% and 18% of the total fresh water discharge to Trout River estuary and McIntyre Creek estuary, respectively. Comparison of the results from catchment-scale groundwater flow models and the spring discharge measurements suggest that diffuse seepage to both estuaries comprises only about 25% of the total groundwater discharge.

RÉSUMÉ
Dans cette étude le volume total d'eaux souterraines qui se déverse dans deux petits estuaires de l'Ile du Prince Edouard a été déterminé en utilisant une combinaison unique d'imagerie aérienne infrarouge thermique, de mesures directes des débits et de simulations numériques des écoulements des eaux souterraines. Les résultats montrent que le débit direct d'eaux souterraines est conséquent, et compte respectivement pour 13% et 18% du flux total d'eau douce qui se déverse dans les estuaires de Trout River et McIntyre Creek. La comparaison des résultats de modèles numériques d'écoulements à l'échelle du bassin versant et des mesures de débits des sources suggère que les suintements d'eau diffus ne constituent qu'environ 25% de la contribution totale des écoulements d'eaux souterraines dans les deux estuaires.

1 INTRODUCTION

Previous research indicates that rates of anthropogenic nutrient loading have increased in most coastal waters of the world and that this increased loading is the main driving force of ecological alteration of coastal waters (e.g. *Valiela et al. 2000, Bowen et al. 2007*). Groundwater transport of nutrients has received less attention than nutrient transport by surface runoff, although some studies have shown that it may be significant in coastal areas underlain by permeable regional aquifers (e.g. *Corbett et al. 1999, Miller and Ullman 2004*). An accurate evaluation of the magnitude and controls on groundwater discharge in coastal areas is of critical importance for understanding how coastal waters and ecosystems may respond to anthropogenic or natural perturbations (e.g. *Rabouille et al. 2001, Slomp and van Cappellen 2004*).

Groundwater discharge may occur at relatively low rates over large areas (diffuse) or conversely, as localized high discharge (e.g. springs). Previous studies demonstrate that diffuse seepage to estuaries can have volumetric values comparable with those of discrete springs, but research in which direct comparisons are made is lacking (*Taniguchi et al., 2002*).

Locating areas of groundwater discharge in estuaries or coastal lagoons is complicated; however, remote sensing technologies have proven useful in some settings (e.g. *Burnett et al., 2006*). Airborne Thermal Infrared Radiometry (TIR) imaging is a technique that can be used for mapping groundwater discharge in shallow estuaries provided there is a thermal contrast between groundwater and the receiving surface waters. Previous TIR surveys in estuaries have been conducted during various seasons and times of the day (e.g. *Portnoy et al. 1998, Miller and Ullman 2004*) benefiting from a thermal contrast ranging from 8 to 17^{o}C. *Roseen (2002)* showed that prime survey windows are limited by the need to coordinate maximum temperature gradient, low tide, clear sky, no (or low) moon, calm wind, and darkness or high noon to minimize shadows.

Aerial TIR surveys used alone give only a qualitative estimate of the extent and amount of groundwater discharge. Thus other methods, such as hydraulic studies, conductivity profiles and tracers (e.g. *Akawwi 2006, Mulligan and Charette 2006, Johnson et al. 2008*) are typically used to quantify groundwater discharge. The only studies that have attempted to relate the magnitude of the thermal signature of groundwater seepage with the volumetric discharge are those of *Roseen (2002)*, who used the magnitude of the thermal signature to determine the extent of the seepage area, and *McKenna et al., (2006)*, who developed correlations between the watershed-area/shoreline-length ratio and the thermal signature.

Investigation of groundwater discharge to estuaries in Prince Edward Island (PEI) is important because of the presence of elevated nitrate concentrations in groundwater that have resulted, in part, from intensive potato production (e.g. Young et al. 2002, Savard et al. 2007). The objective of this paper is to assess the magnitude of fresh groundwater discharge, relative to the total freshwater inflows, to two small estuaries in PEI and to further develop methods which use TIR images to quantify groundwater discharge. The accurate determination of the discharge of freshwater is a prerequisite for assessing the nutrient loads from adjacent land areas to the two estuaries, and ultimately for developing management responses. Prior to this research there have been no attempts to quantify the magnitude of direct groundwater discharge to the numerous small estuaries that dot the coastline of Atlantic Canada.

