Hydraulic Geometry and Fish Habitat in Semi-Alluvial Bedrock Controlled Rivers

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Thank you, grandpa, for encouraging me to learn as much as I can.

Abstract

The cross-sectional form of semi-alluvial bedrock channels was investigated. Channel geometry data were collected from a variety of streams in Ontario and Québec, Canada to develop empirical downstream scaling relationships. The relationships revealed that bedrock, mixed, and alluvial channels scale at similar rates with respect to discharge. The widest channels were formed in low-relief sedimentary bedrock with minimal alluvial cover. Channels influenced by resistant igneous/metamorphic bedrock produced a strong scaling relationship, whereas channels influenced by weak sedimentary bedrock produced a weak scaling relationship. Alluvial cover appeared to exhibit more control on channel width in low-relief settings in comparison to high-relief settings, with increased alluvial cover promoting channel narrowing. Channels influenced by igneous/metamorphic bedrock produced identifiable thalwegs, presumably due to well-defined bedload transport pathways. Channels influenced by sedimentary bedrock tended to have planar beds. Additionally, fish habitat was investigated at one semi-alluvial bedrock stream in Ontario, Canada. Fish sampling was conducted at proximate bedrock and alluvial sections followed by a survey of physical habitat parameters to evaluate habitat preferences. Adult logperch (*Percina caprodes*), juvenile white sucker (*Catostomus commersonii*), adult round goby (*Neogobius melanostomus*), and adult longnose dace (*Rhinichthys cataractae*) demonstrated preference toward alluvial substrate, whereas juvenile logperch and adult banded killifish (*Fundulus diaphanus*) demonstrated preference toward bedrock. Juvenile silver shiner (*Notropis photogenis*) and juvenile yellow perch (*Perca flavescens*) were indifferent to substrate type. Empirical depth and flow velocity habitat suitability indices (HSIs) were developed for each fish species. This study presents the first fish habitat suitability criteria developed from a small semi-alluvial bedrock stream and may provide valuable information for fisheries management endeavours in such environments.

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A	Drainage area (km^2)
A_g	Drainage area of gauge (km^2)
A_s	Drainage area of survey location (km^2)
aDcp	Acoustic Doppler current profiler
b	Discharge-based channel width scaling exponent
b'	Drainage area-based channel width scaling exponent
CEHQ	Centre d’expertise hydrique du Québec
CFL	Courant-Friedrich-Lévy number
CI	Confidence interval
d	Bankfull channel depth (m)
DEM	Digital elevation model
f	Discharge-based channel depth scaling exponent
f'	Drainage area-based channel depth scaling exponent
FWS	U.S. Fish and Wildlife Service
GPS	Global Positioning System
H_0	Null hypothesis
H_1	Alternative hypothesis
HSI	Habitat suitability index
IFIM	Instream Flow Incremental Methodology
k_d	Discharge-based channel depth scaling coefficient
k'_d	Drainage area-based channel depth scaling coefficient

k_w	Discharge-based channel width scaling coefficient
k'_w	Drainage area-based channel width scaling coefficient
n	Number of specimens
NAD83	North American Datum of 1983
NSERC	Natural Sciences and Engineering Research Council of Canada
P	Statistical P-value
p_f	Proportion of specimens observed in bedrock or alluvial section
p_h	Proportion of optimal habitat provided by bedrock or alluvial section
PHABSIM	Physical Habitat Simulation System
Q	Discharge (m^3/s)
$Q_{1.5}$	1.5 year return period discharge (m^3/s)
Q_g	Discharge at gauge (m^3/s)
Q_s	Discharge at survey location (m^3/s)
RTK-DGPS	Real-time kinematic differential global positioning system
SE	Standard error of regression
w	Bankfull channel width (m)
w_a	Bankfull channel width of alluvial channel (m)
w_b	Bankfull channel width of bedrock channel (m)
w_m	Bankfull channel width of mixed bedrock-alluvial channel (m)
w_r	Reference channel width
WSC	Water Survey of Canada

1 Introduction

Almost the entire Canadian landscape was covered by glacial ice sheets during the maximum extent of the most recent glacial episode, known as Wisconsinan glaciation, approximately 18 000 years before present (Gilbert, 1994; Dyke, 2004). Various mechanisms of erosion and deposition due to ice progression, melt, and retreat have given rise to a variety of complex physiographic landforms (Gilbert, 1994). Consequently, the surficial geology of the postglaciated Canadian landscape is often characterized by a complexity of unconsolidated soils, clay, and bedrock (Chapman and Putnam, 1984). Thus, many Canadian rivers, and rivers in other postglaciated regions, have semi-alluvial channels composed of both mobile alluvial sediments as well as resistant substrates such as rock and cohesive clay (Ebisa Fola, 2007; Ebisa Fola and Rennie, 2010; Jamieson et al., 2013; Whitbread et al., 2015). Although semi-alluvial bedrock rivers are quite common throughout postglaciated regions, the geomorphological characteristics of these systems are currently not well understood. Semi-alluvial bedrock channels also represent a sizeable proportion of Canadian freshwater fisheries. Substrate type is often considered in the evaluation of fish habitat suitability amongst other physical parameters such as depth and flow velocity (Bovee, 1982). However, fish habitat is rarely evaluated in semi-alluvial channels with abrupt transitions between alluvial and bedrock sections.

1.1 Research Objectives

The objectives of this thesis are twofold. Firstly, the study aimed to investigate the adjustment characteristics and channel forms of semi-alluvial bedrock channels. Empirical downstream hydraulic geometry relationships (channel width-discharge scaling relationships) were developed using survey data collected through an extensive field campaign of semi-alluvial bedrock streams in the Canadian provinces of Ontario and Québec. Influences of alluvial cover, topography, and lithology on cross-sectional channel form were also investigated. Secondly, the study aimed to evaluate fish habitat in a semi-alluvial bedrock stream with a focus on the influence of substrate type on fish species distribution and the development of habitat suitability criteria.

1.2 Organization of the Thesis

The thesis is composed of two original research articles. The first article has been submitted to a peer-reviewed journal and the second article is ready for submission pending comments and input from project contributors. An additional section which builds upon the findings of, but is not included in, the second article is also included in the thesis. Each article presents a thorough and exhaustive review of relevant literature.

Chapter 2 of the thesis presents an article entitled *Influence of alluvial cover, topography, and lithology on semi-alluvial bedrock channel width* which has been submitted to *Geomorphology* and is currently under review. A thorough literature review regarding common methods for evaluating cross-sectional channel form is presented in the introduction as well as a review of existing research on bedrock and semi-alluvial bedrock channel form. A general summary of the physiography of southern Ontario and southern Québec is also presented. Field data were collected from a variety of settings in order to produce an extensive inventory of bedrock, mixed bedrock-alluvial, and alluvial channel dimensions. The field data were used to produce empirical width-discharge scaling relationships using common downstream hydraulic geometry methods (Leopold and Maddock, 1953). The empirical relationships developed in this study were compared with existing scaling relationships in literature. The field collected data were also used to investigate the influences of alluvial cover, topography, and lithology on channel form.

Chapter 3 of the thesis presents an article entitled *Fish species distribution in a small semi-alluvial bedrock stream and development of habitat suitability criteria* which will be submitted to *Ecohydrology* pending comments and input from project contributors. The introductory paragraph presents background information on evaluative criteria for fish habitat suitability as well as an overview of existing research regarding bedrock influences on fish habitat. A brief description of the study area, Wilton Creek near Napanee, Ontario, is also presented. Fish sampling was conducted at proximate bedrock and alluvial sections of the study area followed by a survey of physical flow parameters. In essence, these data permitted comparison between the physical habitat utilized by fish species and the physical habitat available to fish species within the study stream. The study was focussed on the eight most abundant fish species and life-stages caught during fish sampling including juvenile and adult logperch (*Percina caprodes*), juvenile white sucker (*Catostomus commersonii*), adult round goby (*Neogobius melanostomus*), adult longnose dace (*Rhinichthys cataractae*), adult banded killifish (*Fundulus diaphanus*), juvenile silver shiner (*Notropis photogenis*), and juvenile yellow perch (*Perca flavescens*). Substrate selectivity of each fish species and life-stage was evaluated using statistical methods. Habitat suitability indices (HSIs) for depth and flow velocity were developed for each fish species and life-stage. The HSIs developed for juvenile white sucker, adult longnose dace, and juvenile yellow perch were compared to existing HSIs from literature.

Chapter 4 of the thesis presents an extension of the article presented in Chapter 3. This section discusses two-dimensional hydrodynamic-habitat modelling of Wilton Creek using the DHI MIKE 21 flexible mesh flow model. The bedrock section and the alluvial section of Wilton Creek were modelled separately. The HSIs discussed in Chapter 3 for juvenile white sucker, adult longnose dace, and juvenile yellow perch were implemented into the model via the MIKE

ZERO ECO Lab module. The model simultaneously interprets habitat suitability based on hydrodynamic simulations of depth and flow-velocity. Both the bedrock and the alluvial models were calibrated using field collected data. The models were used to visualize the distribution of fish habitat suitability throughout the study area.

Chapter 5 presents a brief conclusion summarizing the main findings of the thesis and discusses recommendations for future work.

1.3 Novelty of the Study

Although a large body of research currently exists regarding downstream scaling of bedrock channels, most studies have focussed on high-relief settings or active orogens undergoing tectonic uplift (Snyder et al., 2003; Tomkin et al., 2003; Duvall et al., 2004; Turowski et al., 2008; Yanites and Tucker, 2010; DiBiase and Whipple, 2011). Therefore, existing literature may over-represent high-relief and high-gradient environments. Furthermore, semi-alluvial bedrock channels with longitudinal transitions between bedrock and alluvial sections are largely ignored in existing literature. Only a small number of studies have evaluated the morphology of proximate bedrock and alluvial sections within common channels (Montgomery and Gran, 2001; Wohl and David, 2008; Whitbread et al., 2015). The article included as Chapter 2 of this thesis presents a dataset of bedrock, mixed bedrock-alluvial, and alluvial channel dimensions surveyed from a variety of physiographic settings. The study region encompassed high-relief and low-relief settings, all of which are not undergoing tectonic uplift. Therefore, the dataset includes channels from physiographic settings that are under-represented in existing literature. Furthermore, many researchers have developed downstream width scaling relationships using drainage area as a proxy for discharge because flow data were not available in their study areas (Montgomery and Gran, 2001; Duvall et al., 2004; DiBiase and Whipple, 2011; Spotila et al., 2015; Whitbread et al., 2015). Only two existing studies have developed discharge-based scaling relationships for bedrock and semi-alluvial bedrock channels (Tomkin et al., 2003; Wohl and David, 2008). Discharge-based scaling relationships were developed in this study and represent a valuable addition to a limited dataset.

The HSIs presented in Chapter 3 of this thesis represent the first HSIs developed from a semi-alluvial bedrock channel. The HSIs were developed with the intention of providing criteria more suitable for habitat evaluation in small semi-alluvial bedrock streams in comparison to existing HSIs. Furthermore, HSIs for round goby, banded killifish, and silver shiner could not be found in existing literature. Thus, the HSIs presented in this study represent the first known HSIs for these species.

Many researchers have implemented HSIs into two-dimensional hydrodynamic models to interpret fish habitat from hydrodynamic simulations (Leclerc et al., 1996; Stewart et al., 2005; Clark et al., 2008). However, examples of HSI implementation via the MIKE ZERO ECO Lab module could not be found in existing literature. The thesis demonstrates the utility of the ECO Lab module for such purposes.

1.4 Project Contributors

For the article included as Chapter 2, all field data were collected by the author with assistance from Dr. Colin Rennie, visiting student Rahmouna Benahmida, undergraduate student Dustin Brennan, Jamie Dickhout, and James Ferguson. Data analysis was conducted by the author under the supervision and guidance of Dr. Colin Rennie. The article was written by the author and edited by Dr. Colin Rennie.

For the article included as Chapter 3, physical hydraulic data were collected by the author, Dr. Colin Rennie, and master's student Philippe April-Le Quéré. Fish sampling, identification, and tallying was conducted by a three-person team lead by Dr. Chris Elvidge under the direction of Dr. Steven Cooke. Data analysis was conducted by the author under the supervision and guidance of Dr. Colin Rennie. The article, as it appears in this thesis, was written by the author and edited by Dr. Colin Rennie. The author is awaiting comments and input from Dr. Steven Cooke and Dr. Chris Elvidge prior to submission to *Ecohydrology*.

2 Influence of alluvial cover, topography, and lithology on semi-alluvial bedrock channel width

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2.1 Abstract

Channel geometry data were collected from semi-alluvial bedrock streams in Ontario and Québec, Canada. Data were sourced from a variety of physiographic settings, permitting evaluation of the influence of alluvial cover, lithology, and topography on cross-sectional channel form. Empirical downstream scaling relationships reveal that bedrock, mixed, and alluvial channel widths all scale at similar rates with respect to flow. However, bedrock channels were wider than mixed channels and alluvial channels. The widest channels were formed in low-relief sedimentary bedrock with minimal alluvial cover. Channels influenced by resistant igneous/metamorphic bedrock in high-relief regions produced a strong width-discharge scaling relationship regardless of variations in alluvial cover, whereas channels influenced by weaker sedimentary bedrock in low-relief settings produced a weak scaling relationship. Alluvial cover appeared to exhibit more control on channel width in low-relief settings in comparison to high-relief settings, with increased alluvial cover promoting channel narrowing. Additionally, channels influenced by igneous/metamorphic bedrock generally produced identifiable thalwegs, presumably due to well-defined bedload transport pathways. In comparison, channels formed in sedimentary bedrock tended to have much more planar beds.

2.2 Introduction

Postglaciated regions typically have a complexity of physiographic landforms (Gilbert, 1994). The surficial geology of these regions is often composed of arrangements of exposed bedrock and unconsolidated materials such as glacial tills, glaciofluvial deposits, clays, and silts (Ontario Geological Survey, 2010). As such, river systems which flow through postgalciated regions typically have channels composed of a variety of cohesive and non-cohesive substrates (Ebisa Fola, 2007; Ebisa Fola and Rennie, 2010; Jamieson et al., 2013; Whitbread et al., 2015). The Canadian landscape was almost entirely covered by glacial ice sheets during the maximum extent of the most recent glacial episode 18 000 years before-present (Gilbert, 1994; Dyke, 2004). Thus, many Canadian rivers are neither fully alluvial nor fully non-alluvial, but often have semi-alluvial channels with frequent longitudinal transitions between substrate types. Although semi-alluvial river systems are common throughout postglaciated environments, including Ontario and Québec, the forms and adjustment characteristics of semi-alluvial channels are not well understood.

The study of channel form is typically approached using the concept of downstream hydraulic geometry. This concept is built on the assumption that, over moderately short timespans, the channel form of natural river systems tend to maintain a state of quasi-equilibrium whereby adjustments in width, depth, and velocity fluctuate about respective mean values (Knighton, 1984). As supported by many subsequent studies, Leopold & Maddock (1953) postulated that equilibrium channel width (w) and depth (d) can be described as power functions of discharge (Q)

$$w = k_w Q^b \tag{1}$$

$$d = k_d Q^f \tag{2}$$

These power functions are known as downstream hydraulic geometry scaling relationships. The exponent terms (b and f) describe the rates at which width and depth scale with respect to discharge. The coefficient terms (k_w and k_d) relate to the magnitude of channel width and depth. In the context of downstream hydraulic geometry, discharge is regarded as an independent scaling parameter which can be used to describe channel form. This is complementary to the general assumption that channel form is predominantly controlled by discharge as well as sediment transport and the composition of the channel bed and bank materials (Leopold et al., 1964; Knighton, 1984). Researchers generally strive to develop relationships based on a characteristic discharge predominantly responsible for channel geometry. This discharge is referred to as dominant discharge or channel-forming discharge and is typically assumed to be equivalent to bankfull flow in alluvial streams (Leopold et al., 1964; Knighton, 1984; Copeland et al., 2000). However, some studies have developed downstream hydraulic geometry relationships using other characteristic flows below bankfull conditions (Leopold and Maddock, 1953; Wolman, 1955). Although bankfull flow cannot be explicitly defined by a singular overarching reoccurrence interval (Williams, 1978), researchers have found that a 1 to 2 year reoccurrence interval provides a reasonable estimate and a 1.5 year return period flow is commonly adopted as a best assumption (Wolman, 1955; Leopold et al., 1964; Knighton, 1984; Ebisa Fola, 2007).

The majority of hydraulic geometry studies are based on alluvial river systems where channel substrates are transported and deposited by the flow. However, researchers have demonstrated that the concept of downstream hydraulic geometry may also be applied to non-alluvial and semi-alluvial river systems to develop scaling relationships. A number of downstream hydraulic geometry relationships have been developed for channels influenced by bedrock. Some researchers have developed bedrock scaling relationships using the classic technique where a characteristic discharge is used as a scaling parameter (Tomkin et al., 2003; Wohl and David, 2008). However, the majority of researchers have used drainage area (A) as a substitute for discharge because flow data are not available (Montgomery and Gran, 2001; Spotila et al., 2015; Whitbread et al., 2015)

$$w = k'_w A^{b'} \tag{3}$$

$$d = k'_d A^{f'} \tag{4}$$

The appropriateness of substituting drainage area for discharge is dependent upon the relationship between these two parameters in the study location. The assumption is that discharge is positively correlated to drainage area according to some consistent trend. However, this may not always be true for watersheds containing geographic inconsistencies and may not be an appropriate assumption for studies that source data from multiple watersheds. In this respect, drainage area may not be an appropriate substitute for discharge especially for semi-alluvial channels which, by nature, occur in areas of inconsistent surficial geology. The relationship between discharge and drainage area is rarely investigated, which inhibits interpretation and application of the majority of downstream hydraulic geometry relationships developed for bedrock channels. The development of discharge-based scaling relationships for bedrock channels would be a valuable addition to a limited database.

