AN ECOHYDRAULICS APPROACH TO INCREASING RIVERINE PRODUCTION OF JUVENILE WILD ATLANTIC SALMON (*SALMO SALAR*)

by

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DEDICATION

For the fish

and

for the future generations of New Brunswickers who rely on them.

ABSTRACT

The number of wild Atlantic salmon (*Salmo salar*) in North American rivers is at the lowest level ever recorded and, in some rivers, the number continues to decline. Potential reasons for the decline in abundance include loss at sea, commercial overfishing, and ocean and freshwater habitat degradation. This project is related to the freshwater habitat of the juvenile wild Atlantic salmon.

A large-scale habitat enhancement project was undertaken on the Little Main Restigouche River in northwest New Brunswick to improve juvenile wild Atlantic salmon habitat and to increase juvenile wild Atlantic salmon production. Approximately 300 boulder clusters were constructed at three sites on the river at a total cost about $24,000 and were designed by an interdisciplinary team of engineers and biologists using an ecohydraulics approach. The clusters contained 9-12 rocks oriented in a triangular shape with the largest rock at the apex where rock sizes ranged from 0.08 to 1.4 m. Spacing between clusters ranged from 1.5 to 3.0 m. Preliminary observations have shown that the clusters can withstand high velocities generated by high-flow events and impacts from moving large woody debris, and that invertebrate and macrophyte colonization of the clusters has occurred. Results from an electrofishing survey of the enhanced sites revealed that juvenile Atlantic salmon appear to prefer the clusters compared with the existing river substrate.

A laboratory study at the microhabitat scale was conducted to observe and predict changes in microhabitat hydraulics and physical habitat diversity due to different orientations of modelling rocks, and a field study at the macrohabitat scale was conducted to identify a target physical habitat diversity value for enhancing juvenile Atlantic salmon (*Salmo salar*) habitat in the Little Main Restigouche River. At the

microhabitat scale, a 1 m by 1 m quadrat system was placed over three arrangements of modelling rocks in the laboratory flume: modelling rock oriented with long axis parallel to flow, modelling rock oriented perpendicular to the flow, and five modelling rocks oriented in a triangular cluster with the largest rock at the apex. At each grid node, velocities were measured at three depths in both the x and y directions. Froude and Reynolds Numbers were calculated and were used to create contour plots. The coefficient of variation was calculated from mean Froude and Reynolds Numbers to quantify physical habitat diversity. At the macrohabitat scale, instream physical habitat was quantified by random measurements of velocity, depth, and substrate. Froude and Reynolds Numbers were calculated from velocity and depth data. The coefficient of variation was calculated from mean substrate, Froude Number, and Reynolds Number values to quantify physical habitat diversity. The results from the microhabitat scale experiment showed that Froude and Reynolds Number contour plots identified disturbances to existing flow patterns that are beneficial for juvenile fish. The cluster orientation was found to be more diverse than the single rock orientations. In the macrohabitat experiment, a target physical habitat diversity value could not be identified due to the inconsistent ranking in substrate, Froude Number, and Reynolds Number diversity.

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CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

The wild Atlantic salmon (*Salmo salar*) is considered an endangered species worldwide (Bardonnet and Baglinière 2000); in New Brunswick, the persistence of the species is tenuous. During the years 1999 to 2002, the Department of Fisheries and Oceans (DFO) reported that wild adult Atlantic salmon returns in the Restigouche River in northern New Brunswick failed to meet conservation requirements (DFO 2003). The Atlantic salmon is not only important economically – the recreational salmon fishery in New Brunswick is valued at $28.6 million per year (McIntosh 2001) – but it is also an important ecological, cultural, and historic species in New Brunswick and a population collapse will have negative consequences for the province.

Many factors are believed to have contributed to the problem of declining Atlantic salmon populations including commercial overfishing, reduced food availability at sea, degraded river habitats, and ecological problems linked to salmon farming (Owen 2005). A major factor causing the decline, at least in eastern Canada, is survival at sea, where it is estimated that less than five percent of young ocean-migrating salmon (smolts) survive to return to their native rivers as adults (R.A. Cunjak, pers. comm. 2003). However, investigating the factors that influence marine survival is logistically difficult, inherently complex, and extremely expensive. The focus for this study is based on the premise that if freshwater production of the juvenile phase of wild Atlantic salmon is enhanced, then the opportunities for populations to survive larger scale environmental variability will improve.