2 STUDY SITES

The two estuaries selected for this research have experienced several hypoxic and anoxic events in recent years, as well as the annual proliferation and subsequent die off of *Ulva* species which can smother benthic communities. The estuaries were also selected because of the contrasting land use patterns in their catchments and their relatively small size which would facilitate the collection of field data.

The Trout River estuary (1.1 square kilometres, km^2) is located on the north shore of PEI and has a catchment area of 45.5 km^2 and 15 streams (Figure 1). The second study site, McIntyre Creek estuary, is smaller (0.10 km^2), has a 5.1 km^2 catchment and contains one stream that discharges to the estuary (Figure 1). The density of streams is higher for the Trout River catchment (1.16 km of streams/km^2) compared to McIntyre Creek catchment (0.71 km/km^2). Elevations in the Trout River catchment range from 0 to 120 masl, while for the McIntyre Creek catchment they range from 0 to 70 masl. The tidal range for the two estuaries varies from about 1.2 m (spring tides) to 0.4 m (neap tides). The diurnal and semidiurnal components of the tidal regime gradually vary in importance over two week cycles.

According to the Corporate Landuse Inventory (*PEI Department of Agriculture and Forestry 2003*), land use in the Trout River catchment is dominated by forests (53%) and agriculture (40%), while for the McIntyre Creek catchment agricultural land dominates (80% of the total area) (Table 1).

The surficial geology in the Trout River and McIntyre Creek catchments consists mostly of glacial deposits (*Prest 1973*) and highly fractured sandstone bedrock (*Francis 1989*). The sandstone is the sole-source water supply aquifer for the province. All material types are considered to have relatively high hydraulic conductivities (*Savard et al. 2004, Jiang et al. 2004*).

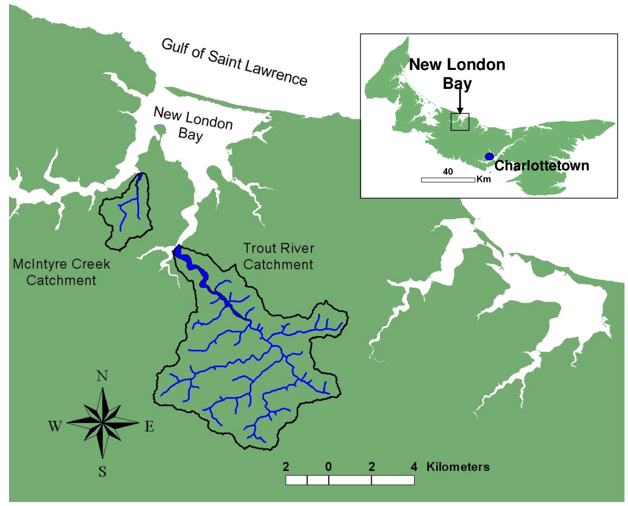

Figure 1. Location of the study sites in the province of Prince Edward Island, Canada (inset).

Table 1. Land use in the study site catchments.

Land Use	Trout River		McIntyre Creek	
	Area (km^2)	% of total area	Area (km^2)	% of total area
Agricultural	17.6	39.7	4.01	80.2
Forested	23.6	53.1	0.57	11.45
Wetlands / Water *	0.2	0.4	0.02	0.32
Other**	3.01	6.77	0.40	7.99

* Estuaries are not included in the definition of this land use type.

** Other land use types include: industrial, institutional, non-evident, recreational, residential, transportation and urban.

The climate of Prince Edward Island is humid-continental, with long, fairly cold winters and warm summers. Data provided by *Environment Canada (2008)* show that mean annual precipitation measured during 1971 to 2000 (for Charlottetown, located ~30 km southeast of the study sites; Figure 1) was 1192 mm, with 74% of the annual precipitation falling as rain and 26% as snow. The mean annual temperature is 5.3°C and mean monthly temperatures range from –8.0°C in January to 18.5°C in July.