As summarized by Knighton (1984), the majority of downstream hydraulic geometry relationships developed for alluvial channels are relatively consistent with the classic relationships proposed by Leopold & Maddock (1953). For alluvial channels, the width and depth exponent terms (b and f) are typically approximately 0.5 and 0.4 respectively. There is less consistency in previous findings for the coefficient terms (k_w and k_d) (Knighton, 1984). In comparison to alluvial channels, the current database of downstream hydraulic geometry relationships developed for bedrock and mixed bedrock-alluvial channels (hereafter referred to as mixed channels) is quite limited. This is especially true for bedrock scaling relationships based on discharge; to our knowledge only two discharged based scaling relationships exist (Tomkin et al., 2003; Wohl and David, 2008). Furthermore, most researchers have focussed on developing width scaling relationships alone. However, some depth scaling relationships do exist in the literature (Wohl and David, 2008; Whitbread et al., 2015). Table 1, largely derived from a summary compiled by Wohl & David (2008), presents the range of exponent and coefficient values for bedrock channels based on existing literature.

Table 1. Existing Range of Downstream Hydraulic Geometry Scaling Parameters for Bedrock Channels

Channel Dimension	Discharge-Based Coefficient Term	Discharge-Based Exponent Term	Drainage Area-Based Coefficient Term	Drainage Area-Based Exponent Term	Sources
Width	$1.12 \leq k_w \leq 10.82$	$0.47 \leq b \leq 0.50$	$0.0004 \leq k'_w \leq 4.61$	$0.22 \leq b' \leq 0.55$	(Wohl and David, 2008; DiBiase and Whipple, 2011; Whitbread et al., 2015)
Depth	-	$f \sim 0.30$	$1.02 \leq k'_d \leq 1.03$	$0.20 \leq f' \leq 0.24$	

Wohl & David (2008) provide of summary of findings from Montgomery & Gran (2001), Snyder et al. (2003), Tomkin et al. (2003), Van der Beek & Bishop (2003), Duvall et al. (2004), Whipple (2004), and Cowie et al. (2006)

A number of researchers have attempted to describe how sediment and alluvial cover may influence bedrock and mixed channel form (Montgomery and Gran, 2001; Sklar and Dietrich, 2001, 2004; Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Johnson and Whipple, 2010; Spotila et al., 2015; Whitbread et al., 2015). Several studies have evaluated the influence of sediment on channel form by performing a direct comparison between bedrock and alluvial sections of semi-alluvial channels (Montgomery and Gran, 2001; Wohl and David, 2008; Spotila et al., 2015; Whitbread et al., 2015). In general, most studies conclude that there is no substantial difference between the scaling behaviour of bedrock and alluvial channels (i.e. the b term is the same for both channel types) (Montgomery and Gran, 2001; Wohl and David, 2008). However, Whitbread et al. (2015) found a continuum of channel width scaling behaviour with respect to drainage area between bedrock, mixed, and alluvial channel dimensions with bedrock channels scaling at the lowest rate, alluvial channels scaling at the greatest rate, and mixed channels scaling at an intermediate rate. Although Wohl & David (2008) found no difference between the scaling rate of bedrock and alluvial channels, they did conclude that alluvial sections tended to be wider than bedrock sections for a given bedrock-alluvial pairing, a conclusion supported by the findings of Whitbread et al (2015). Conversely, Spotila et al. (2015) found bedrock reaches to generally be wider than alluvial reaches in their study of the New River in the Appalachian Mountains. These inconsistencies are also reflected by Montgomery & Gran (2001) who found the relative widths of bedrock and alluvial sections to be case dependant. Nonetheless, the majority of literature suggests that, in general, increased alluvial cover promotes channel widening and deep and narrow channels form where there is a limited sediment supply mobilized as bedload overtop of bedrock (Sklar and Dietrich, 2001, 2004; Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Yanites and Tucker, 2010;

Whitbread et al., 2015). To explain this phenomenon, researchers typically comment on the duality of sediment load to behave as both abrasive tools and as shielding cover in bedrock channels (Gilbert, 1877). Under conditions of low sediment supply, bedload transport tends to concentrate in the deepest portions of the channel; thus, vertical channel incision will be focussed in the thalweg promoting the development of deeper and narrower channels (Finnegan et al., 2007; Turowski et al., 2008; Johnson and Whipple, 2010). Conversely, if abundant sediment supply or bed resistance induces alluvial deposition, the bed will be shielded and incision will be focussed on the channel margins promoting channel widening (Sklar and Dietrich, 2001; Finnegan et al., 2007; Turowski et al., 2008; Johnson and Whipple, 2010; Yanites and Tucker, 2010).

Unlike alluvial systems, where channel geometry is characterized by the distribution of loose sediments that are transported and deposited by the flow, bedrock channel geometry is characterized by the shape of the resistant channel boundaries sculpted through erosive processes. As such, the lithologic characteristics of the channel boundaries exhibit some degree of control on the channel form (Sklar and Dietrich, 2001; Wohl and Achyuthan, 2002; Wohl and David, 2008; Allen et al., 2013; Spotila et al., 2015; Whitbread et al., 2015). In general, most research has indicated that channels formed in more resistant substrates tend to be deeper and narrower than channels formed in substrates which are more easily eroded (Montgomery and Gran, 2001; Wohl and Achyuthan, 2002; Allen et al., 2013). Recent research has demonstrated that bedrock channel form is largely governed by the mechanism through which the channel erodes its boundaries. Spotila et al. (2015) demonstrated that narrow and deep bedrock channels tend to form in abrasion-dominated systems and that wide and shallow bedrock channels tend to form where erosion is primarily achieved through plucking. Plucking refers to the loosening, detachment, and entrainment of intact pieces from the bedrock mass and typically dominates in heavily jointed rock types (Whipple et al., 2000). Accordingly, Spotila et al. (2015) used discontinuity spacing as a metric to characterize bedrock erodibility and argued that rock types with smaller discontinuity spacing were more likely to erode through plucking. In this context, the findings of Spotila et al. (2015) are contradicted by Whitbread et al. (2015) who found that the narrowest channels in their study area tended to form in the most strongly jointed lithology.

Although bedrock channels exist in a variety of physiographic settings, they are most characteristically associated with mountainous regions (Whipple, 2004). Accordingly, a majority of studies to-date are reserved to active orogens where tectonic uplift is generally considered a key contributor to landform evolution. Here, mountain streams adjust their boundaries in such a way to maintain an equilibrium state with the rate of base-level fall imposed by tectonic uplift (Yanites and Tucker, 2010). Responses to tectonic uplift are accounted for through adjustment of both the cross-sectional and longitudinal channel form; steeper and narrower channels tend to develop in regions of rapid uplift, and vice versa, in order to maintain equilibrium between vertical incision rates and base level fall (Duvall et al., 2004; Wobus et al., 2006; Yanites and Tucker, 2010). Venditti et al. (2014) recently described the flow structure in canyons to explain mechanisms for vertical incision. However, the relative adjustment between channel width and gradient in response to changes in uplift is unclear and is further complicated by the influences of sediment and lithology (Snyder et al., 2003; Duvall et al., 2004; Wobus et al., 2006; Yanites and Tucker, 2010). Furthermore, since most studies on bedrock channel morphology have been conducted in mountainous regions, existing literature may over-represent high-relief and high-gradient environments. Although channel gradient is often viewed as a responsive and adjustable morphological component (Duvall et al., 2004; Yanites and Tucker, 2010), gradient also exhibits control on cross-sectional channel form (Finnegan et al., 2005; Wobus et al., 2006). Finnegan et al. (2005) proposed that steeper gradients are more likely to produce narrower bedrock channels simply due to the fact that faster flows will occupy less cross-sectional area.

The geometry of bedrock channels is often governed by a complexity of factors including, but not limited to, sediment load, alluvial cover, lithology, and tectonic activity. Although a large body of research has focussed on deducing physical controls on bedrock channel form, inconsistencies still remain, even in recent literature, and there is a necessity for further investigation. This is especially true for bedrock channels in low-relief, tectonically stable environments, which have only recently received limited attention. Furthermore, semi-alluvial bedrock channels with longitudinal variations between mobile sediments and exposed bedrock outcropping are largely ignored in existing literature and only a few studies have evaluated proximate bedrock and alluvial sections within common channels (Montgomery and Gran, 2001; Wohl and David, 2008; Whitbread et al., 2015). In this study, we present a dataset of semi-alluvial bedrock channels surveyed in the Canadian provinces of Ontario and Québec. Our study area enabled us to survey channel dimensions from a variety of physiographic settings, all of which are not undergoing tectonic uplift. All of the surveyed channels are semi-alluvial in nature meaning they contain either mixed sections, or any combination of bedrock, mixed, and alluvial sections. The dataset also encompasses a variety of rock types which may be broadly categorized as either sedimentary or igneous/metamorphic. Thus, we are able to evaluate the influences of topography, alluvial cover, and lithology on semi-alluvial bedrock channel form. Furthermore, we present discharge-based empirical scaling relationships. Since most existing relationships have been developed using drainage area as a scaling parameter, a practice which we demonstrate is not appropriate for our study area, this is a valuable addition to a limited dataset.

2.3 Study Area

The physiography of southern Ontario and southern Québec may be broadly categorized based on the geology of the bedrock. The metamorphic and igneous Precambrian bedrocks of the ancient Grenville orogen form the southeast portion of the Canadian Shield (Davidson, 1998a, 1995). This portion of the Canadian Shield, known as Grenville Province, encompasses a vast majority of southern Québec as well as a small portion of south-eastern Ontario (Chapman and Putnam, 1984; Davidson, 1998a; Ontario Geological Survey, 2010). However, the majority of southern Ontario is underlain by sedimentary Paleozoic bedrock formed via the lithification of marine sediments overtop of the older Precambrian rock (Chapman and Putnam, 1984). The Precambrian bedrock of the Canadian Shield is frequently exposed to the surface or is overlain by only a thin layer of surficial deposits (Chapman and Putnam, 1984). Conversely, the Paleozoic bedrock of southern Ontario is typically overlain by thick layers of soil eroded, mobilized, and deposited during Wisconsinan Glaciation (Chapman and Putnam, 1984). These thick soil deposits largely originate from the Paleozoic rocks themselves which are relatively weak and easily eroded (Chapman and Putnam, 1984). As is expected, bedrock channels are a common feature of the Canadian Shield where bedrock represents a large portion of the surficial geology. Although they are less common in regions of southern Ontario where the surficial geology is primarily composed of glacial deposits, many channels here are in fact influenced by exposed bedrock.

Although not considered in this study, a brief discussion of landscape evolution due to uplift is warranted. The study area is located in a postorogenic postglaciated setting. Thus, tectonic uplift does not play a factor in landscape evolution. Instead, landscape evolution is primarily driven by base level fall induced by isostatic rebound following glacial retreat approximately 12 700 years ago (Gilbert, 1994; Bishop, 2011). Although spatially variable (Bruxer and Southam, 2008), rates of isostatic rebound in the study area generally follow a continuum with a northward increasing trend (~1 mm/yr near the southern bound of the study area to ~4 mm/yr near the northern bound) (Gilbert, 1994). In contrast to tectonic uplift driven by convergence, isostatic rebound driven by denudation of the land is attributed with prolonging the timescale of landscape evolution (Bishop, 2011). Time-scales of isostatic rebound are assumed to be sufficiently long that all channels in the study area are considered to be in quasi-equilibrium.

2.4 Methods

The field campaign included a survey of 29 channel sections from 12 rivers located throughout southern Ontario and southern Québec. Of the 29 surveyed sections, 7 were classified as bedrock, 11 were classified as mixed, and 11 were classified as alluvial. Of the 18 bedrock or mixed sections, 10 were influenced by igneous/metamorphic Precambrian bedrock and 8 were influenced by sedimentary Paleozoic bedrock. The dataset of river sections influenced by igneous/metamorphic bedrock included a variety of resistant igneous, meta-igneous, and metasedimentary rock types including marble, gneiss, granite, and other granitic rocks (Davidson, 1998b). All sections influenced by sedimentary bedrock were, more specifically, influenced by limestone or dolostone, except for East Sixteen Mile Creek where the bedrock was composed of shale (Chapman and Putnam, 1984). Figure 1 displays the general location of each river and Table 2 summarizes the relevant data for each of the 29 survey locations.

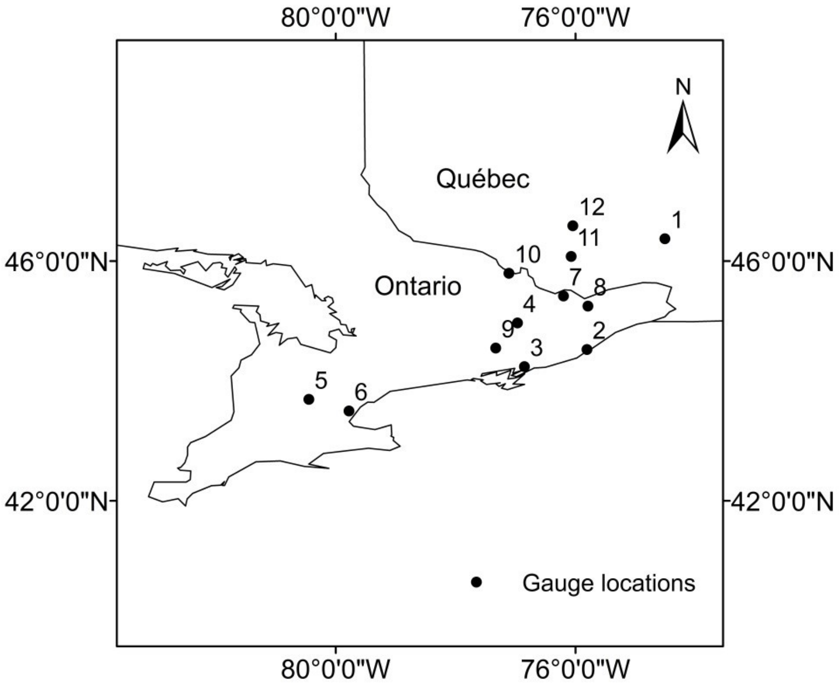

Figure 1. Gauge locations of the 12 rivers included in the study. Provincial boundary outline sourced from ESRICanadaED. Numbering conforms to Table 2.

Several criteria were established for the selection of rivers to be included in the study: (1) each river must be semi-alluvial meaning they contain either mixed sections, or any combination of bedrock, mixed, and alluvial sections, (2) flow data must be available from gauge records, and (3) each river must have a natural flow regime as identified by the Water Survey of Canada (WSC) or Centre d'expertise hydrique du Québec (CEHQ). Additionally, survey locations were selected in such a way to avoid anthropogenic influences on channel morphology (i.e. bridges which obviously constrict the flow, roadways which inhibit lateral migration, etc.).