It is widely recognized that the environment inhabited by juvenile Atlantic salmon (parr) is a critical factor in riverine production of Atlantic salmon (deGraaf and Bain

1986, Armstrong et al. 2003). The Little Main Restigouche River (hereafter referred to as the Little Main) is the headwater tributary of the Restigouche River (Figure 1.1). Yearly electrofishing surveys conducted in the Little Main since 1997 by biologists at JD Irving Ltd. (JDI) have identified that, in some areas, up to 100 percent of the juveniles are either not surviving or are emigrating (JDI, unpublished data 2005). According to Coulombe-Pontbriand and Lapointe (2004), "...large cobble and boulder substrate is an essential component of rearing, sheltering, and overwintering habitat and it has been speculated that in some river systems, long reaches with little substrate coarser than small cobbles could be limiting to parr production". Field surveys and geological maps of the Little Main indicate a cobble and boulder deficiency and an otherwise homogeneous substrate in size and shape that could, in the worst case, contribute to high parr mortality from lack of shelter from avian predators and lack of winter habitat (Cunjak 1988) and, in the best case, parr emigration to better habitat (Cunjak 1996). In either scenario, the lack of suitable cobble and boulder sized substrates in the Little Main could cause undue stress and low parr abundance.

A potential means to increase the abundance of riverine Atlantic salmon in the Little Main is to improve access to favourable rearing habitat. The purpose of this project is to enhance juvenile Atlantic salmon habitat by adding cobble and boulder-sized rock (boulder clusters) in riffle and run/glide reaches to increase habitat suitability, complexity, and hydraulic diversity in the long-term. It is hoped that an increased number of surviving parr will lead to an increase in wild adult Atlantic salmon returning to spawn. However, to have a measurable effect, the boulder clusters must be effective for many years. Thus to ensure the integrity and sustainability of the boulder cluster structures, analyses of past projects, field surveys, and hydraulic modelling in the laboratory were conducted.

There are two phases to this five-year multi-disciplinary study. In the first phase, an engineering graduate student designed, lab-tested, and guided construction of boulder cluster habitats in the study river. In the second (ongoing) phase, a biology graduate student will investigate the biological effectiveness of the boulders and the subsequent Atlantic salmon response to the structures.

The objectives of the first phase, or the design and construction phase of the study described in this thesis, were to:

1. characterize the hydrology, hydraulics, and geomorphology of the study rivers;
2. in the laboratory, observe and describe changes to the microhabitat hydraulics around boulders due to different flow regimes, boulder sizes and shapes, and boulder configurations; and
3. design and construct sustainable boulder clusters that will serve as juvenile Atlantic salmon habitat in the study river.

This thesis is composed of four chapters. The first chapter contains background information and data collected concerning the study rivers in general. The following two chapters (Chapters 2 and 3) contain two manuscripts to be submitted to peer-reviewed publications. The first describes a method to measure microhabitat hydraulics and to calculate physical diversity at micro and macrohabitat scales; the second describes the design and construction of habitat enhancement structures in the Little Main Restigouche River. The author of this thesis designed the research methodology, conducted the research, analyzed the data, and was the primary investigator and author for both manuscripts. Chapter 4 contains conclusions and recommendations, and is followed by appendices.

1.1 BACKGROUND

1.1.1 Ecohydraulics

It is becoming increasingly accepted by the scientific community that complex phenomena cannot be studied within a single discipline. For example, climate change studies must involve an interdisciplinary team of atmospheric scientists, ecologists, sociologists, engineers, computer programmers and many others collaborating to provide an array of potential societal and ecological impact scenarios. While fish habitat is not as multivariable as our atmosphere, it is a complex mix of interdependent physical and biological components that include channel structure, streamflow, water quality, and food-web relationships (Rundquist and Baldrige 1990, Armstrong et al. 2003). It was, therefore, a goal of this study to involve an interdisciplinary team of biologists and engineers because, according to Kemp et. al (1999), "given the complex nature of river and stream habitats, knowledge of river form, function, and corresponding ecological processes is required to ensure long term sustainability of stream habitat enhancement projects". An important consideration in the design of the enhancement structures was the long-term impact on the population dynamics of the Atlantic salmon; thus the collaboration of the engineers' knowledge of hydraulic stability and river processes, and the biologists' knowledge of Atlantic salmon and river ecology were critical.