A major groundwater recharge event due to snow melt typically occurs in April, followed by a recession of groundwater levels throughout the summer and early fall. A second groundwater recharge event often occurs in October or November due to increased rains and decreased evapotranspiration. According to *Jiang et al., (2004)* and *Francis (1989)*, aquifer recharge rates on the island range between 30% and 40% of annual precipitation.

3 METHODS

Precipitation, stream and (fresh) groundwater inflows to the two estuaries were quantified over a two-year period (2005 to 2007).

The methods used for quantification of precipitation and stream discharge to the two estuaries are presented in *Danielescu et al. (submitted*). The baseflow contribution to stream flow was estimated using eight hydrograph separation techniques applied to the continuously monitored discharge of the largest stream of each catchment.

Direct groundwater discharge to the estuaries was conceptualized to occur via two pathways: groundwater discharge through near-shore springs, and diffuse groundwater seepage. Groundwater discharge to streams (i.e. baseflow) was considered as part of stream flow and therefore it was not included in the calculation of (direct) groundwater discharge to the two estuaries.

3.1.1 Discharge via near-shore springs

To assess groundwater discharge via springs, the locations were first identified using airborne TIR (e.g. *Portnoy et al. 1998, Mulligan and Charette 2006*). TIR sensors measure the temperature of the water surface, therefore to detect groundwater discharge in estuaries, the discharge must be of sufficient magnitude or buoyancy to create a thermal signature at the water surface.

TIR surveys of McIntyre Creek estuary and Trout River estuary were conducted in September 2005, during low tide, warm weather and clear sky conditions, using a SC-3000 thermal infrared radiometer (0.02^{0}C thermal sensitivity, FLIR Systems, OR, USA) mounted inside a Cessna 172 airplane. The conditions during the survey were near optimum for detecting thermal contrasts between the cold groundwater (approximately 10^{0}C) and the warmer estuarine water (approximately 20^{0}C). Approximately 50 line-km of images were collected during a one hour flight at an altitude of 900 m. The thermal images were calibrated and verified using data from 46 temperature loggers (Minilog, VEMCO Limited, NS, Canada) deployed at 10-15 cm depths in the estuaries and tributaries at the time of the aerial survey. The raw TIR digital images were converted to temperatures and a 1 m-resolution thermal grid for both estuaries was produced.

Based on a procedure adapted from *Roseen (2002)*, the spatial extent of the groundwater thermal discharge plume for each spring was determined by using an inflection point technique. The two-dimensional thermal grid was subsampled in Arcview 3.3 (ESRI, CA, USA) and the cells of this grid were used to produce the distribution of water temperature versus cumulative area (i.e. the area covered by each temperature value). Each plot typically displayed three distinct zones delimited by two inflection points. The first zone corresponded to cold water (i.e. groundwater), followed by the transition zone between groundwater and estuary water, and by the warm water zone (i.e. estuary water). The area corresponding to the first inflection point was selected to represent the area of the thermal plume generated by each spring.

In July 2007, the discharge was measured directly at nine springs that were exposed at low tide (seven in Trout River estuary and two in McIntyre Creek estuary) using a portable RBC flume (*Bos et al., 1984*). The measured discharge was corrected for flow that could not be captured by the portable flume (i.e. small seeps separated from the main flow) and for the presence of saltwater. The average contribution of saltwater to spring discharge at the time of measurement was below 10%. The corrected spring discharges were then regressed against the spatial extent of the thermal plume of the springs, and the resulting logarithmic correlation was used to determine the discharge for springs that were not directly monitored.

To produce daily discharge hydrographs for the springs, the ratio between the measured spring discharge and the stream baseflow in the closest tributary to the spring (i.e. for the date when the spring discharge was measured) was used. Assuming that near-shore spring discharge follows the same dynamics as stream baseflow, the stream baseflow hydrograph was then used to generate the daily spring discharge hydrograph.

3.1.2 Diffuse groundwater seepage

The second component of direct groundwater discharge to the estuaries may occur at relatively low rates over larger spatial regions than groundwater discharged through springs. This component was estimated using results from steady-state and transient, three-dimensional, finite difference models for groundwater flow (Visual MODFLOW, Waterloo Hydrogeologic Inc., ON, Canada). The diffuse seepage was calculated as the difference between the total simulated groundwater discharge to the estuaries and the spring discharge obtained from the TIR-direct measurement correlation.