Table 2. Characteristics of Bedrock, Mixed, and Alluvial Channels

	River	Channel Type	Substrate	Number of cross-sections surveyed	A (km^2)	$Q_{1.5}$ (m^3/s)	w (m)	d (m)	Relief[b] [Range / Standard Deviation] (m)
1.	Saint-Louis Creek	Bedrock	Igneous/metamorphic rock	3	40.0[a]	10.5	20.0	0.7	437 / 95.7
		Mixed	Igneous/metamorphic rock, cobble, and boulder	2	40.0[a]	10.5	10.9	0.7	437 / 95.7
2.	Lyn Creek	Bedrock	Igneous/metamorphic rock	2	107.3	18.7	18.4	1.4	47 / 8.2
		Alluvial	Sand and silt	1	107.4	18.8	16.9	1.4	47 / 8.2
3.	Wilton Creek	Bedrock	Sedimentary rock	2	112.0	17.0	36.1	0.3	34 / 4.8
		Mixed	Sedimentary rock, gravel, and cobbles	2	112.0	17.0	16.5	0.6	34 / 4.8
		Alluvial	Gravel, and cobbles	1	112.3	17.0	22.5	0.4	34 / 4.8
4.	Buckshot Creek	Bedrock	Igneous/metamorphic rock	1	151.1	8.5	15.6	0.5	97 / 14.8
		Mixed	Igneous metamorphic rock, gravel, cobbles, and some boulders	2	151.2	8.5	18.0	1.0	97 / 14.8
		Alluvial	Sand, gravel, and some boulders	1	151.5	8.5	13.5	0.9	97 / 14.8
5.	Irvine River	Alluvial	Gravel	2	165.4	45.6	21.5	-	46 / 8.0
		Mixed	Sedimentary rock, gravel, and cobbles	3	186.5	49.9	34.4	-	46 / 8.0
6.	East Sixteen Mile Creek	Mixed	Sedimentary rock and gravel	4	187.6	25.6	17.9	-	40 / 6.7
7.	Carp River	Alluvial	Clay and organics	1	258.8	37.8	31.1	-	45 / 8.4
		Mixed	Igneous/metamorphic rock gravel, and cobbles	4	277.1	39.8	28.8	0.6	38 / 8.9
		Bedrock	Sedimentary rock	2	302.4	42.5	58.1	0.8	62 / 16.2
		Mixed	Sedimentary rock, gravel, and clay	2	303.5	42.6	57.2	0.7	62 / 16.2
8.	Jock River	Mixed	Sedimentary rock and gravel	2	288.2	41.8	30.8	0.9	22 / 3.8
		Alluvial	Sand and silt	1	390.6	52.5	52.4	1.2	9 / 1.2
		Bedrock	Sedimentary rock	1	390.6	52.5	43.6	0.5	9 / 1.2
		Alluvial	Silt	1	453.4	58.7	36.0	-	8 / 1.4
9.	Skootamatta River	Mixed	Igneous/metamorphic rock and sand	2	591.8	45.3	23.7	-	66 / 12.6
		Alluvial	Sand	2	591.8	45.3	28.6	-	66 / 12.6
10.	Muskrat River	Alluvial	Sand and gravel	1	660.9	28.7	24.2	1.1	26 / 4.4
		Mixed	Igneous/metamorphic rock, sand, and gravel	3	660.9	28.7	19.6	1.3	26 / 4.4
11.	Picanoc River	Alluvial	Silt	1	1277.0[a]	83.2	31.1	-	78 / 14.9
		Mixed	Igneous/metamorphic rock and silt	1	1277.0[a]	83.2	26.8	-	78 / 14.9
12.	Désert River	Alluvial	Silt	1	1780.0[a]	109.7	40.7	-	171 / 41.3
		Bedrock	Igneous/metamorphic rock	1	1780.0[a]	109.7	36.3	-	171 / 41.3

[a] Drainage area acquired from CEHQ gauge information

[b] Relief quantified based on a 3000 km^2 and 10000 km^2 region surrounding each study area for Ontario and Québec locations respectively

Potential survey locations were preliminarily identified using surficial geology GIS data and soil maps (Lajoie, 1962; Ontario Geological Survey, 2010). Field observations of channel substrates proved to be generally consistent with the published information. Each survey location was classified as either bedrock, mixed, or alluvial. There is much debate regarding the definition of a bedrock channel (Whipple, 2004; Turowski et al., 2008). However, bedrock, mixed, and alluvial channels are generally categorized based on the degree of alluvial cover (Wohl and David, 2008; Whitbread et al., 2015). In this study, we define a bedrock channel as one where the bed is virtually bare of alluvial cover across the channel width and for an extended longitudinal distance. One exception was the most upstream section of Lyn Creek which was classified as bedrock even though some alluvial cover was present in the form of large boulders. This exception was made because this portion of Lyn Creek flows through a slot canyon where there is extensive bedrock control. Conversely, channels with continuous alluvial cover across the channel width and for an extended longitudinal distance were classified as alluvial. Mixed channels represent any intermediate channel type between bedrock and alluvial and encompass a wide variety of forms. Mixed channels influenced by sedimentary bedrock typically had riffle-pool morphology with riffles composed of alluvium and bedrock exposure in the pools (a sequence observed in a number of locations). Mixed channels influenced by igneous/metamorphic bedrock typically had a thin layer of alluvium overtop of bedrock. Channels influenced by abrupt bedrock outcropping in an otherwise alluvial setting were also classified as mixed channels. Figure 2 displays some examples of the bedrock and mixed channels included in the dataset.

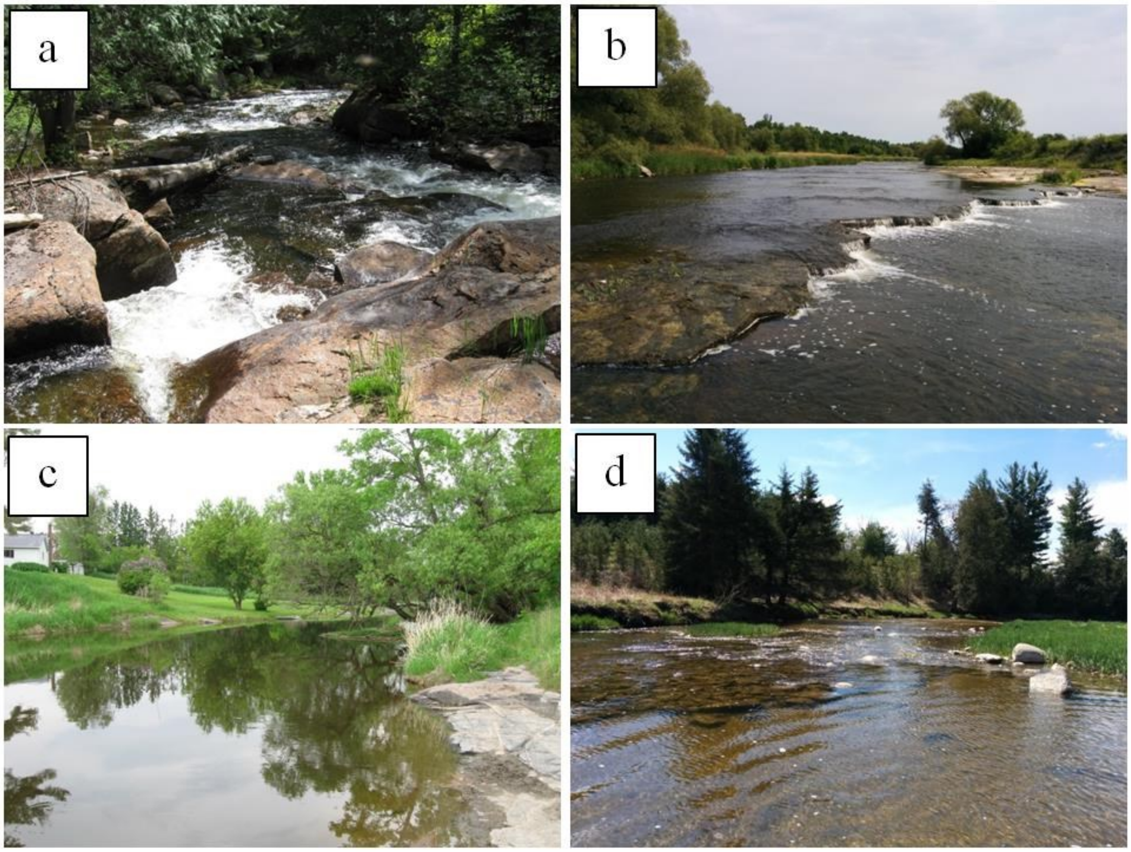

Figure 2. Examples of bedrock and mixed sections included in the dataset. (a) A pure igneous/metamorphic bedrock section of Saint-Louis Creek. (b) A pure sedimentary bedrock section of Carp River. (c) A mixed section of Muskrat River. Igneous/metamorphic bedrock outcrops are emergent in the otherwise sandy and gravelly channel. (d) A mixed section of Irvine River. Width-spanning riffles composed of gravel and cobbles overlie the sedimentary bedrock bed.

Bankfull channel dimensions were measured through an extensive field campaign conducted throughout the summer and fall of 2015 and the spring of 2016. A variety of indicators were used to identify bankfull stage. In alluvial channels, bankfull stage was typically easily identified using breaks in the bank slope or the location of adjacent tree-lines parallel with the channel (Bomhof, 2014). Identifying bankfull stage was often more difficult in bedrock and mixed channels. Here, bankfull stage was typically identified using adjacent tree-lines, the transition from bare rock to rooted vegetation, or stains on vertical rock faces. In most cases, bankfull indicators were identified on either side of each surveyed cross-section and measures were taken to ensure the two points existed in relatively the same horizontal plane. Where observable channel units were present, such as riffle-pool sequences, several cross-sections were surveyed to define average channel dimensions. However, for the alluvial section of Wilton Creek, surveyed pool dimensions had to be discarded leaving only data collected from a riffle unit. Four survey methods were employed. Where possible a SonTek RiverSurveyor M9 acoustic Doppler current profiler (aDcp) equipped with a real-time kinematic differential global positioning system (RTK-DGPS) was used to survey the wetted portion of the channel cross-section and a stand-alone RTK-DGPS system was used to survey dry portions of the cross-section up to bankfull. This was the preferred survey method as aDcps are an effective tool for collecting dense bathymetric data (Ebisa Fola and Rennie, 2010; Venditti et al., 2014). Furthermore, the RTK-DGPS system typically enabled positional accuracy within centimeters (Rennie and Rainville, 2006). Where channels were too shallow to use the aDcp, the stand-alone RTK-DGPS system was used to survey the entire cross-section. In cases where the RTK-DGPS could not be used due to poor satellite signal (typically due to tree cover), a simple tape and rod surveying method was employed. In some cases, channel width alone was surveyed using a Leica Disto D8 laser rangefinder.

Wohl and David (2008) argued that bedrock channel geometry is governed by extreme flow events with reoccurrence intervals ranging from decades to centuries. Conversely, Sklar and Dietrich (2004) argued that more frequent and moderate flood events have greater influence on bedrock erosion. In order to maintain consistency in our evaluation of bedrock, mixed, and alluvial channels, 1.5 year return period flow was used to evaluate all channel types as a best estimate for bankfull discharge and channel forming flow (Leopold et al., 1964; Copeland et al., 2000). Flow data were available for each river from historical WSC or CEHQ gauge records.

Flood frequency analyses were conducted using the Log-Pearson III distribution in order to determine 1.5 year return period flow at each gauge (U.S. Interagency Advisory Committee on Water Data, 1982). Originally, only rivers with at least 10 years of gauge records were selected for inclusion in the dataset to ensure robust flood frequency estimates. However, Irvine River, with only an 8 year gauge record, was also included in order to expand the dataset. Gauge records were used to directly estimate flow for surveyed cross-sections located within vicinity of a gauge; this included Saint-Louis Creek, the bedrock section of Lyn Creek, the alluvial section of Buckshot Creek, the alluvial section of Carp River, Picanoc River, and Désert River. The following equation, based on the modified index flood method, was used to estimate flow at all other survey locations (Dharamdial and Faghaly, 1997)

$$Q_s = Q_g \left(\frac{A_s}{A_g}\right)^{0.75} \tag{5}$$

where Q_s is the flow at the survey location, Q_g is the flow at the gauge, A_s is the drainage area of the survey location, and A_g is the drainage area of the gauge. ArcGIS hydrology tools were employed to extract drainage areas from Ontario Integrated Hydrology Data (30 m resolution enforced DEM, enhanced flow direction grid, and stream network grid). Effort was made to survey as close to gauge locations as possible in order to limit reliance on equation 5. Most survey locations not located within the immediate vicinity of a gauge had drainage areas within +/- ~15% of the associated gauge drainage area. However, the three most upstream survey locations of the Jock River had drainage areas 53%, 73%, and 73% of the gauge drainage area respectively.

Due to time constraints and equipment limitations, slope was not explicitly measured at most survey locations. Additionally, many of the surveyed channels were located in low-relief areas where available DEMs proved to be too coarse for slope estimations. Instead, geographic relief was calculated for each survey location as a proxy for channel gradient. This information should not be interpreted as a substitute for channel slope, but rather as a descriptor of the geographic setting. The Ontario Integrated Hydrology Data 30 m resolution enforced DEM was used to estimate relief for Ontario locations and the Canada3D 30” resolution (~785 m resolution projected) DEM was used to estimate relief for Québec locations. Relief was measured as both the range and standard deviation of elevations within a region.

2.5 Results

2.5.1 Flow-Area Scaling

As discussed in the introduction, a majority of existing empirical scaling relationships were developed from regions where flow data are not available from gauge records. Thus, most scaling relationships use drainage area as a proxy for discharge. Since flow data and drainage area are available for each river in our dataset, we were able to evaluate the scaling relationship between the two parameters. As displayed in Figure 3, there is a general positive trend between the two parameters as expected. However, there is too much scatter in the data for the scaling behaviour to be represented by one overarching relationship. This is likely indicative of the complex postglaciated nature of the study area. Since all of our study streams are semi-alluvial, it is reasonable to assume that the associated drainage areas have inconsistent surficial geology. As such, poor scaling relationships between drainage area and flow are to be expected within a given drainage area, and similarly, on a trans-watershed basis. Therefore, for our dataset, drainage area alone does not adequately describe the flow at a location.

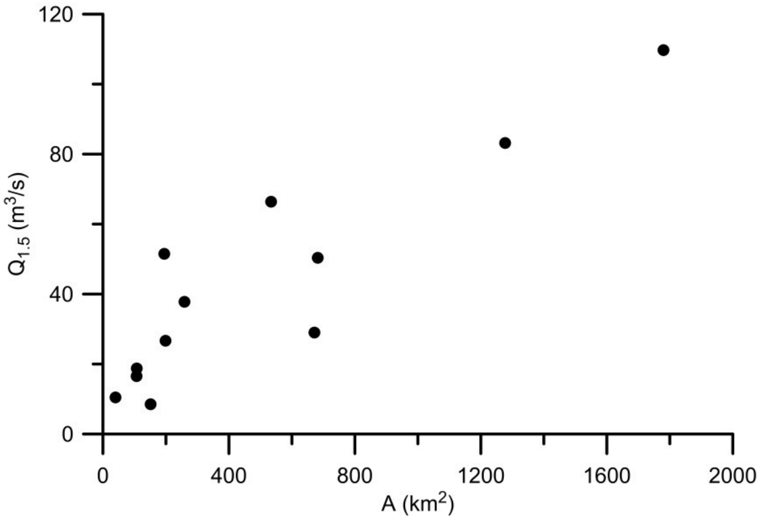

Figure 3. Relationship between the 1.5 year return period flow and drainage area at each gauge location. Drainage areas of Ontario gauges were determined from the Ontario Integrated Hydrology Data 30 m DEM. Drainage areas of Québec gauges are those reported in CEHQ gauge information.

2.5.2 Bedrock, Mixed, and Alluvial Channels

As displayed in Figure 4, alluvial channels produced the strongest scaling relationship with flow, accounting for 68% of the variation in width. Bedrock and mixed channels produced weaker scaling relationships with flow, accounting for 54% and 51% of the variation in width respectively.

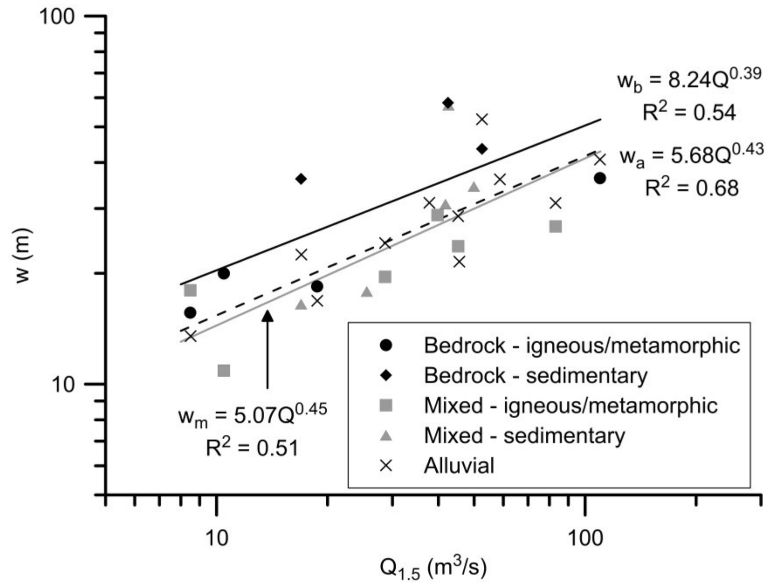

Figure 4. Scaling of bankfull channel width with respect to 1.5 year return period flow for bedrock, mixed, and alluvial channels.

The exponent for the alluvial relationship falls within the range of expected values for alluvial channels (Knighton, 1984). The exponent for the bedrock relationship is lower than, but does not differ greatly from, the range of previously reported values. However, only a limited number of discharge-based bedrock scaling relationships exist for comparison (Tomkin et al., 2003; Wohl and David, 2008). The scaling relationships were compared to one another using statistical methods presented by Zar (1996). The exponents of all three relationships are not statistically different from one another implying that there is no difference between the scaling behavior of bedrock, mixed, and alluvial channels with respect to flow. However, the coefficient k_w for bedrock channels was statistically greater than the coefficients of the mixed and alluvial channels ($P \sim 0.10$). Thus, contrary to general observation, bedrock channels were statistically wider than mixed and alluvial channels. This is especially apparent in bedrock channels influenced by sedimentary bedrock which represent the widest channels in the dataset. Mixed and alluvial data produced very similar scaling relationships which are almost indistinguishable from one another.

Unfortunately, depth could not be surveyed at each channel location due to time constraints and equipment limitations. The dataset is too small to evaluate scaling behaviour with respect to flow. However, we present the data in Figure 5 to primarily serve as an addition to a currently limited dataset. Channel depth was calculated by dividing cross-sectional bankfull flow area by channel width. Unlike the width data, there appears to be much more scatter in the depth data when plotted with respect to flow.