The approach used in this study, coined "ecohydraulics", provides a neutral venue to link river ecology and river engineering (Katopodis 1996) and has been shown to be clearly advantageous in other studies (e.g. Kemp et. al 1999; Kemp et. al 2000; Bockelmann et al. 2004). Ecohydraulics is defined as the study of water and its relationships with biota and the physical environment and is, by nature, an interdisciplinary endeavour. In this study, ecohydraulic principles were incorporated by assimilating Atlantic salmon habitat requirements into the design of the habitat enhancement structures.

1.1.2 Juvenile Atlantic salmon biology

Atlantic salmon have a very distinct life cycle; they spend part of their lives in freshwater and part of their lives in salt water. For each freshwater life cycle stage different water velocities, water depths, and substrate sizes are required. This study focused on the juvenile (parr) stage that refers to the free-swimming, freshwater stage of salmonid fishes that are between 0.5 to 6 years old. It precedes the 'smolt' stage when parr make physiological and behavioural transformations to permit them to enter saltwater (deGraaf and Bain 1986). The parr stage is widely recognized as a critical survival point for young salmon (deGraaf and Bain 1986, Armstrong et al. 2003); therefore, creating favourable riverine conditions for parr can potentially improve the survival of the species as a whole. For Atlantic salmon parr, the ideal physical habitat conditions during summer (no-ice conditions) are shown in Table 1.1.

Table 1.1. Preferred summer (no-ice conditions) habitat for Atlantic salmon parr (Adapted from Rundquist and Baldrige 1990; Armstrong et. al 2003).

Physical habitat feature	Juvenile preference
Water velocity	10 – 65 cm/s
Water depth	20 – 70 cm
Substrate size	6.4 – 51.2 cm

Limited winter habitat has also been identified as being a major factor affecting parr abundance (Rundquist and Baldrige 1990; Cunjak 1996; Cunjak et. al 1998). Surface ice formation reduces available and suitable habitat for juveniles, such that intraspecific competition and emigration increases due to overcrowding, potentially causing severe stress to juveniles (Cunjak et al. 1998, Prowse 2000). Active frazil ice can be conveyed to the bottom of a river in shallow, turbulent flow and form anchor ice that can quickly grow and spread over sections of the channel bed (Cunjak et. al 1998). Although solid ice growth into the substrate is detrimental to young salmonids as it can freeze redds and juvenile fish (Rundquist and Baldrige 1990, Cunjak et al. 1998, Prowse 2000). Thus, considerable attention was given to the winter habitat requirement needs of parr to improve the efficacy of the habitat enhancement project in winter. For Atlantic salmon parr, ideal winter water velocity, depth, and substrate sizes are shown in Table 1.2.

Table 1.2. Preferred winter habitat for Atlantic salmon parr (Adapted from Rundquist and Baldrige 1990; Heggenes et al. 1999).

Physical habitat feature	Juvenile preference
Water velocity	0 – 30.5 cm/s
Water depth	> 20 cm
Substrate size	> 8.0 cm

1.1.3 Habitat Enhancement

Habitat enhancement is defined by Brookes et al. (1996) as "any instream structure designed to improve habitat quality". A common method to improve habitat for fish is to alter the instream physical environment to increase heterogeneity in cover, velocity, depth, and substrate by placing artificial structures in the stream. Such artificial structures include log-weirs, drop structures, blast pools, large woody debris, as well as boulder clusters which are the in-stream habitat enhancement method used in this study.

Instream habitat enhancement structures are becoming more popular due to perceived uncomplicated designs, perceived beneficial impacts, ease of construction, and low cost. The designs for most enhancement structures attempt to replicate natural conditions and recommend the use of natural materials (such as local rock) that are easy to acquire and inexpensive to use. However, it is estimated that less than half of the known instream structures have been evaluated and for those that have been evaluated, both successes and failures have been documented (Brookes et al. 1996). In some cases, the failures have been due to a lack of understanding of river processes and in others due to a lack of understanding of river ecology.