Both the steady-state and transient groundwater flow models were built and calibrated for each of the study sites based on data obtained from monitoring, existing hydrogeological information, and previous studies conducted in the Wilmot River catchment located about 10 km south of the study sites (*Jiang et al. 2004, Savard et al. 2004*). Either site-specific data (such as elevation, stream network geomorphology, spatial extent of estuarine area and contributory area) or literature data (in the absence of site-specific data), have been used to construct the models.

The models were based on a 10 m horizontal grid, using three hydrostatigraphic layers with a thickness of 40 m for the upper layer, 50 m for second layer, and a fixed elevation of -150 m for the bottom layer (*Jiang et. 2004, van der Kamp 1981*). Recharge, determined using the method presented by *Armstrong and Narayan (1998)* and water level data from four wells located in the Trout River catchment, was assigned to the upland model cells. Eight hydraulic conductivity zones were defined for Trout River and six for McIntyre Creek. The values of the hydraulic conductivities for the aquifer layers, as well as those for the stream and estuary bed sediments, were adjusted during the model calibration. The MODFLOW River Package (*Harbaugh et al. 2000*) was used to simulate cells of the grid belonging to the estuary. The thickness of the estuary bed sediments was assumed to be 1.5 m (*Jiang et al.* 2004) and the hydraulic conductivity was calibrated during the model runs. The Stream Package (*Harbaugh et al. 2000*) was used to simulate the streams of both catchments.

The steady-state and transient models were calibrated such that the simulated baseflow (i.e. stream leakage from MODFLOW) was close to that resulting from hydrograph separation, and the difference between simulated groundwater heads and water levels measured in four wells located in Trout River catchment was minimized. The steady-state models for Trout River and McIntyre Creek were calibrated primarily by adjusting the hydraulic conductivities of the upland areas, estuary and stream beds and the transient-state models were calibrated by adjusting the specific yield and the temporal distribution of recharge. The strength of the calibration was determined using the Nash-Sutcliffe efficiency coefficient (*Nash and Sutcliffe 1970*), correlation coefficient and the standard error ratio (e.g. *McCuen 1992*).

4 RESULTS

The average annual precipitation recorded at the Charlottetown weather station between July 2005 and July 2007 was 1098.9 mm (*Environment Canada, 2008*), which translates into a direct inflow of 0.037 m^3/s for the Trout River estuary and 0.0035 m^3/s for McIntyre Creek estuary.

Daily stream discharge hydrographs (not shown) exhibit similar patterns for both study years, with discharge being correlated with precipitation and partial or complete snowmelt processes. The average stream inflow for the entire monitoring period from all streams, based on hourly data, was 0.67 m^3/s for Trout River estuary and 0.071 m^3/s for McIntyre Creek estuary.

The baseflow for Trout River varied between 78 to 92% of the total stream discharge, with an average of 85%, while for McIntyre Creek it varied between 78 and 91% with an average of 84% of stream flow. After the baseflow estimate for Trout River was extrapolated to the other streams, based on the correlations among the measured stream discharges, the average contribution of groundwater to stream flow was estimated as 0.55 m^3/s for the Trout River catchment and 0.059 m^3/s for McIntyre Creek.

4.1 Groundwater discharge via near-shore springs

Following the calibration, correction and geo-referencing of TIR images, 49 cold water discharge locations were detected in the Trout River estuary and nine in the smaller McIntyre Creek estuary (e.g. Figure 2). An example of a detailed view of two cold-water discharge locations is shown in Figure 3. Here the plume of cold groundwater from spring T20, which discharges directly to the estuary, can be clearly delineated and differentiated from the warmer water of the estuary. Parson's Spring (19), which is a small groundwater-fed stream, displays higher temperature upon entering the estuary because it first flows through a small marsh area. Localized areas of cold water temperature, such as shown in Figure 3, were commonly observed and this finding suggests that groundwater discharge locations are controlled by heterogeneity in the glacial deposits or fractured bedrock aquifer.