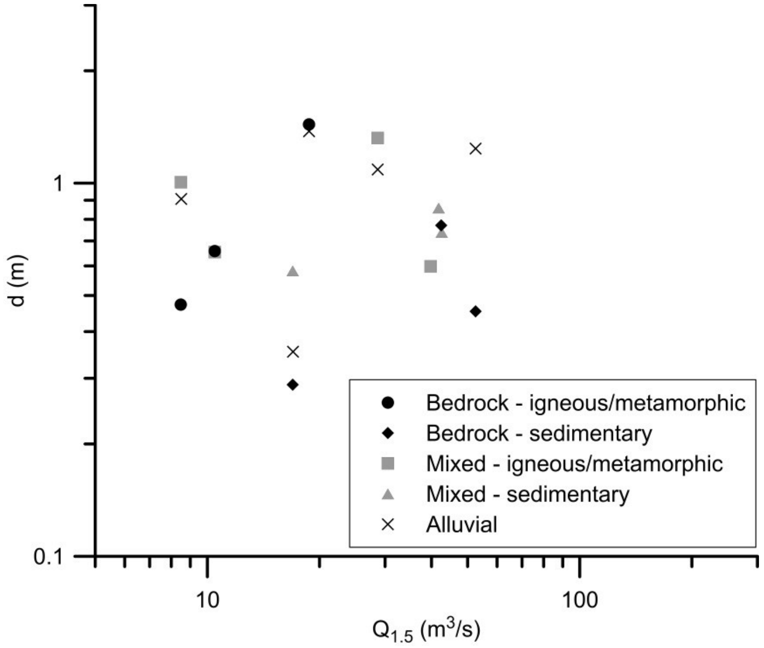

Figure 5. Scaling of bankfull channel depth with respect to 1.5 year return period flow for bedrock, mixed, and alluvial channels.

2.5.3 Influence of Lithology

Bedrock and mixed channels were grouped based on bedrock type in order to investigate the influence of lithology on channel form as displayed in Figure 6. The data suggest that channels influenced by igneous/metamorphic bedrock do not adjust their width as rapidly as channels influenced by sedimentary bedrock which appear to scale quite rapidly with respect to flow. However, the exponents of the igneous/metamorphic and sedimentary datasets are not statistically different ($P \sim 0.22$). Channels influenced by igneous/metamorphic bedrock also tended to be narrower than channels influenced by sedimentary bedrock. This is consistent with existing literature which states that channel width is inversely proportional to substrate resistance (Montgomery and Gran, 2001; Wohl and Achyuthan, 2002; Allen et al., 2013). Interestingly, the greatest scaling coefficient from existing literature, k_w=10.82 (Table 1), originates from a study conducted in a region of sedimentary sandstone and shale rock (Tomkin et al., 2003). The igneous/metamorphic dataset produced a strong scaling relationship with flow, accounting for 71% of the variation in width. Conversely, the sedimentary dataset produced a weak scaling relationship with flow, accounting for only 39% of the variation in width. As such, flow appears to be a good descriptor of channel form where igneous/metamorphic bedrock influence is present. However, flow only poorly describes channel form where sedimentary bedrock influence is present. Thus, for channels influence by sedimentary bedrock, physical parameters other than flow may need to be considered in order to describe channel width.

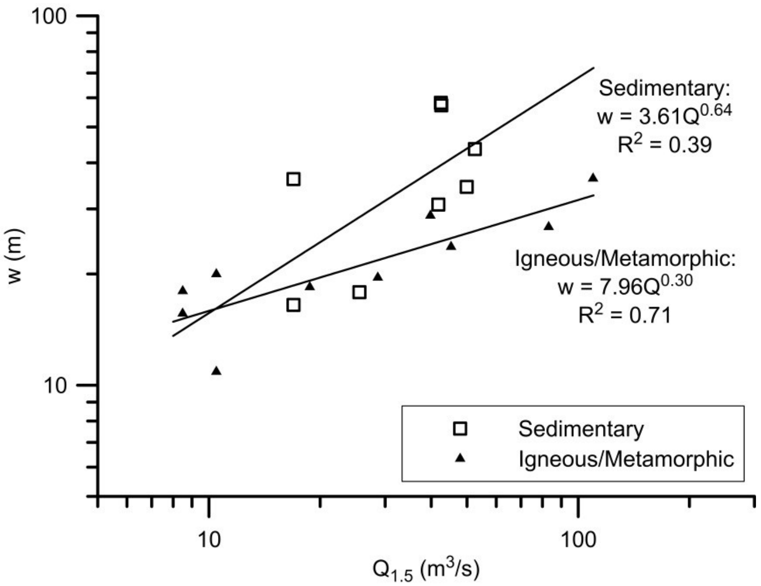

Figure 6. Scaling of bankfull channel width with respect to 1.5 year return period flow for bedrock and mixed channels influenced by sedimentary and igneous/metamorphic bedrock.

2.5.4 Geographic Relief

Geographic relief was calculated in order to provide a quantitative descriptor of each study area. We propose that the standard deviation of elevations within a region provides the most suitable representation of the topography. Relief is used as a proxy for channel gradient under the assumption that steeper channels are more likely to occur in areas of high relief. Although we are unable to investigate this assumption, the relief values extracted from the DEMs reflect qualitative field observations. In order to evaluate the relationship between channel width and relief, measured channel widths were normalized to eliminate the influence of discharge (Yanites and Tucker, 2010; Whitbread et al., 2015)

$$w_r = \frac{w}{k_w Q^b} \tag{6}$$

where w_r represents normalized reference width. In order to normalize the data, the scaling parameters produced by the entire dataset were substituted into equation (6) (k_w = 6.48, b = 0.41). As displayed in Figure 7, there appears to be a well-defined divide between channels influenced by igneous/metamorphic bedrock and channels influenced by sedimentary bedrock. Channels influenced by igneous/metamorphic bedrock tended to occur in high-relief regions and channels influenced by sedimentary bedrock tended to occur in low-relief regions. The results are intuitive given that most of the igneous/metamorphic channel data were sourced from the ancient Grenville orogen of the Canadian Shield. Conversely, sedimentary channel data were sourced from the Saint-Lawrence Lowlands of southern Ontario which has considerably milder topography. In general, the reference widths of the channels influenced by igneous/metamorphic bedrock appear to be relatively narrow with only mild scatter in the data. There is much more scatter in the reference widths of channels influenced by sedimentary bedrock. Pure sedimentary bedrock channels appear to be exceptionally wide whereas mixed sedimentary channels mostly cluster with the alluvial dataset and channels influenced by igneous/metamorphic bedrock.

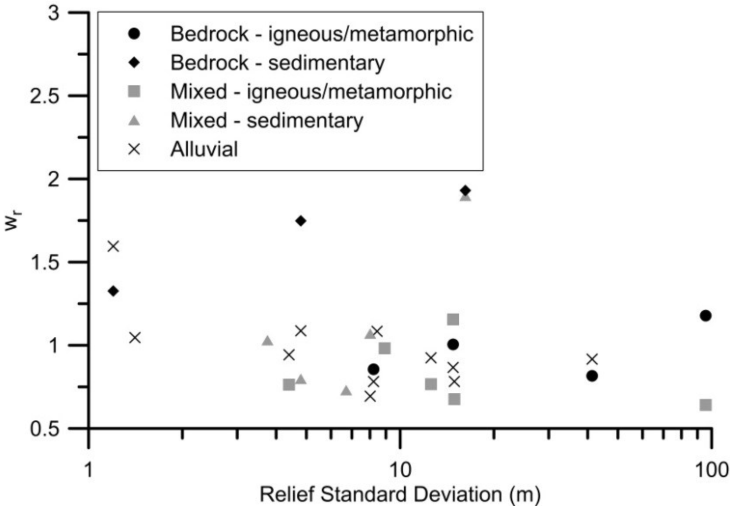

Figure 7. Reference channel width with respect to geographic relief. Relief is quantified as the standard deviation of topographic elevation in the vicinity of each study location.

2.6 Discussion

Bedrock, mixed, and alluvial channels all produced similar scaling exponents comparable to values typically reported for alluvial channels. This suggests that downstream changes in flow will induce similar responses in channel form regardless of alluvial cover. However, the coefficient produced by the bedrock dataset was greater than the coefficients of the mixed and alluvial datasets. Thus, our results are in concordance with previous studies which report similar scaling behaviour amongst bedrock and alluvial channels (Montgomery and Gran, 2001; Wohl and David, 2008) but contradict the general assumption that bedrock channels are narrower than alluvial channels and alluvial cover promotes channel widening (Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Johnson and Whipple, 2010; Yanites and Tucker, 2010; Whitbread et al., 2015).

It is difficult to discriminate between the relative influences exhibited by alluvial cover, lithology, and channel gradient. Pure bedrock channels in low-relief sedimentary settings were wider than pure bedrock channels in high-relief igneous/metamorphic settings. Amongst the data sourced from low-relief sedimentary settings, pure bedrock channels were wider than mixed channels. On the other hand, amongst the data sourced from high-relief igneous/metamorphic settings, alluvial cover did not appear to influence channel width.

Pure bedrock channels in low-relief sedimentary settings produced the widest channels. However, pure bedrock channels in high-relief igneous/metamorphic setting produced much narrower channels. We propose that this can be explained in terms of channel gradient. Certainly, one might expect the relatively soft sedimentary bedrock of southern Ontario to produce deeply-incised channels. However, significant channel incision was not observed at pure bedrock channels in these locations. The channel beds are best described as flat and planar and the channel banks are often composed of a thin layer of vegetated organics or surficial sediments. Conversely, pure bedrock channels in high-relief igneous/sedimentary settings produced observably narrower channels deeply incised into the surrounding bedrock. Although these findings are consistent with previous research indicating that more resistant substrates produce narrower channels (Montgomery and Gran, 2001; Wohl and Achyuthan, 2002) we propose that our observations are, in fact, attributed to channel gradient (Finnegan et al., 2005; Wobus et al., 2006). The mild channel gradients of the sedimentary channels in our dataset are likely incapable of producing significant vertical incision in sections free of alluvial cover. However, erosion of the malleable channel banks enables channel widening resulting in expansive and flat cross-sectional forms. One might speculate that even under low sediment supply, we would observe vertical incision in our relatively soft sedimentary bedrock channels if they were subject to channel gradients characteristic of the Grenville orogen. Similarly, if resistant igneous/metamorphic bedrock channels were subject to milder channel gradients, we may expect negligible vertical incision. We propose that the expansive muskeg wetlands of the interior Canadian Shield may represent an extreme example akin to our observations of wide low-relief bedrock channel forms. Here, the sprawling wetlands may be a product of the low-relief resistant bedrock topography.

Although significant vertical incision was not apparent in pure sedimentary bedrock channels, it was apparent at two of the five mixed sedimentary channels. Near-vertical bedrock faces, developed through vertical incision, were apparent along portions of the channel banks of Irvine River and East Sixteen Mile Creek. Significant vertical incision was not evident at the other three mixed sedimentary channels. Correspondingly, Irvine River and East Sixteen Mile Creek were the narrowest channels of the sedimentary dataset. The near-vertical bedrock banks caused the channels to be more confined than the unincised channels. However, due to the limited number of mixed sedimentary channels in our dataset, it is difficult to explain why significant vertical incision was apparent in some mixed sedimentary channels but not in others. Given that significant incision of sedimentary bedrock only occurred when alluvial cover was present, we suspect that vertical incision in low-relief channels is only possible where abrasive tools are available to erode the bed (Gilbert, 1877; Finnegan et al., 2007; Turowski et al., 2008). Conversely, vertical incision was apparent at all channels influenced by igneous/metamorphic bedrock where the bed was composed of bedrock (some mixed igneous/metamorphic channels had primarily alluvial beds with banks influenced by bedrock outcrops). Even pure igneous/metamorphic bedrock channels virtually free of alluvial cover were well-incised with near-vertical bedrock banks. Furthermore, channels influenced by igneous/metamorphic bedrock produced strong scaling relationships regardless of the degree of alluvial cover. Therefore, we propose that the channel gradients of these high-relief settings are steep enough to produce channel incision regardless of alluvial cover. Even though significant alluvial cover may not exist in pure igneous/metamorphic bedrock sections, the steep channel gradients likely enable significant incision of the bed during flood events which mobilize bedload through the channel. Thus, in high-relief settings, we propose that alluvial cover exhibits less control on channel incision and channel form in comparison to low-relief settings.

It is generally accepted that the greatest bedrock incision will be achieved where a limited sediment supply is mobilized as bedload overtop of bedrock (Sklar and Dietrich, 2001, 2004; Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Johnson and Whipple, 2010; Yanites and Tucker, 2010; Whitbread et al., 2015). In such cases, the bedload will tend to concentrate in the thalweg of the channel promoting channel narrowing (Finnegan et al., 2007;

Turowski et al., 2008; Johnson and Whipple, 2010). However, abundant alluvial cover will shield the bed and promote erosion of the channel margins (Sklar and Dietrich, 2001; Finnegan et al., 2007; Turowski et al., 2008; Johnson and Whipple, 2010; Yanites and Tucker, 2010). Since we found mixed channels to be narrower than bedrock channels, our results indicate that alluvial cover in our study streams tended to serve as abrasive tools as opposed to protective cover (Gilbert, 1877). Contrary to DiBiase & Whipple (2011), our low-relief and high-relief channels did not appear to produce similar width scaling relationships. The high-relief igneous/metamorphic dataset produced a much stronger scaling relationship than the low-relief sedimentary dataset. Unlike channels influenced by igneous/metamorphic bedrock, which had well-defined thalwegs, channels influenced by sedimentary bedrock typically had exceptionally flat beds (Figure 8). Even mixed sedimentary channels where vertical incision was apparent had flat beds abutted by abrupt near-vertical faces. We suspect that bedload tends to concentrate in the well-defined thalwegs characteristic of our igneous/metamorphic channels. However, bedload transport pathways through sedimentary settings are likely much more complex due to the flat nature of the rock. In these channels, we suspect that bedload moves through the channel in a much more sprawling nature across the channel width. This is supported by the observation of riffle-pool sequences in sedimentary mixed channels (Figure 2d). Instead of longitudinal concentrations of alluvium, as we might expect in channels with well-defined thalwegs, alluvium tended to concentrate in width-spanning riffles. As such, we propose that the distribution of mobile abrasive tools is much less predictable in our low-relief channels influenced by sedimentary bedrock in comparison to our high-relief channels influenced by less-planar igneous/metamorphic bedrock. This may partially explain the scatter observed in the sedimentary dataset and the uniformity of the igneous/metamorphic dataset. Our findings are supported by a recent study conducted by Inoue et al. (2016) who demonstrated the strong control of sediment supply and bedload transport pathways on bedrock incision using a plane-bed model. Their model results showed that where sediment supply rates are similar to transport capacity, sediment deposition will form alternate-bars with exposed bedrock in the pools. They further explained that downstream migration of the alternate-bars will induce bedrock incision across the entire width of the channel with the deepest incision actually occurring along the outer banks. However, reducing sediment supply, their model predicted bedrock incision in longitudinal grooves with bedload deposition and transport concentrated in the grooves. Inoue et al. (2016) further describe a model run with intermediate sediment supply rates which produced an intermediate morphologic result.

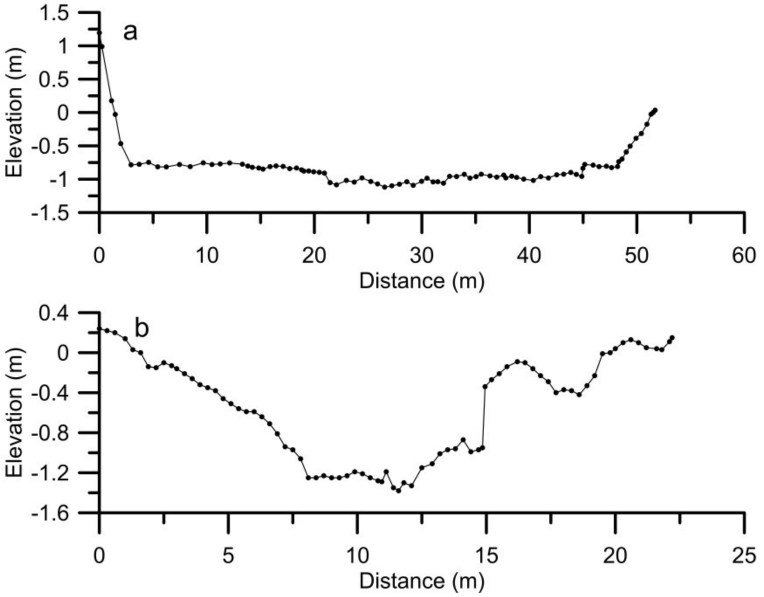

Figure 8. Example cross-sectional profiles of (a) a sedimentary bedrock section and (b) an igneous/metamorphic bedrock section. The displayed cross-sections were surveyed from (a) Carp River and (b) Saint-Louis Creek. Cross-sections are displayed looking downstream. An elevation of 0 m represents the bankfull level estimate.

Although we did not define explicit metrics to assess dominant erosion mechanisms, we are able to provide some insight through qualitative assessment of the channel boundaries. Channels influenced by igneous/metamorphic bedrock generally had smooth boundaries and rock protrusions typically had rounded edges. As such, abrasion appeared to be the dominant erosive mechanism in channels influenced by igneous/metamorphic bedrock. Erosive mechanisms in channels influenced by sedimentary bedrock tended to be more complex. Typically, jagged plate-like grains recently separated from the sedimentary bedrock mass and pot-holes were present, suggesting erosion through plucking. However, bedrock ridges and pot-holes typically had smooth edges suggesting that abrasive erosion also occurs. These qualitative assessments are reasonable given the lithologic properties of the two broad rock types. It is to be expected that the weak sedimentary bedrock is more susceptible to plucking and flaking than the igneous and metamorphic bedrock of the Canadian Shield. Figure 9 displays evidence of the different erosion mechanisms identified in the field.