1.1.4 Boulder Cluster Habitat Enhancement

Large cobble and boulder sized substrates are essential components to parr survival as they provide overhead shelter, aeration, food source habitat, home territory, and over-wintering habitat (Saldi-Caromile et al. 2004). It was Kalleberg (1958) who first documented a relationship between the density of juvenile salmonids and the size and density of available substrate. Studies have since shown that instream placement of boulder clusters has led to a temporary increase in local populations of salmonids (eg. Saunders and Smith 1962; Fuller 1990; Huusko and Yrjana 1997; Ward 1997) and of juvenile Atlantic salmon in particular (e.g. Gilbert 1978; Bourgeois et al. 1993; Van Zyll de Jong et. al 1997). However a lack of documentation exists on fish responses to habitat improvement measures (Cowx and Van Zyll de Jong 2004) and on whether boulder clusters are stable in the long-term. In some cases such as the Gilbert (1978) project on the Tracadie River New Brunswick, the clusters failed a few years after construction (J.C. Gilbert, pers. comm. 2004) due to the infilling and eventual paving of the clusters with smaller substrate particles.

Boulder clusters are groups of large rocks – usually greater than 30 centimetres in diameter – placed in a stream to improve fish habitat by increasing or restoring structural complexity and hydraulic diversity (Fuller 1990; Fischenich and Seal 1999, Saldi-Caromile et al. 2004). At present, only rough guidelines have been developed to guide the construction of clusters (Shamloo et al. 2001) and little information is available on their proper placement to achieve enhancement objectives. Even less information is available on their influence on stream hydraulics (Boelman and Stein 1997). Guidelines to construct boulder clusters (Table 1.3) were developed with fish habitat in mind, but not production of Atlantic salmon parr; thus it was unclear as to whether the guidelines were suitable for this species. Therefore, the existing guidelines were used solely as a reference. Other factors that were considered for generating practical guidelines for construction of boulder clusters in the Little Main were derived from river hydraulic and geomorphic surveys, juvenile Atlantic salmon habitat preference data, and laboratory hydraulic modelling that will be discussed in Chapter 3.

Table 1.3. Recommended boulder cluster construction guidelines developed by river scientists for the construction of adult fish habitat enhancement (Adapted from Rundquist and Baldrige 1990; FISRWG 1998; Fischenich and Seal 1999).

Boulder Cluster Construction Guidelines
Current speed must exceed 0.6 m/s
Boulders must be large (0.9 – 1.5m), irregularly shaped, and weigh more than 150 kilograms
Boulders should be spaced 1m from adjacent boulders and 1m from stream bank, preferably in the thalweg to ensure habitat availability during low flow
Clusters should consist of 3 to 5 boulders in a triangular configuration
Clusters should be separated by a distance equal to 1/3 of the stream width
Clusters should occupy less than 10 percent of flow area at bank full flow
Clusters should be located in the downstream half of riffles
Avoid cluster placement in braided and/or unstable sections
Clusters are not recommended for use in sandy streams

1.2 THE STUDY RIVERS

This section describes the hydrology, geology, and geomorphology of the study rivers that include the Restigouche River, the Little Main Restigouche River (the headwater tributary to the Restigouche River; Figure 1.1) and the Gounamitz River (a tributary to the headwaters; Figure 1.1). The habitat enhancement project was constructed in the Little Main Restigouche River and the Gounamitz River was used as a reference river.

1.2.1 The Restigouche River

1.2.1.1 Description

The Restigouche River (67° 30' W; 47° 45' N) originates in the Chaleur Highlands in north-western New Brunswick and flows in a north-easterly direction where it forms the border between New Brunswick and Quebec before emptying into the Baie des Chaleurs (Figure 1.1). The river is famous for having the second largest abundance of Atlantic salmon in Atlantic Canada; this abundance supports an Aboriginal sustenance fishery and a recreational fishery (DFO 2003) that contributes to the $28.6 million recreational salmon fishery in New Brunswick (MacIntosh 2001).

Two minor rivers, the Little Main Restigouche River (drainage area 1570 km^2) and the Gounamitz River (drainage area 460 km^2) are the study rivers for this project. Four major tributaries join the Restigouche on its course: the Kedgwick River (drainage area 1584 km^2), the Patapedia River (drainage area 919 km^2), the Upsalquitch River (drainage area 2503 km^2), and the Matapedia River (drainage area 3734 km^2) (Inland Waters Directorate 1980). The Restigouche Basin is relatively unspoiled, with sparse human habitation and no major dams; however its abundant forests support a large forestry industry (Inland Waters Directorate 1980).