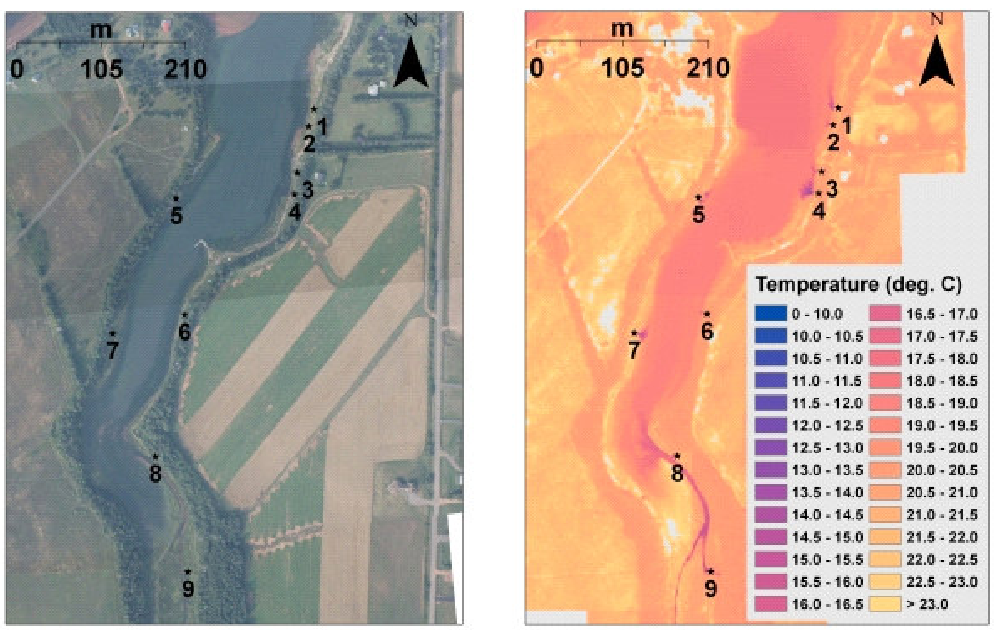

Figure 2. Groundwater discharge locations identified in McIntyre Creek estuary. The left panel is the aerial photograph and the right is the thermal infrared image. The groundwater discharge locations are denoted by numbers 1 thru 9.

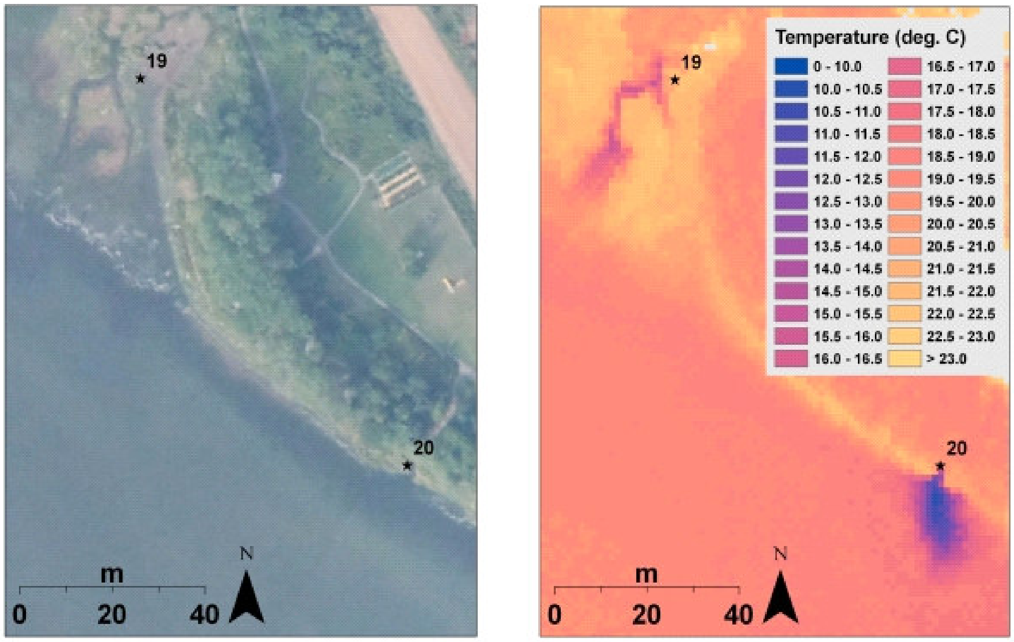

Figure 3. Detailed image of locations 19 (small stream) and 20 (spring T20) on aerial photograph (left) and thermal infrared image (right), Trout River estuary.