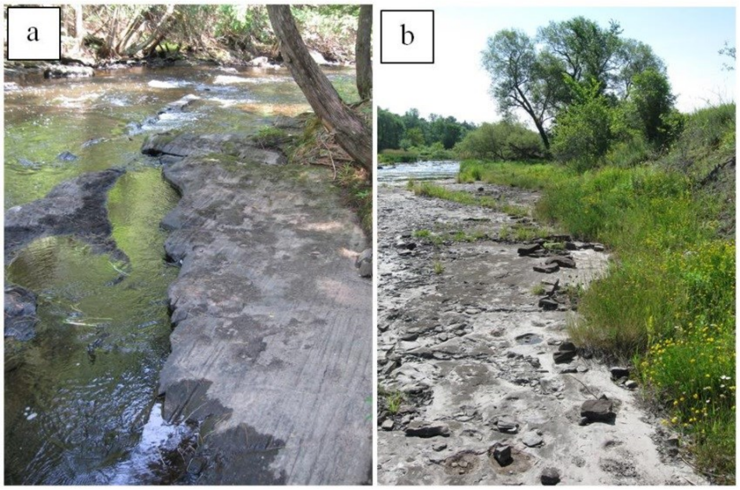

Figure 9. Visual evidence of bedrock erosion mechanisms. (a) The smooth and rounded bedrock of Buckshot Creek suggests that abrasion is the dominant erosion mechanism. (b) The presence of jagged plate-like grains and smoothed pot-holes suggests that the sedimentary bedrock section of Carp River erodes through both plucking and abrasion.

Spotila et al. (2015) proposed that plucking-dominated erosion enhances channel widening whereas abrasion-dominated erosion promotes channel narrowing. Our results generally support their findings. The narrowest channels tended to develop in igneous/metamorphic bedrock where abrasion was evidently the dominant erosion mechanism. Conversely, both abrasion and plucking tended to be evident in channels developed in sedimentary bedrock. Plucking was most apparent in the mixed channel of East Sixteen Mile Creek. Here, the channel boundaries are formed of brittle red shale which also forms massive near-vertical valley walls. Although the bedrock is easily eroded through plucking, this channel was amongst the narrowest of channels observed in the entire dataset. Thus, our observations suggest that the findings of Spotila et al. (2015) are subject to an upper threshold. In other words, bedrock that is easily plucked by the flow will tend to produce wide channels. However, bedrock that is exceptionally brittle will enhance vertical incision and promote channel narrowing.

2.7 Conclusions

Our study area of southern Ontario and southern Québec enabled us to evaluate an assortment of semi-alluvial bedrock channels in a variety of physiographic settings. Categorizing channels based on alluvial cover, we were able to develop discharge-based scaling relationships for bedrock, mixed, and alluvial channels. Furthermore, we were able to evaluate the influence of lithology by broadly categorizing bedrock as either igneous/metamorphic or sedimentary. The discharge-based scaling relationships developed in this study present a valuable addition to a currently limited dataset. Bedrock, mixed, and alluvial channels all scaled at similar rates with respect to flow. However, contrary to most previous research, we found bedrock channels to be statistically wider than mixed and alluvial channels. This is especially apparent in pure sedimentary bedrock channels located in low-relief regions. Our results also suggest that significant vertical incision in low-gradient bedrock streams will only occur where sufficient abrasive tools are available to erode the bed during flood events. However, significant vertical incision in high-gradient bedrock streams is possible even under very low sediment supply. Furthermore, channels influenced by igneous/metamorphic bedrock produced much stronger scaling relationships than channels influenced by sedimentary bedrock. We propose that this may be attributed to the complex bedload transport pathways produced by planar sedimentary bedrock in comparison to the somewhat predictable bedload transport pathways in channels influenced by igneous/metamorphic bedrock with well-defined thalwegs.

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3 Fish species distribution in a small semi-alluvial bedrock stream and development of habitat suitability criteria

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3.1 Abstract

Fish habitat was evaluated in a small semi-alluvial bedrock stream in Ontario, Canada. Fish sampling was conducted at proximate bedrock and alluvial sections of the study stream followed by a survey of physical habitat parameters. The data were used to evaluate substrate selectivity of several game fishes and small nongame fishes. Adult logperch (*Percina caprodes*), juvenile white sucker (*Catostomus commersonii*), adult round goby (*Neogobius melanostomus*), and adult longnose dace (*Rhinichthys cataractae*) demonstrated preference toward alluvial substrate, whereas juvenile logperch and adult banded killifish (*Fundulus diaphanus*) demonstrated preference toward bedrock. Juvenile silver shiner (*Notropis photogenis*) and juvenile yellow perch (*Perca flavescens*) were indifferent to substrate type. Empirical depth and flow velocity habitat suitability indices (HSIs) were developed for each fish species. HSIs developed for juvenile white sucker, adult longnose dace, and juvenile yellow perch were compared to existing HSIs from literature; the HSIs developed in this study provided a better description of the habitat suitability distribution throughout the study area. This study presents the first fish habitat

suitability criteria developed from a small semi-alluvial bedrock stream and may provide valuable information for fisheries management endeavours in such environments.

3.2 Introduction

The objective of this paper is to evaluate fish habitat availability and utilization in a semi-alluvial creek, where both surficial alluvium and bedrock substrate are available. Fish habitat is evaluated using the Instream Flow Incremental Methodology (IFIM) and the associated Physical Habitat Simulation System (PHABSIM) described by Bovee (1982), whereby fish habitat suitability is interpreted from physical flow and channel parameters. IFIM assessments require an understanding of the distribution of physical habitat conditions present in the study location as well as an understanding of the preferred habitat conditions of the species of interest. Fish habitat criteria are typically represented as univariate habitat suitability indices (HSIs) which plot habitat suitability on a scale from 0 to 1 as a function of relevant physical habitat parameters such as depth, flow velocity, substrate, and cover (Bovee, 1986, 1982). In order to conduct robust habitat assessments, ultimately leading toward informed fisheries management and stream restoration decisions, it is essential that the applied HSIs adequately reflect the true nature of the subject species to select certain habitat attributes.

Bovee (1986) described three hierarchical categories of HSIs. Category I HSIs are developed based on expert judgment or information from literature. Category II HSIs, also known as utilization HSIs, are developed based on observed utilization of the physical habitat. In essence, Category II HSIs are curves fitted to a normalized histogram of fish observation frequency versus the magnitude of relevant habitat parameters. Category III HSIs are similar to Category II HSIs given that they are also empirical relationships developed from field collected data. However, Category III HSIs incorporate the influence of the available habitat present within the area used for HSI development. For instance, if a fish species was mostly observed utilizing shallow depths which were very limited throughout the environment from which the HSIs were developed, then the preference for shallow depths would be exaggerated in Category III HSIs. Conversely, if shallow depths were abundant, then the preference for shallow depths would be diminished. Hybrid HSIs are also possible where expert judgment is used to alter existing HSIs to fit a particular environmental setting (Thorn and Conallin, 2006; Conallin et al., 2010). Conallin et al. (2010) discuss further segmentation of Category I, II, and III HSIs into four types: site-specific HSIs developed for a specific location, river type HSIs developed using data from a number of similar rivers, regional HSIs which are developed from a variety of rivers throughout a regional setting, and generic HSIs which are developed using known biological responses to changes in relevant habitat parameters.

Although it is possible for researchers and managers to develop HSIs specific to the project at hand and location of interest, the process is time consuming and often involves intensive field data collection, especially if Category II or III HSI are desired. Thusly, extensive research has been conducted regarding the transferability of HSIs across different geographic settings, dissimilar environments, and across a variety of flow conditions (Beecher et al., 1993; Thomas and Bovee, 1993; Groshens and Orth, 1994; Beecher et al., 1995; Glozier et al., 1997; Holm et al., 2001; Mäki-Petäys et al., 2002; Moir et al., 2005; Conallin et al., 2010; Teresa and Casatti, 2013). Of the three HSI categories, Category III HSIs are considered to be the most transferable since they are developed with consideration of both observed habitat utilization and habitat availability (Bovee, 1986). Furthermore, river type and regional HSIs are considered to be more transferable than site-specific HSIs (Groshens and Orth, 1994; Glozier et al., 1997; Conallin et al., 2010). However, of course, site-specific HSIs will provide the most accurate habitat criteria if applied within the stream from which they were developed (Groshens and Orth, 1994; Glozier et al., 1997; Vismara et al., 2001; Mäki-Petäys et al., 2002). The numerous research studies regarding HSI transferability have produced variable, and sometimes conflicting, results. Most research has indicated that habitat assessments can be very sensitive to the selection of HSIs and highly inaccurate results may be produced if HSIs are employed without consideration of applicability to the study stream (Holm et al., 2001; Moir et al., 2005; Conallin et al., 2010). Although quantitative transferability tests have been developed (Thomas and Bovee, 1993), they have faced criticism and can be difficult to employ due to data requirements (Glozier et al., 1997). In general, researchers have been able to demonstrate successful transfer of HSIs within a specific stream (Beecher et al., 1993, 1995), or amongst different, even geographically distant, streams provided that the study stream is biologically and physically similar to the stream from which, or for which, the curves were developed (Moir et al., 2005; Conallin et al., 2010). Researchers have also demonstrated poor transferability of HSIs between physically dissimilar streams (Glozier et al., 1997; Moir et al., 2005; Conallin et al., 2010). As such, it is clear that if researchers and managers wish to apply existing HSIs for research or fisheries management endeavours, it is best to obtain HSIs developed from an environment that is similar to their study stream.

Postglaciated regions typically have complex physiographic landforms resulting from various mechanisms of erosion and deposition due to ice progression, melt, and retreat (Gilbert, 1994). Likewise, the surficial geology of these regions is often characterized by complex arrangements of unconsolidated soils, clay, and bedrock (Chapman and Putnam, 1984). Thus, many rivers formed in postglaciated regions have semi-alluvial channels which have channel boundaries formed of both mobile alluvial sediments as well as more resistant substrates such as rock and cohesive clay (Ebisa Fola, 2007; Ebisa Fola and Rennie, 2010; Jamieson et al., 2013; Whitbread et al., 2015). The current physiographic landforms of southern Ontario were largely derived through the advancement and retreat of the Laurentide Ice Sheet during Wisconsinan glaciation (Gilbert, 1994). Throughout much of Southern Ontario, thick soil deposits overlie erodible Paleozoic sedimentary bedrock (typically limestone and dolostone) which in turn overlie the more ancient Precambrain metamorphic and igneous bedrock of the Canadian Shield (Chapman and Putnam, 1984; Gilbert, 1994). However, in many locations throughout the province, the bedrock foundation is exposed to the surface or is overlain by only a thin layer of soils (Chapman and Putnam, 1984; Gilbert, 1994). Naturally, many streams located in such environments have semi-alluvial channels with frequent and sporadic transitions between alluvial and bedrock channel substrates. Although semi-alluvial bedrock streams are quite common throughout southern Ontario, as well as other Canadian and international regions, only limited research has been conducted regarding fish habitat in these types of rivers (Coulombe-Pontbriand and Lapointe, 2004; May and Lee, 2004). Although the subject of substrate suitability is addressed in typical IFIM HSI development protocol through field observation of substrate utilization, where substrate types are categorized according to some index code (Bovee, 1982), fish habitat is rarely evaluated in semi-alluvial channels with abrupt transitions between segmented alluvial and bedrock sections. Milner & Gilvear (2012) suggested that differing physical heterogeneity between alluvial and bedrock channels may translate to distinct differences in available aquatic habitat and flow refugia. Differences between the ability for bedrock and alluvial substrates to maintain wetted pools and hydraulic connectivity during summer low flow have been observed in the field with repercussions for fish survival (May and Lee, 2004). Alluvial and bedrock sections may also differ with respect to the degree and type of cover provided. For instance, cover in bedrock sections may be provided by bedrock ridges (Nakamoto, 1994), whereas spaces between channel substrates in alluvial sections may provide cover for some small fish species (Meyer et al., 2013). Furthermore, it is reasonable to assume that the segmented nature of semi-alluvial channel substrates may influence habitat connectivity (May and Lee, 2004; Clark et al., 2008).

The potential for semi-alluvial bedrock channels to provide distinct habitat characteristics compared to purely alluvial systems, and the lack of existing research on the subject, establishes a need for further investigation. In regions such as southern Ontario, where many semi-alluvial bedrock channels exist within proximity of populated and developed areas, understanding fish habitat in these systems may be particularly important in order to make informed fisheries management decisions. In this study, we investigated fish habitat in a small semi-alluvial bedrock river located near Napanee, Ontario. Fish sampling and an extensive survey of physical habitat parameters were conducted at proximate bedrock and alluvial sections of the study stream. Survey data were further processed using interpolative methods to interpret habitat availability. Based on this information, we were able to evaluate the substrate selectivity of several game fishes and small nongame fish species. The data were also used to develop depth and velocity HSIs with the objective of providing habitat suitability criteria more suitable for use in small semi-alluvial bedrock streams in comparison to existing HSIs. The HSIs developed in this study represent the first habitat suitability criteria developed from a semi-alluvial bedrock channel. Furthermore, HSIs for round goby (*Neogobius melanostomus*), banded killifish (*Fundulus diaphanus*), and silver shiner (*Notropis photogenis*) could not be found in existing literature. Thus, we present the first known HSIs for these species.

3.3 Study Location

Data were collected from proximate bedrock (44°13’22.60”N, 76°51’44.20”W) and alluvial (44°13’17.30”N, 76°51’53.30”W) sections of Wilton Creek near the town of Napanee, Ontario. The bedrock section is located upstream of the alluvial section and the two are separated by a longitudinal distance of approximately 250 m. Between the bedrock and alluvial sections, the channel is best described as mixed bedrock-alluvial. No tributaries enter the stream between the bedrock and alluvial sections. The substrate of the bedrock section is defined by a relatively planar expanse of limestone bedrock (Chapman and Putnam, 1984; Ontario Geological Survey, 2010). The bedrock is continuous throughout the bedrock section and is virtually bare of alluvial cover except for some sparse gravelly deposits in bedrock crevasses. Although the limestone is very flat, well-defined bedrock ridges are present in some locations. The wetted width of the bedrock channel is highly variable due to the flat nature of the rock. Average width of the low-flow channel of the bedrock section is approximately 12 m and ranges between 9 m and 16 m. The substrate of the alluvial section is primarily composed of a mixture of gravel and cobbles with some sand and large boulders. The substrate composition appears to be relatively consistent throughout the low-flow channel of the alluvial section. The width of the low-flow channel of the alluvial section is much more consistent than the bedrock section; average width is approximately 6 m and ranges between 4.5 m and 10 m. Both sections have average channel slopes of approximately 0.006 m/m. However, there is a sharp rise in elevation at the downstream end of the bedrock section due to a prominent ridge. Both sections have similar riparian vegetation defined by grasses, and wetland macrophytes. The study location drains an upstream area of approximately 112 km^2 as determined using Ontario Integrated Hydrology Data (30 m resolution enforced DEM, enhanced flow direction grid, and stream network grid). Flow data were available from a Water Survey of Canada gauge located approximately 2.7 km upstream of the study location. Simple flow transposition techniques based on relative drainage area (Dharamdial and Faghaly, 1997) were used to estimate basic flow metrics at the study location based on the 50 year gauge record. Average annual flow and average median annual flows at the study location were estimated as 1.6 m^3/s and 0.6 m^3/s respectively. Assuming the 1.5 year return period flow produces bankfull conditions (Leopold et al., 1964; Copeland et al., 2000), bankfull flow was estimated as 17.0 m^3/s at the study location.

3.4 Methods

3.4.1 Fish Sampling

Fish sampling was conducted on the afternoon of November 4, 2015 via electrofishing. The bedrock and alluvial sections were divided longitudinally into 5 m fishing sectors each spanning the entire width of the channel except for the most-downstream portion of the alluvial section which was further divided across the channel width due to midstream dry islands (Figure 10). The alluvial section was divided into 19 fishing sectors covering a total fished area of 593 m^2. The bedrock section was divided into 7 fishing sectors covering a total fished area of 411 m^2. Originally, 10 fishing sectors were included in the bedrock section, but 3 had to be discarded due to insufficient depth and flow data (discussed in the next section). Electrofishing was conducted by a three-person crew in an upstream direction beginning at the most downstream fishing sector of the alluvial section. After each sector was fished, a separate shore team identified, tallied, measured, and assigned to a size-class (juvenile or adult) each captured specimen.

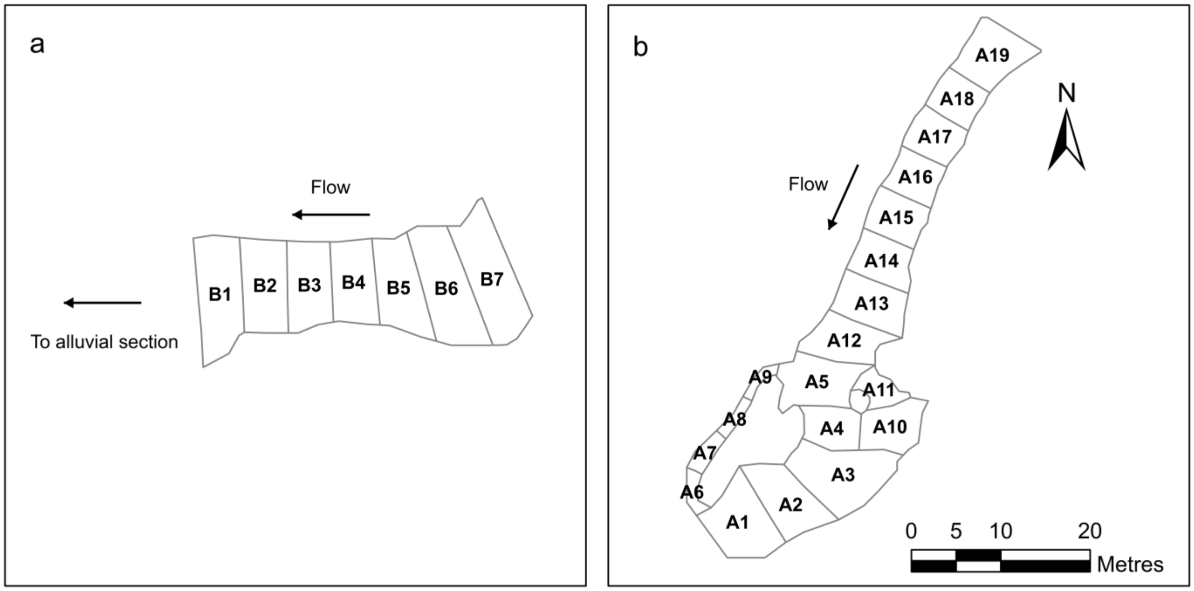

Figure 10. Fishing sectors of the (a) upstream bedrock section and (b) downstream alluvial section.