1.2.1.2 Hydrology

Two Water Survey of Canada hydrometric stations exist in the Restigouche River, one below the confluence of the Kedgwick and Little Main Restigouche Rivers (01BC001, referred to as the Kedgwick station) and one below the confluence of the Upsalquitch and Restigouche Rivers (01BJ007, referred to as the Rafting Ground Brook station) (Figure 1.1). The nearest station to the habitat enhancement project site is located at the Kedgwick station where the drainage area tributary to the gauging station is 3160 km^2.

The Peak Annual Daily Flow discharge record from 1963-2001 at the site is shown in Appendix A.

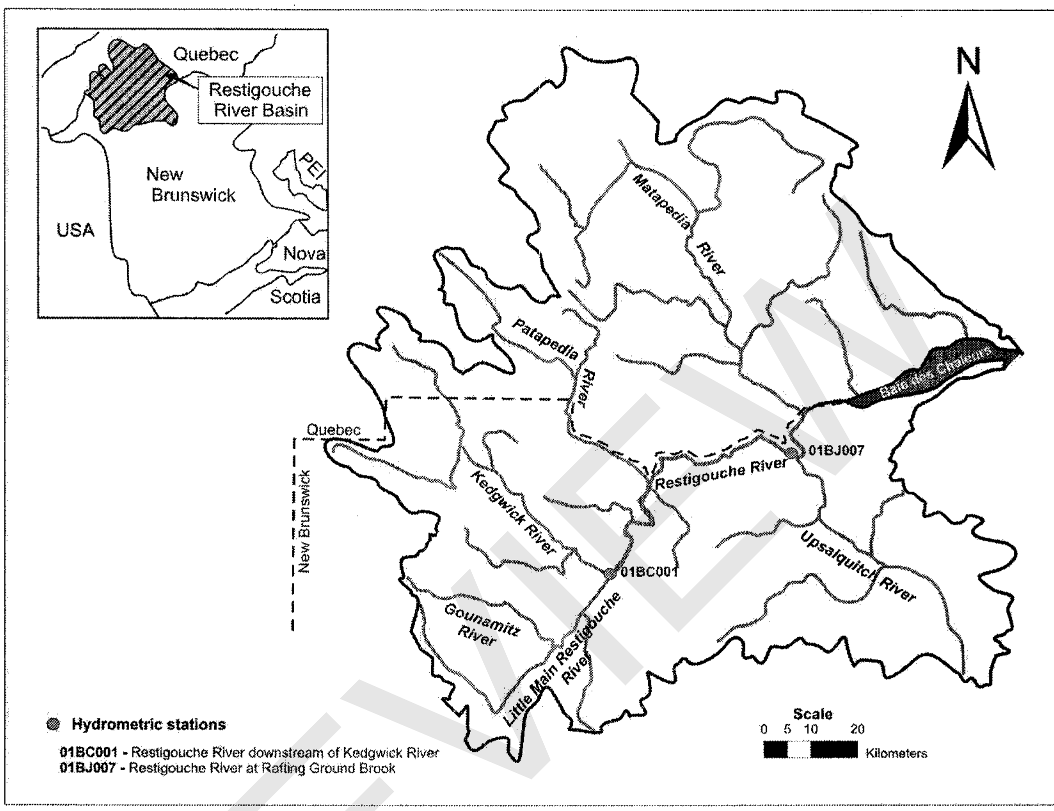

Figure 1.1. The Restigouche River Basin (Adapted from Inland Waters Directorate 1980). Water Survey Canada hydrometric stations are located downstream of the confluence of the Kedgwick and Restigouche Rivers (01BC001) and upstream of the confluence of the Upsalquitch and Restigouche Rivers at Rafting Ground Brook (01BJ007).