In April 2006 the location of springs and seeps was verified in the field using handheld temperature measurements and direct observations, and after removing the false positive thermal signals (i.e. cold water originating from streams and not groundwater springs), 34 groundwater springs in Trout River estuary (denoted with "T") and nine in McIntyre Creek estuary (denoted with "M") were used for further analyses.

The area of the thermal plumes created by the springs, identified by using the inflection point technique (e.g. Figure 4), varied between 39 and 1145 m^2 for Trout River estuary and between 25 and 491 m^2 for McIntyre Creek estuary. All the cumulative area plots showed a similar sigmoid shape, but because of the variation in the thermal plume size and the local conditions (i.e. mixing of waters, channel type, etc.) the relative position of the inflection points varied.

For the locations where spring discharge was measured, there was a good logarithmic correlation between discharge and the area of the thermal plumes (Figure 5). Although the reason for a logarithmic relationship is not entirely clear, it is likely related to the rate of groundwater discharge and mixing of the discharged groundwater in the estuaries. Two of the springs where the discharge was measured (i.e. M09 and T22) were excluded from the correlation because they were located in areas of very low temperature contrast between groundwater and estuarine water. The discharge and thermal plume area determined for spring T40 (0.0154 m^3/s and 678 m^2) were not consistent with other spring locations, and it also was not used in the correlation analysis.

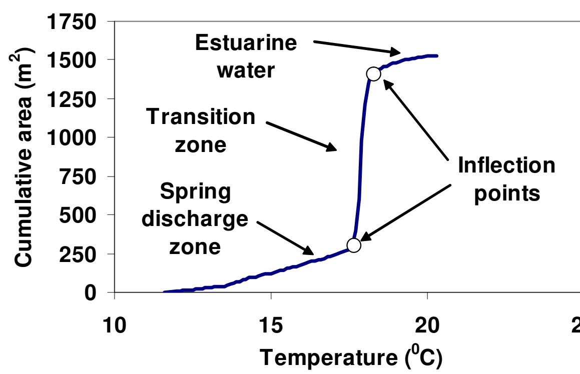

Figure 4. Delimitation of spring thermal signature area for spring T03, Trout River estuary.

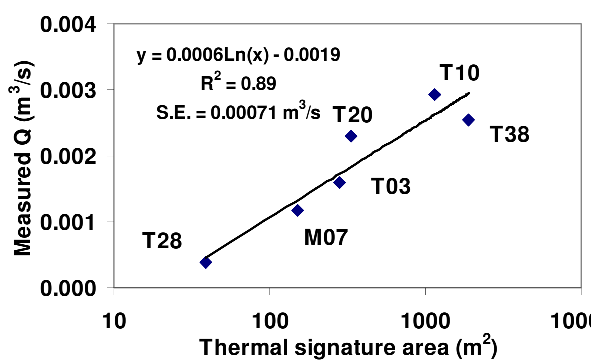

Figure 5. Relationship between measured spring discharge and area of the spring thermal signature. "M" denotes a spring in the McIntyre Creek estuary, while "T" denotes springs in the Trout River estuary.

The regression equation was applied to all the springs, and subsequently, the ratio between the discharge for each spring and the stream baseflow in the closest tributary to each particular spring, was used to produce a daily hydrograph of spring discharge. Total annual spring discharge (Table 2) was then obtained from these hydrographs. The total annual spring discharge for the monitoring period was 0.067 m^3/s for Trout River estuary and 0.013 m^3/s for McIntyre Creek estuary. With a few exceptions, the flows from individual groundwater springs were on the order of 10^{-3} m^3/sec (Figure 6).