During fish sampling, flow was approximately 2.25 m^3/s as measured using an acoustic Doppler current profiler (aDcp). Average flow reported at the upstream gauge on November 4, 2015 was 1.99 m^3/s which is comparable to, but greater than, the average monthly value for November (1.64 m^3/s). For reference, the greatest and lowest average monthly flows at the gauge are 3.95 m^3/s and 0.15 m^3/s which represent March and August respectively. Thus, fish were sampled during moderate flow conditions greater than summer low-flow, but certainly less than bankfull or snowmelt conditions. Average air temperature during the time of fish sampling was 16.8 °C. Water temperature during fish sampling was approximately 17.5 °C and 11.5 °C for the alluvial and bedrock section respectively. However, the water temperature difference is likely attributed to the fact that the bedrock section was surveyed later in the afternoon than the alluvial section as a steady decline in water temperature was observed over time throughout the sampling period in both sections.

A total of 19 fish species were caught during fish sampling. However, only relatively small sample sizes were achieved for even the most abundant species. Only the most abundant species surveyed from the 19 alluvial and 7 bedrock fishing sectors were selected for further analysis. These include juvenile and adult logperch (*Percina caprodes*, $n = 37$ and $n = 11$ respectively), juvenile white sucker (*Catostomus commersonii*, $n = 26$), adult round goby (*Neogobius melanostomus*, $n = 19$), adult longnose dace (*Rhinichthys cataractae*, $n = 17$), adult banded killifish (*Fundulus diaphanus*, $n = 15$), juvenile silver shiner (*Notropis photogenis*, $n = 12$), and juvenile yellow perch (*Perca flavescens*, $n = 8$). It is important to note that round gobies are an invasive species in the study location and the information in this study is not presented with the purpose of enhancing round goby habitat, but with the purpose of providing a better understanding of round goby habitat for fisheries management purposes (Charlebois et al., 2001). It is also interesting to note that, as of 2011, silver shiner has been classified as a threatened species by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2011).

3.4.2 Physical Habitat Survey

Depth and depth-averaged flow velocity were surveyed immediately following fish sampling using a Sontek RiverSurveyor M9 acoustic Doppler current profiler (aDcp) equipped with real-time kinematic differential GPS (RTK-DGPS) and mounted on a small Oceanscience trimaran boat. This technology enabled the collection of dense point data with approximately 2 cm positional accuracy (Rennie and Rainville, 2006). The survey method involved tethering the boat-mounted aDcp to an operator on each channel bank and pulling the unit throughout the study area in a zig-zagging manner. Velocity data were collected with an average vertical resolution, or bin size, of approximately 0.07 m. Measurements were recorded at a sampling frequency of 1 Hz. Depth-averaged flow velocities were calculated using Matlab code developed by Rennie and Church (2010). The point data were filtered to eliminate points collected with poor GPS signal as well as some points that were clearly erroneous (unrealistic point spikes in depth or velocity). A total of 3536 depth measurements and 1729 velocity measurements were recorded in the alluvial section, while 972 depth measurements and 540 velocity measurements were recorded in the bedrock section. Typical spacing between consecutive survey points was approximately 0.24 m.

The survey spanned the entire fished area in the alluvial section. However, 3 of the 10 fishing sectors in the bedrock section were too shallow to use the aDcp and had to be eliminated from the study. The alluvial and bedrock data were interpolated using the Empirical Bayesian Kriging function of ArcGIS's Geostatistical Analyst to form depth and velocity grids with 15 cm resolution (Figure 11). Classical kriging models assume stationarity; that is to say, the spatial dependence at any location can be represented by a singular semivariogram (Krivoruchko, 2012). However, Empirical Bayesian Kriging produces predictions by estimating and simulating a number of semivariograms for subsets of data (Krivoruchko, 2012). Thus, Empirical Bayesian Kriging was considered to be more suitable for the study location, and perhaps river systems in general, where stationarity is a poor assumption due to channel slope and cross-sectional form. The interpolated data were used to characterize the available habitat within the study area (Figure 12a-b).

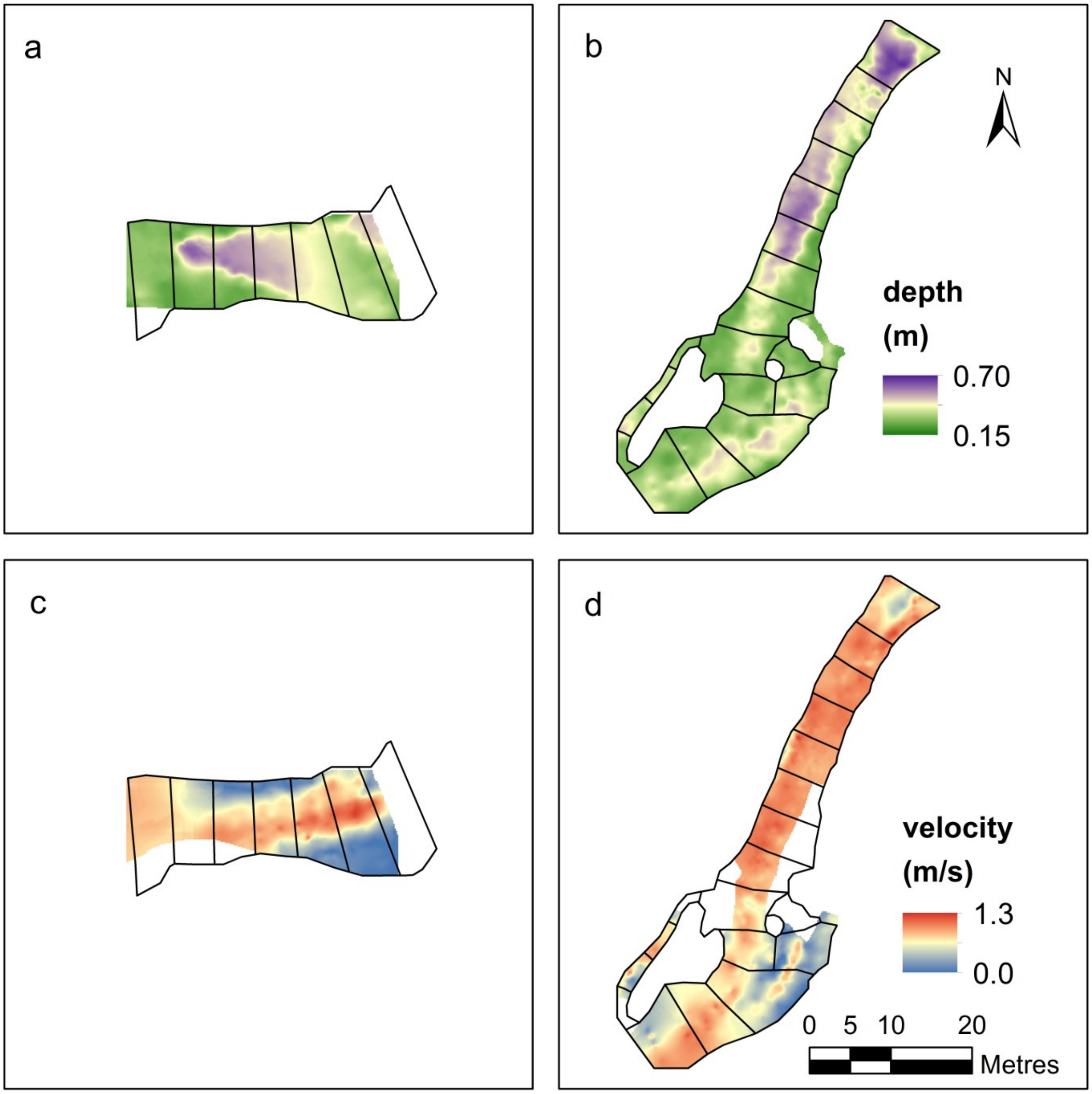

Figure 11. Distribution of depths throughout the (a) bedrock section and (b) alluvial section, and distribution of flow velocity throughout the (c) bedrock section and (d) alluvial section. Fishing sectors are displayed overtop of the interpolated data. Blank spaces represent where insufficient data were available for interpolation or where dry mid-channel islands existed.

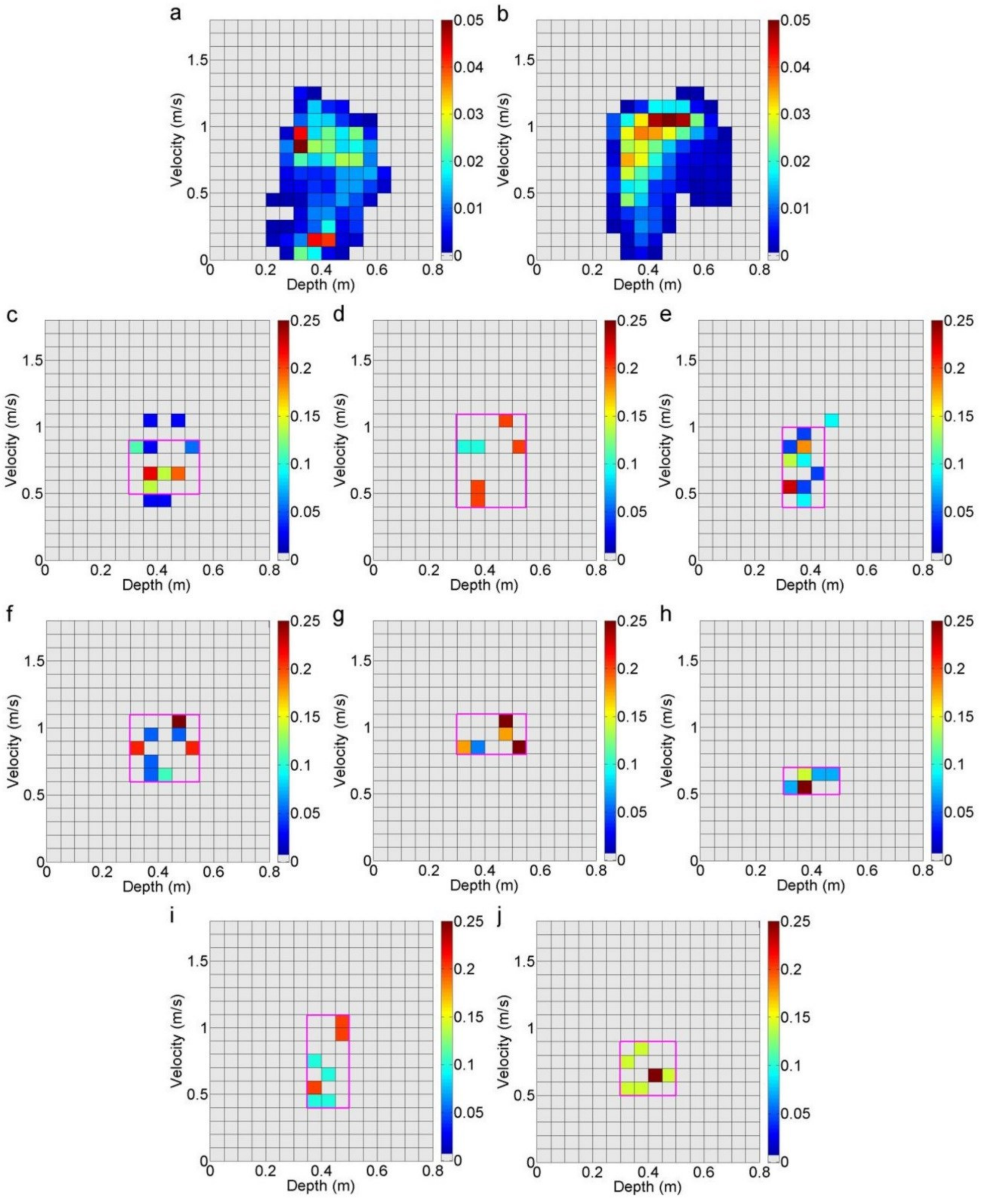

Figure 12. Proportion of depth-velocity habitat available in the (a) bedrock section and (b) alluvial section and catch-proportion of (c) juvenile logperch, (d) adult logperch, (e) juvenile white sucker, (f) adult round goby, (g) adult longnose dace, (h) adult banded killifish, (i) juvenile silver shiner, and (j) juvenile yellow perch observed utilizing available depth-velocity habitat. Purple boxes delineate optimal habitat ranges for each species and life-stage.

The survey data were used in conjunction with the fish sampling data to characterize habitat utilization. Average depth and velocity values were calculated for each fishing sector based on the interpolated depth and velocity data. Thus, each fishing sector represents one possible combination of utilized depth and velocity. In other words, any fish observed within a fishing sector was considered to be utilizing the average depth and velocity present within that fishing sector. For fishing sector A11, an average velocity could not be estimated due to insufficient velocity point data. However, sufficient depth point data were available to provide an estimate for average depth. Thus, fishing sector A11 provided depth utilization information only.

3.4.3 Statistical Evaluation of Substrate Selectivity

As opposed to typical IFIM HSI development protocol, where a range of substrates are evaluated to create substrate HSIs, substrate selectivity was evaluated using a binary approach; fish species could demonstrate preference toward alluvial substrate or bedrock substrate, or they could be indifferent to substrate type. In order to perform this assessment, it was first necessary to evaluate the depth-velocity combinations utilized by each fish species and life-stage. Using all observations (bedrock and alluvial) for each species and life-stage, joint-density plots for depth-velocity utilization were created. Based on visual observation, regions of optimal depth-velocity combinations (hereafter referred to as optimal habitat) were estimated for each species (Figure 12c-j). The optimal habitat range for each species and life-stage was then used to calculate the amount of habitat within that range provided by the bedrock and alluvial sections (Figure 12a-b).

The proportion of a fish species observed in the bedrock section or the alluvial section (p_f) was tested against the proportion of optimal habitat provided by the bedrock section or the alluvial section (p_h) using one-tailed hypothesis testing of a single proportion, where proportion is a parameter of the binomial distribution (Walpole et al., 2007). For instance, if the bedrock section provides 2 m^2 of optimal habitat and the alluvial section provides 1 m^2 of optimal habitat for a particular fish species, as defined by the optimal depth-velocity range for that species, then the null hypothesis assumes that we would expect 2/3 of the total observations to come from the bedrock section and 1/3 of the total observations to come from the alluvial section ($H_0: p_f = p_h$). The alternative hypothesis may either be that the proportion of fish observed in the bedrock section or alluvial section was greater than ($H_1: p_f > p_h$) or less than ($H_1: p_f < p_h$) the proportion of optimal habitat available in the section. Fish species were considered to exhibit selectivity of one substrate over the other if the null hypothesis was rejected at a 0.05 significance level (P-value less than 0.05). Otherwise, the species was considered to be indifferent to substrate type.

A key assumption of this methodology is that particular fish species and life-stages will select the same depths and velocities regardless of substrate composition. Unfortunately, the dataset does not provide sufficient information to evaluate the validity of this assumption.

3.4.4 HSI Development

HSIs were developed for each fish species and life-stage. Category III HSI were developed using the procedure outlined by Bovee (1986) whereby habitat utilization histograms are divided by habitat availability histograms and then normalized to produce habitat preference criteria. Fish utilization histograms were developed using abundance data which has been shown to produce superior results compared to occurrence data (Lee and Suen, 2013). For species and life-stages that preferred one substrate type over the other, HSIs were developed using utilization and availability data from the section of preferred substrate. This methodology was chosen so that the distribution of alluvial availability data did not influence the HSIs for a species that was primarily observed in the bedrock section and vice versa, even though similar ranges of habitat parameters were available in both the alluvial and bedrock section. Alluvial and bedrock utilization and availability data were pooled to produce HSIs for species and life-stages that were indifferent to substrate type. As such, utilization histograms for species which preferred bedrock, alluvium, and were indifferent to substrate type were constructed from 7, 19, and 26 possible observation points (fishing sectors). According to Bovee (1986), 150-200 observations are typically required in order to produce a smooth histogram. Thus, we acknowledge small sample sizes as a limitation of this study. Nonetheless, care was taken to ensure that bin spacing of the utilization histograms, and resulting preference HSIs, were selected in order to provide the most even spread of possible observation parameters. This was especially important for HSIs developed for species which preferred the bedrock section where only 7 possible observation points existed. Habitat availability histograms were constructed using the interpolated depth and velocity data displayed in Figure 11, with each 15 cm grid cell representing one point value.