Discharge data from the Kedgwick and Rafting Ground Brook hydrometric stations (Figure 1.1) were analyzed over the past four decades using the Mann-Kendall statistical test to examine trends in mean annual discharge, mean monthly discharge, annual peak daily discharge, and annual peak daily discharge timing (see Appendix A) that may affect Atlantic salmon habitat enhancement efforts. It was found that mean annual and peak annual daily streamflow are declining, that discharge is declining mostly in the late spring and summer months, and that annual peak daily discharge is occurring earlier in the year (see Appendix A). Declining river mean and peak annual discharges may cause changes in river morphology, ice regimes, and flood flows (Leopold et al. 1964, Schumm 1977) that may contribute to the difficulty in ensuring favourable results for habitat enhancement projects in the long-term.

The flood frequency for the Restigouche River at the Kedgwick hydrometric station was estimated from the Peak Annual Daily Flow records and is plotted in Figure 1.2. The probability of occurrence of a particular sized flood flow, used extensively in flood forecasting, is calculated from flood frequency curves. Calculations are shown in Appendix A. The annual flood frequency curves for the Little Main and Gounamitz Rivers were determined using the Peak Annual Discharge data from the Kedgwick hydrometric station (the only available data from the area) multiplied by the ratio of the area of the drainage basin to the drainage area tributary to the hydrometric station. The straight line through the data is the best-fit line in log space (Figure 1.2).

Table 1.4 shows the average return period in years that is associated with a particular flood flow. The average return period can be used to identify the bankfull flow at a specific location. The bankfull flow, identified as the flow that occurs every 2 years, or in other words, the flow that is equalled or exceeded by 50 percent of the annual flood flows, for the Restigouche River at the Kedgwick station is approximately 600 m^3/s. The bankfull flow is used in sizing rocks for instream works. Other flood flows for 1, 2, 5, 10, 25, 50, and 100 year return periods are shown in Table 1.4. Calculations are shown in Appendix A.

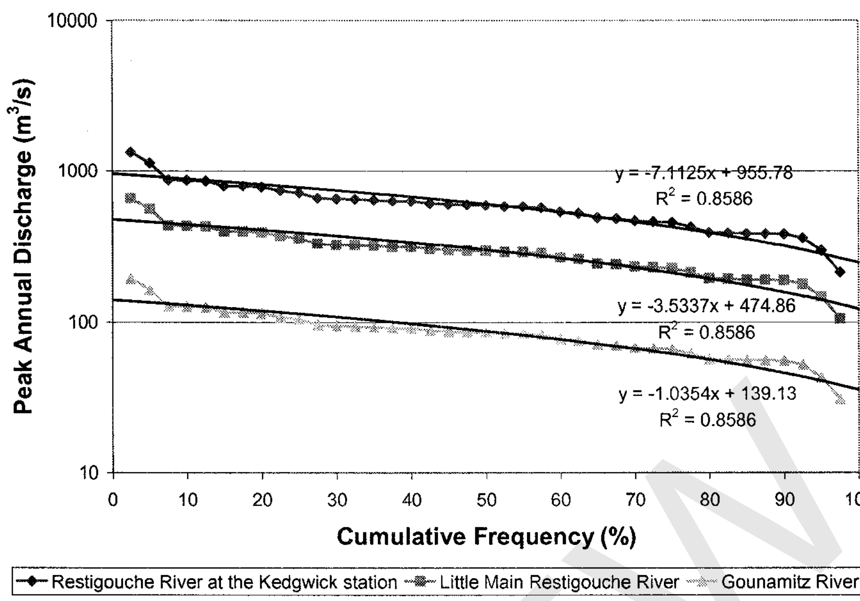

Figure 1.2. Annual flood frequency curves for the Restigouche River at the Kedgwick hydrometric station, Little Main Restigouche River, and the Gounamitz River.

Table 1.4. Return periods and the associated flood flows on the Restigouche, Little Main Restigouche, and Gounamitz Rivers. The flood flows were calculated based on the best fit line from the Peak Annual Discharge curve.

Return Period (years)	Restigouche River peak flood flow (m³/s)	Little Main Restigouche River peak flood flow (m³/s)	Gounamitz River peak flood flow (m³/s)
1	245	121	36
2	600	298	87
5	814	404	118
10	885	440	129
25	927	461	135
50	942	468	137
100	956	475	139

1.2.2 The Little Main Restigouche River (study river)

1.2.2.1 Description

The Little Main Restigouche River (67° 48' W; 47° 25' N) is located in north-western New Brunswick (Figure 1.3), where it flows in a north-eastward direction until it combines with the Kedgwick River, where together they form the Restigouche River.