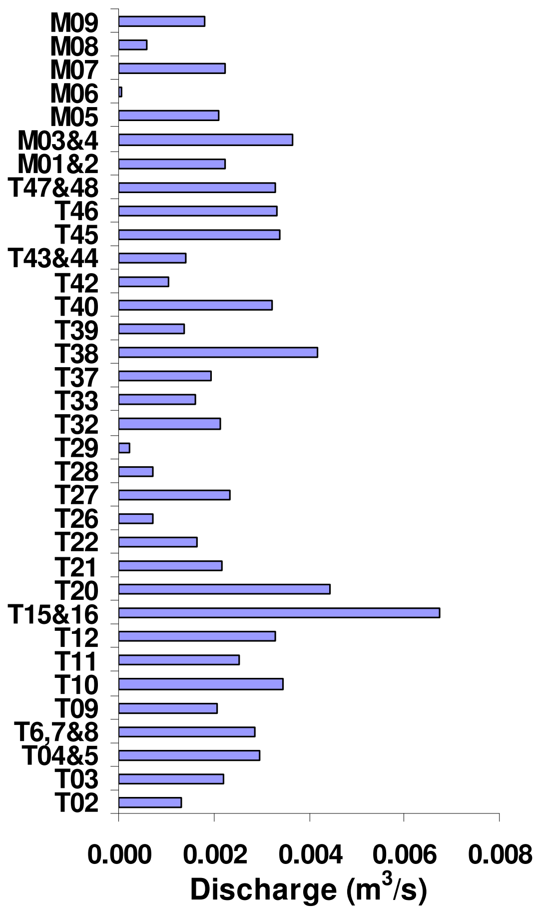

Figure 6. Annual average discharge for shore-line springs in Trout River estuary (prefix T) and McIntyre Creek (prefix M) estuary.

Application of the equation of state presented by *Crowley (1968)* indicates that, given the range of temperatures and salinities measured in springs and estuaries, the density of fresh groundwater is less than that of estuary water and thus freshwater discharging to the estuaries will be buoyant. A visual inspection of the thermal infrared results shows no obvious thermal contrast in the offshore areas, unlike the obvious plumes that were detected near the shore line. Previous studies (e.g. *Taniguchi et al,. 2002; Bowen et al., 2007*) suggest that diffuse groundwater discharge is inversely correlated with distance from shore and therefore a lack of thermal contrast in the offshore areas may be expected.

4.2 Groundwater flow modeling results

For recharge, an estimate of 462 mm/yr (i.e. 42% of precipitation), based on a specific yield of 0.085 and hourly water levels recorded between November 2005 and July 2007 in four wells, was obtained. Stream-bed hydraulic conductivities were adjusted during model calibration, yielding values between 2 x 10^{-7} and 6 x 10^{-7} m/s for Trout River streams and 2.8 x 10^{-5} m/s for McIntyre Creek. The hydraulic conductivity of model cells that represented the estuary sediments was also calibrated during the model runs producing values of 8 x 10^{-9} m/s for Trout River estuary and 10^{-7} m/s for McIntyre Creek estuary. Hydraulic conductivities of the layers of the model were adjusted during model calibration and were on the order of 10^{-8} to 10^{-7} m/s for horizontal hydraulic conductivity.

After calibration of the transient simulations, the difference between the total stream baseflow estimated using hydrograph separation and the simulated stream leakage component was less than 1.3% for both estuaries. The Nash-Sutcliffe model efficiency coefficient value was 0.35 (moderate) for Trout River estuary, with a correlation coefficient of 0.44 (moderate) and a standard error ratio of 0.77 (moderate improvement provided by the model compared to the mean), while for McIntyre Creek estuary the Nash-Sutcliffe coefficient value was 0.90 (high), with a correlation coefficient of 0.90 (high) and 0.33 for the standard error ratio (significant improvement provided by the model compared to the mean).

4.3 Diffuse groundwater seepage to estuaries

The diffuse seepage component of groundwater discharge to the estuaries was obtained by subtracting the monthly spring discharge from the simulated total monthly groundwater discharge. For the three instances when the difference yielded slightly negative values (i.e. discharge through springs larger than total groundwater discharge to the estuary), the total groundwater discharge was considered to consist of only discharge through near-shore springs.