In general, the normalized preference histograms produced reasonable HSI shapes without adjustment. However, in some cases, the preference histograms were manually smoothed through interpolation, averaging, or judgement to create the finalized HSIs. Furthermore, since depth and velocity data were averaged within each fishing sector, the range of utilization data was slightly less than the range of availability data. As such, in many cases, the upper and lower limits of the HSIs were extended based on literature, extrapolation, or judgement (Bovee, 1986).

3.4.5 HSI Implementation and Comparison with Existing HSIs

Existing HSIs are available from the U.S. Fish and Wildlife Service (FWS) for white sucker, longnose dace, and yellow perch. The HSIs developed in this study and the FWS HSIs were implemented in ArcGIS to visually compare the habitat suitability distribution produced by each suite of HSIs for the November 4th condition. Depth and velocity suitability were interpreted from the interpolated depth and velocity data. Combined suitability at a point was calculated as the product of depth suitability and velocity suitability (Bovee, 1982; Vismara et al., 2001; Clark et al., 2008). The Category I FWS HSIs for white sucker and longnose dace were developed from literature (Edwards et al., 1983; Twomey et al., 1984). The Category II FWS HSIs for yellow perch were developed from utilization data obtained from the Missouri River (Krieger et al., 1983).

3.5 Results

3.5.1 Substrate Selectivity

Of the eight species and life-stages included in the analysis, four demonstrated preference toward alluvial substrate, two demonstrated preference toward bedrock substrate, and two were indifferent to substrate type (Table 3). All tests resulting in either bedrock or alluvial preference were statistically significant ($P < 0.05$).

Table 3. Fish Species and Life-Stage Abundance, and Substrate Preference

Species and Life-Stage	Bedrock Observations	Alluvial Observations	Optimal Habitat Available in Bedrock Section (m^2)	Optimal Habitat Available in Alluvial Section (m^2)	Preference
Juvenile logperch	30	7	167	196	Bedrock
Adult logperch	0	11	256	433	Alluvial
Juvenile white sucker	1	25	152	249	Alluvial
Adult round goby	3	16	221	370	Alluvial
Adult longnose dace	0	17	156	267	Alluvial
Adult banded killifish	12	3	27	74	Bedrock
Juvenile silver shiner	3	9	127	273	Indifferent
Juvenile yellow perch	3	5	138	185	Indifferent

In most cases, substrate preference results correlated well with known species habitat characteristics. For instance, round gobies are known to prefer large rocky alluvial substrate over finer substrates and may be susceptible to predation in more open environments such as that provided by the bedrock section (Belanger and Corkum, 2003; Young et al., 2010; Kornis et al., 2012). Similarly, longnose dace are known to prefer gravel or boulder substrate and typically inhabit riffle portions of streams (Gibbons and Gee, 1972; Scott and Crossman, 1973; Edwards et al., 1983; Meyer et al., 2013). Adult banded killifish preferred bedrock substrate over alluvial substrate which seems like a reasonable observation considering that they are known to occupy quiescent areas with sandy or detritus substrate which may be more comparable to the bedrock section (Scott and Crossman, 1973; Houston, 1990; Fisheries and Oceans Canada, 2011). The results indicate that silver shiner were indifferent to substrate type. Using field data from four Ontario streams, Bouvier et al. (2013) reported similar results, concluding that silver shiner occupy a wide range of substrates including bedrock.

In some cases, substrate preference results differed from known species habitat characteristics. For instance, although yellow perch are a versatile fish species (Scott and Crossman, 1973), existing literature typically reports low preference for bedrock substrate (Krieger et al., 1983; Singkran, 2007). However, the results suggest that yellow perch were indifferent to substrate type. Existing Category I HSIs for juvenile white sucker suggest that all substrate types are suitable including bedrock (Twomey et al., 1984). However, in this study, juvenile white sucker exhibited strong preference of alluvium over bedrock. One may conjecture that the juvenile white suckers in this study simply chose to reside in the alluvial section from which they likely hatched as fry (Scott and Crossman, 1973). However, electrofishing was conducted in November, well after the spring spawn and hatch (Scott and Crossman, 1973). Furthermore, the specimens that were caught ranged from 70 mm to 170 mm in length (except for one specimen which was 41mm), which is indicative that some were older than the current year's hatch (Scott and Crossman, 1973). This suggests that juvenile white suckers had abundant time to select preferred habitat characteristics.

Probably the most interesting result was the division of substrate preference between juvenile and adult logperch. Logperch are known to occupy sandy, gravelly, or rocky substrates (Scott and Crossman, 1973; Buchanan and Stevenson, 2003). Preference indices developed by Singkran (2007) show preference for substrate partially composed of bedrock, but low preference for completely bedrock substrate. Adult logperch were only observed in the alluvial section suggesting strong preference of alluvium over bedrock substrate. However, a large majority of juvenile logperch were observed in the bedrock section suggesting preference of bedrock over alluvium. Although it may be possible that the results actually represent true preference characteristics of the species, it is also possible that the results are simply a product of species competition. Balshine et al. (2005) directly evaluated competition between round gobies and logperch, which have similar general habitat preferences and diets, and concluded that round gobies successfully outcompete and displace logperch. Round gobies were particularly abundant in the alluvial section which may inhibit logperch utilization, especially for smaller juvenile specimens. It is reasonable to assume that, given the opportunity, juvenile logperch would occupy the alluvial section in larger numbers similar to their adult counterparts. However, logperch may only be capable of successfully competing for alluvial habitat once they have grown to a sufficient size and life-stage. Thus, it is difficult to conclude whether or not the selection of bedrock substrate demonstrated by juvenile logperch actually implies preference toward the substrate type.

3.5.2 Depth and Velocity HSIs

Figures 13, 14, and 15 display the depth and velocity HSIs developed for species which demonstrated bedrock preference, alluvial preference, and indifference to substrate type respectively. Existing FWS HSIs for white sucker, longnose dace, and yellow perch are also displayed.

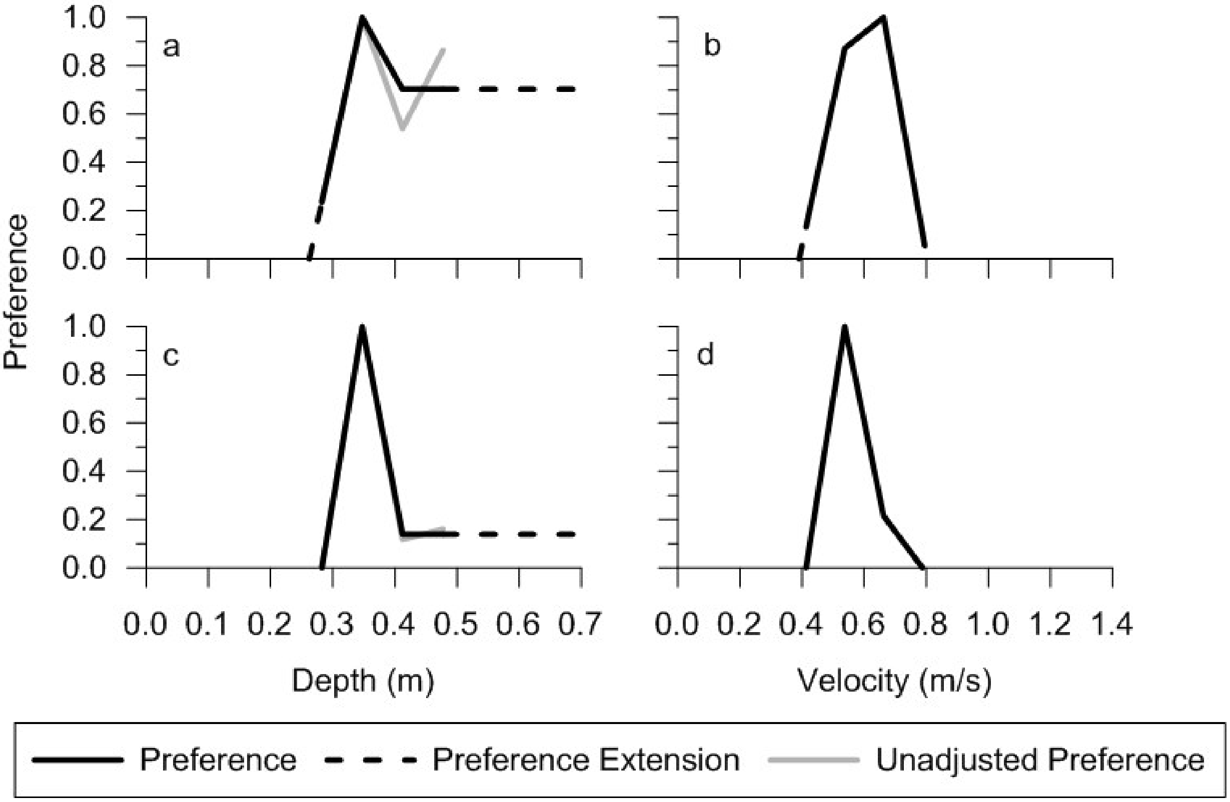

Figure 13. HSIs for species that preferred bedrock substrate. Depth and velocity suitability curves are displayed for (a and b) juvenile logperch and (c and d) adult banded killifish.

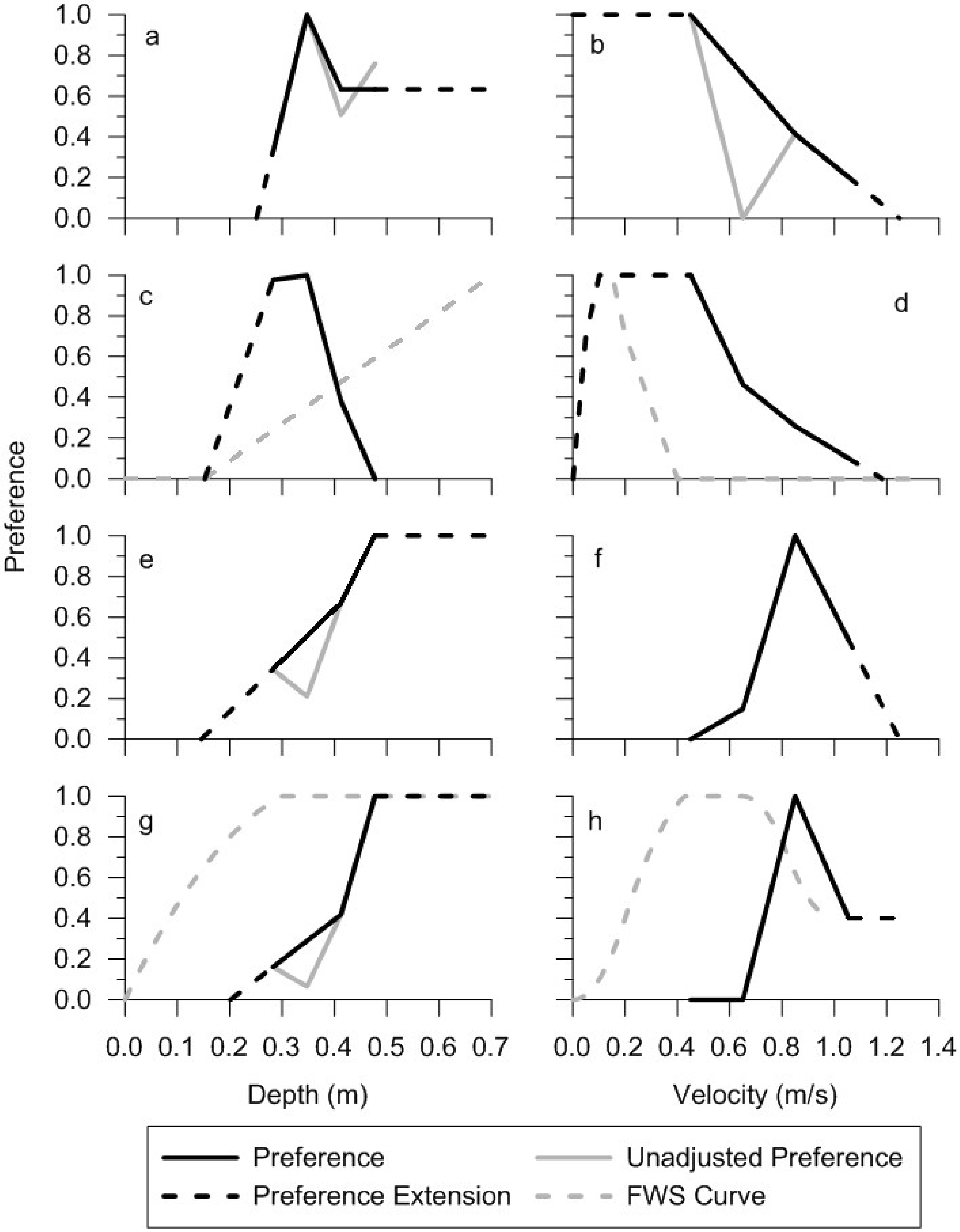

Figure 14. HSIs for species that preferred alluvial substrate. Depth and velocity suitability curves are displayed for (a and b) adult logperch, (c and d) juvenile white sucker, (e and f) adult round goby, and (g and h) adult longnose dace.

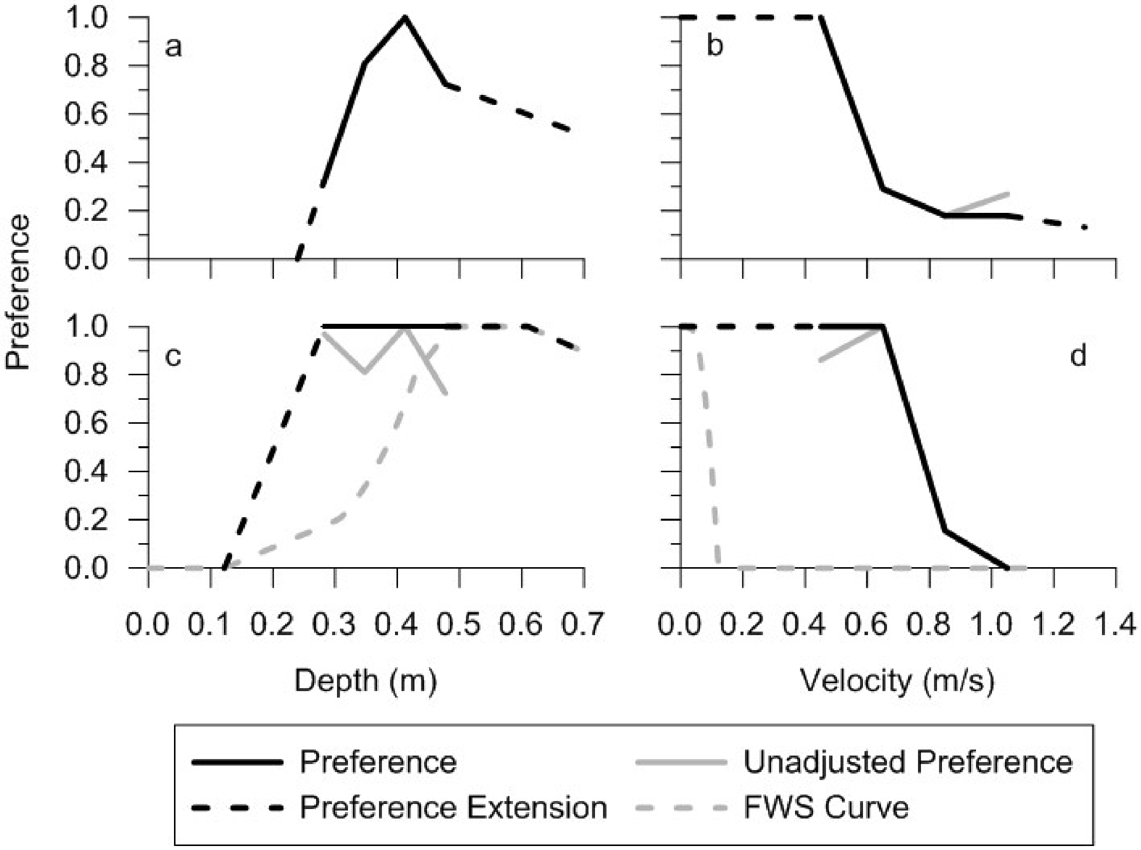

Figure 15. HSIs for species that demonstrated indifference toward substrate type. Depth and velocity suitability curves are displayed for (a and b) juvenile silver shiner and (c and d) juvenile yellow perch.

In most cases, the unadjusted preference curve could be used to represent the finalized HSI or could otherwise be adjusted to create a reasonable HSI through averaging, interpolation, or judgement. Similarly, the HSIs could generally be extended outside of the observed limits using extrapolation or judgement. Some exceptions include juvenile white sucker and juvenile yellow perch where the lower extensions of the depth and velocity HSIs, and the upper extension of the depth HSI for juvenile yellow perch, were estimated based on existing FWS HSIs (Krieger et al., 1983; Twomey et al., 1984). Similarly, the upper extensions of the depth and velocity HSIs for adult longnose dace were estimated based on the existing FWS HSIs (Edwards et al., 1983). It is important to note that the FWS depth HSI displayed for longnose dace actually represents suitability based on maximum depth over riffle portions of the stream, not at any given point (Edwards et al., 1983). The upper extensions of the depth and velocity HSIs for silver shiner are based on observed depth and velocity ranges reported by Bouvier et al. (2013).

There is some variability amongst the depth suitability HSIs created for each species and life-stage. Most species exhibited preference for greater depth except for juvenile white sucker and adult banded killifish. As expected, most depth HSIs show a clear lower threshold for depth preference except for juvenile white sucker and juvenile yellow perch where lower thresholds were estimated as described above. It is also worth noting that the depth HSIs for juvenile and adult logperch have a similar shape even though they were developed using data from different sections. Both depth HSIs show optimal suitability occurring at approximately 0.35 m followed by a small decline in preference with greater depths. Although they represent different life-stages, the similarity between the two depth HSIs supports the assumption that a species will utilize similar depths and velocities regardless of substrate type.