The maximum contribution of diffuse seepage to groundwater discharge was in the late winter – early summer period, with a maximum of 54% for Trout River estuary in March 2006 (i.e. 0.060 m^3/s) and 53% (i.e. 0.0065 m^3/s) for McIntyre Creek estuary in July 2005. The average diffuse seepage for the two estuaries was estimated as 0.038 m^3/s for Trout River estuary and 0.0038 m^3/s for McIntyre Creek estuary.

5 DISCUSSION: RELATIVE CONTRIBUTIONS OF FRESHWATER

Groundwater discharge, dominated by the discharge via near-shore springs, plays an important role with a 13% contribution to the total inflow for Trout River estuary and an 18% contribution for McIntyre Creek estuary. The increased importance of groundwater discharge for McIntyre Creek estuary may be explained by the lower density of streams in that catchment, which provides fewer upland discharge locations for baseflow when compared to the Trout River catchment. The average diffuse seepage is 36.2% of the total groundwater discharge for Trout River estuary and 22.8% for McIntyre Creek estuary.

The results obtained for total groundwater discharge in this study are somewhat larger than global-scale estimates of groundwater discharge to coastal areas, which have been suggested to be between 6 to 10% of surface water inputs (*Taniguchi et al., 2002*); total groundwater discharge to the Trout River and McIntyre Creek estuaries is 16% and 24% of the stream discharge, respectively. However, as noted in the studies summarized by *Taniguchi et al., (2002)*, at the scale of individual estuaries results can span a much wider range.

Table 2. Average annual freshwater inflows to the estuaries and relative contribution of each pathway during the study period.

Component	Trout River estuary (m^3/s)	% of total inflow	McIntyre Creek estuary (m^3/s)	% of total inflow
Precipitation	0.038	4.6	0.0038	3.9
Stream discharge	0.67	82.5	0.071	78
Groundwater discharge via near-shore springs	0.067	8.2	0.013	14
Groundwater discharge via diffuse seepage	0.038	4.7	0.0038	4.1
Total inflow	0.81	100	0.092	100

Although near-shore springs and seeps are relatively widely spaced in both the Trout River and McIntyre Creek estuaries, it is clear from the data presented that their role in groundwater discharge is significant. It may therefore be possible to obtain a first-order estimate of total groundwater discharge to estuaries on Prince Edward Island by quantifying only the discharge from near-shore springs. *Corbett et al. (1999)* made a similar observation in Florida Bay, where tidal springs and solution holes in the underlying limestone allow for significant groundwater discharge.

6 CONCLUSIONS

Airborne Thermal Infrared Radiometry (TIR) imagery proved to be a reliable and rapid technique for locating groundwater discharge locations along the shorelines of these two estuaries, and we have shown that the area of the thermal plumes generated by near-shore springs correlates well with the discharge measured at a sub-set of the springs. This information, coupled with the finding that diffuse seepage is much less significant than spring discharge, could be used in other studies in the region to provide a relatively rapid estimate of the contribution of groundwater discharge to estuaries.

The results from this two-year study reveal that the magnitude of direct groundwater discharge to two small estuaries is significant, at 13 to 18% of the total inflow, and this pathway, which has not previously been quantified in PEI, may be an important contributor to nutrient loading depending on the relative nutrient concentrations in streams and groundwater. Near-shore springs have been identified as the dominant mode of groundwater discharge, and this is likely a result of the fractured nature of the contributing aquifer. Although stream discharge is the major influx of freshwater, it must be noted that in the catchments we have investigated (which are similar to most PEI catchments), approximately 85% of the annual stream flow is derived from groundwater baseflow. The interactions between groundwater and surface water (streams and estuaries) are thus very significant and cannot be ignored when assessing the fate of nutrients from agriculture. Because much of the eastern coastline of New Brunswick and the northern shore of Nova Scotia are underlain by similar hydrogeological units, we expect that these results will also be relevant to other areas in Atlantic Canada.

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