Variability also exists amongst the velocity suitability HSIs. Most velocity HSIs show an upper threshold, or at least decreased preference, for faster velocities except for adult longnose dace which are known to inhabit fast flowing portions of streams (Scott and Crossman, 1973). Juvenile logperch, adult banded killifish, adult round goby, and adult longnose dace also show decreased preference for slower velocities. This seems like a reasonable observation for longnose dace and logperch which have been known to inhabit fast flowing water (Scott and Crossman, 1973), and for round gobies, which are capable of finding refuge from fast velocities by pressing themselves to channel substrates (Hoover et al., 2003). However, banded killifish typically inhabit quiescent flows (Scott and Crossman, 1973). Thus, as expected, the velocity

HSI for adult banded killifish shows a sharp decline in preference with increasing flows, but unexpectedly shows a lower threshold as well.

3.5.3 HSI Implementation and Comparison with Existing HSIs

The depth HSIs produced for juvenile white sucker and juvenile yellow perch show greater suitability of relatively shallow depths in comparison to FWS depth HSIs. Depth suitability for juvenile white sucker decreases with depths greater than approximately 0.35 m, whereas the FWS depth HSI shows increased suitability with depth over the range of observed values. Conversely, the depth HSI produced for adult longnose dace shows depths less than approximately 0.2 m to be unsuitable, whereas the FWS depth HSI shows any wetted depth to be at least somewhat suitable. As noted in the previous section, the FWS depth HSI for longnose dace represents suitability based on maximum depth of riffles, whereas the depth HSI developed in this study considered all available depths in the alluvial section; this may explain the observed discrepancy. The velocity HSIs produced for juvenile white sucker and juvenile yellow perch both have similar shapes in comparison to the FWS velocity HSIs but show much greater upper thresholds. This implies that the white suckers and yellow perch in the study stream were able to utilize and tolerate much greater velocities than typically expected. The velocity HSI produced for adult longnose dace also has a similar shape compared to the FWS velocity HSI. However, the FWS velocity HSI shows greater suitability for low to mid-range velocities.

Figure 16 displays the habitat suitability distribution produced by the HSIs developed in this study and the HSIs available from the FWS. It is to be expected that the curves developed in this study will provide a more accurate description of habitat suitability distribution throughout the study location in comparison to the FWS HSIs since they were developed using data collected from the site. The purpose of this comparison is to evaluate the potential implications of using

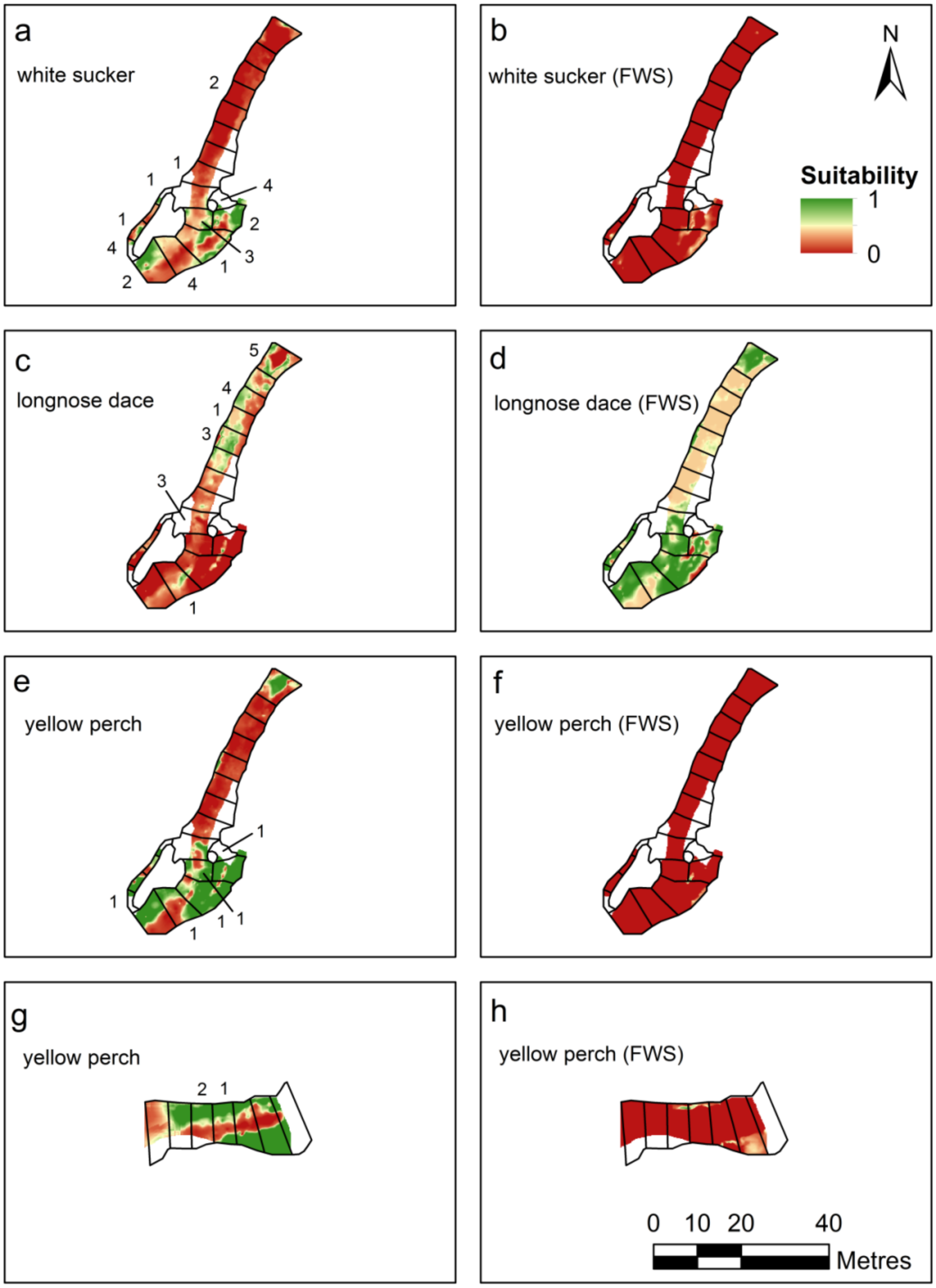

Figure 16. Habitat suitability distributions for the November 4, 2015 flow condition as calculated using (a,c, e, and g) the HSIs developed in this study and (b, d,f, and h) existing HSIs available from the FWS. (a) through (f) pertain to the alluvial section, and (g) and (h) pertain to the bedrock section. The numbers of fish caught in each fishing sector are also displayed.

the FWS HSIs in a small semi-alluvial stream without considering applicability to the study location. For this comparison, the FWS depth HSI for longnose dace is assumed to represent suitability at any given point throughout the stream even though it is intended to describe suitability based on maximum depth over riffles.

As expected, the habitat suitability distribution produced by the HSIs developed in this study correlate well with the fish catch data. In the alluvial section, suitable habitat for both juvenile white sucker and juvenile yellow perch is generally reserved to the moderate-to-shallow depths and slow velocities of the most downstream portion of the alluvial section. Conversely, the most suitable habitat for longnose dace is located throughout the deep and fast flow provided by the upstream portion of the alluvial section. The predicted habitat suitability distribution for juvenile yellow perch throughout the bedrock section provided much less convincing results. Yellow perch were in fact observed in bedrock fishing sectors where suitable habitat was predicted. However, yellow perch were absent from many bedrock fishing sectors where abundant suitable habitat was also predicted.

In comparison to the HSIs developed in this study, the FWS HSIs generally produced poorer predictions of habitat suitability distribution. For both juvenile white sucker and juvenile yellow perch, the FWS HSIs show the majority of physical habitat throughout both the bedrock and alluvial sections to be unsuitable. This is mostly due to poor velocity suitability predictions throughout the study location nullifying any suitable depths that may be present. However, the sparse locations of suitable juvenile white sucker or juvenile yellow perch habitat predicted using the FWS HSIs do occur within the vicinity of fish observations. Thus, although the FWS HSIs for juvenile white sucker and juvenile yellow perch are not as descriptive of the true habitat in comparison to the HSIs developed in this study, they do appear to have some predictive utility.

Interestingly, habitat suitability predictions produced by the FWS HSIs for longnose dace show the most suitable habitat to occur within the vicinity of riffles, which generally provide good habitat for the species (Gibbons and Gee, 1972; Edwards et al., 1983). Longnose dace were in fact observed in the vicinity of riffles. However, the FWS HSIs predicted only moderate suitability of the midstream portion of the alluvial section where many longnose dace were also observed.

It is important to note that the lower extents of the depth and velocity HSIs for juvenile white sucker and juvenile yellow perch, the upper extent of the depth HSI for juvenile yellow perch, and the upper extents of the depth and velocity HSIs for longnose dace, were estimated based on FWS HSIs. Consequently, the HSIs produced in this study and the FWS HSIs will inherently predict similar habitat suitability for juvenile white sucker at exceptionally shallow and quiescent locations, and similarly for adult longnose dace at deep and fast locations. Additionally, the two sets of HSIs will predict similar habitat suitability for juvenile yellow perch at exceptionally shallow and quiescent, or deep and quiescent, locations. However, the ranges of depth-velocity combinations for which the study HSIs and the FWS HSIs produce identical results represent the fringes of available habitat in the study area or do not exist at all (compare curve overlap with FWS HSIs in Figures 14 and 15 with available depth-velocity combinations in Figures 12a and 12b). The upper extensions of the depth HSIs for adult longnose dace and juvenile yellow perch encompass quite a lot of the available depth, but dissimilarities between the respective velocity HSIs diminished the occurrence of identical overall habitat suitability predictions between the study HSIs and FWS HSIs throughout the study area.

3.6 Discussion

All fish species and life-stages evaluated in this study utilized both bedrock and alluvial environments except for adult longnose dace and adult logperch which were present in only the alluvial section. Six of the eight species and life-stages were disproportionately abundant in one of the two sections implying selectivity of one substrate type over the other. Adult logperch, juvenile white sucker, adult round goby, and adult longnose dace demonstrated preference toward alluvial substrate, whereas juvenile logperch and adult banded killifish demonstrated preference toward bedrock. As such, the results suggest that the fragmented nature of semi-alluvial bedrock streams provides an environment which enables, or perhaps induces, fish species and life-stage segregation.

The observed difference between juvenile and adult logperch substrate selectivity brings into question whether the segregation is a product of substrate preference or species competition. Although existing literature suggests that logperch generally occupy alluvial substrates (Scott and Crossman, 1973; Buchanan and Stevenson, 2003), they are also known to exist where bedrock is present (Singkran, 2007). Therefore, it is especially difficult to decipher the true cause of segregation since they are not known to show overwhelming affinity to one substrate type (unlike longnose dace for instance which are known to strongly prefer alluvium (Scott and Crossman, 1973; Edwards et al., 1983; Meyer et al., 2013)). Round gobies were abundant throughout the study stream, particularly in the alluvial section, and are known to outcompete and displace logperch (Balshine et al., 2005). In fact, round gobies are particularly aggressive and adult life-stage round gobies have been known to outcompete and displace smaller juvenile round gobies to less desirable habitat (Charlebois et al., 2001; Ray and Corkum, 2001). The fact that adult logperch were observed in only the alluvial section strongly implies preference for alluvial substrate for the adult life-stage. It is reasonable to assume that, given the opportunity to inhabit the substrate of their choice without overwhelming competition, a greater proportion of juvenile logperch would inhabit the alluvial section in comparison to the proportion observed. Additionally, 7 of the 37 juvenile logperch were observed in the alluvial section discrediting the possibility that alluvium may in some way be unsuitable for the juvenile life-stage. Logperch may only be capable of competing for coveted alluvial habitat once they have grown to a sufficient size and life-stage. Therefore, the observed substrate preference results for juvenile logperch may be more indicative of competition dynamics than actual preference. These observations may serve as encouragement for those who wish to investigate species competition to focus their efforts on semi-alluvial stream environments where distinctly different physical habitats naturally exist in close proximity.

Although preference of one substrate type does not necessarily imply absolute inhabitability of another, semi-alluvial bedrock channels may provide poor habitat connectivity for species that have strong affinity for a specific substrate type. Habitat connectivity may be of particular importance for small streams especially if dry islands or inhabitable shallow depths exist during summer low-flow (May and Lee, 2004; Clark et al., 2008). One may conclude that, in comparison to purely alluvial or purely bedrock streams, small semi-alluvial bedrock channels may provide poor overall habitat for species that strongly prefer a certain substrate type. However, the presence of proximate alluvial and bedrock sections may actually enhance biodiversity by providing greater substrate variety in comparison to purely alluvial or purely bedrock streams. Such environments may be capable of providing suitable habitat for species that prefer bedrock, species that prefer alluvium, and species that are able to inhabit both substrate types.

The HSIs developed in this study successfully predicted suitable habitat to exist where fish were observed. This result was to be expected considering that the predicted habitat suitability distribution was compared to the fish abundance data from which the HSIs were developed. In comparison, the habitat suitability distribution produced by the FWS HSIs only poorly correlated with fish observations. The literature-based HSIs for white sucker and longnose dace may provide criteria that are too generalized for application in a small semi-alluvial stream such as Wilton Creek. The Category II FWS HSIs for juvenile yellow perch were likely poor predictors of the habitat suitability distribution in Wilton Creek because they were developed from data obtained from an exceptionally different environment (Glozier et al., 1997; Moir et al., 2005; Conallin et al., 2010); they were developed from a portion of the Missouri River where channel widths ranged between 300 and 1500 m, available depths ranged between approximately 0 and 8 m, and available velocities ranged between 0 to 2.1 m/s (Krieger et al., 1983). Thus, we corroborate the conclusions of many other researchers who demonstrated poor transferability of HSIs between dissimilar physical environments (Glozier et al., 1997; Moir et al., 2005; Conallin et al., 2010). It is important to note that site-specific and flow-specific HSIs, such as those developed in this study, are generally considered to be less transferrable than HSIs developed from pooled data (Groshens and Orth, 1994; Glozier et al., 1997; Holm et al., 2001; Conallin et al., 2010). Furthermore, the HSIs should be interpreted with a degree of caution since they were developed using small fish observation samples and relatively coarse averaging techniques. However, we propose that the HSIs developed in this study likely have superior utility for small semi-alluvial bedrock streams in comparison to general literature-based HSIs or HSIs developed from dissimilar environments.

It is difficult to comment on the relative influence of depth and velocity on overall habitat suitability. It is reasonable to expect that in a small stream environment such as Wilton Creek, the two parameters may in fact be closely linked. For instance, the deepest portions of the stream are generally reserved to the thalweg or immediately downstream of riffles in plunge-pools where the greatest velocities are also present. As such, there are very few locations that are both deep and quiescent or shallow and fast. Therefore, a lack of preference for deeper locations may actually reflect avoidance of faster velocities and vice versa. With that said, possible next-steps for future research may involve developing bivariate habitat suitability criteria where preference is defined by a two-dimensional surface function of depth and velocity (Bovee, 1982; Vismara et al., 2001).

3.7 Conclusions

Fish habitat was evaluated in a small semi-alluvial bedrock stream for several fish species. Results suggest that the distribution of bedrock and alluvial sections correlate with, and may even govern, the distribution of fish species throughout the stream. Adult logperch, juvenile white sucker, adult round goby, and adult longnose dace demonstrated preference toward alluvial substrate, whereas juvenile logperch and adult banded killifish demonstrated preference toward bedrock. Juvenile silver shiner and juvenile yellow perch were indifferent to substrate type. Field collected habitat utilization and habitat availability data were used to develop empirical preference HSIs. The HSIs developed in this study provided a better description of the habitat suitability distribution throughout the study area in comparison to existing HSIs sourced from literature, and may be applicable to other small semi-alluvial bedrock channels similar to the study area.

3.8 Acknowledgements

We thank Rahmouna Benahmida, Philippe April-Le Quéré, Andrea J. Reid, and William M. Twardek for their assistance in field data collection. Funding was provided by NSERC. Cooke is supported by the Canada Research Chairs program. The electrofisher was purchased with support from the Faculty of Science at Carleton University. Sean Ferguson acknowledges student funding from an Ontario Graduate Scholarship.

4 Implementation of HSIs in MIKE 21

4.1 Hydrodynamic Model Development

The bedrock section and the upstream portion of the alluvial section discussed in Chapter 3 were modelled using the DHI MIKE 21 flexible mesh flow model. The alluvial model domain was terminated just upstream of the mid-channel dry islands (near the downstream extent of fishing sector A13 displayed in Figure 10b). Hydrodynamic simulations in MIKE 21 are based on the numerical solution of the depth-integrated incompressible Reynold's averaged Navier-Stokes equations; the equations are solved based on a cell-centered finite volume method (DHI, 2011). Both the bedrock domain and alluvial domain were discretized using an unstructured triangular mesh created using the MIKE ZERO Mesh Generator. For the bedrock domain, the main channel and floodplains were discretized using a maximum cell size of 0.4 m^2 and 3.5 m^2 respectively. Similarly, for the alluvial section, the main channel and floodplains were discretized using a maximum cell size of 0.3 m^2 and 3.5 m^2 respectively. The model bathymetries were produced using the aDcp point data collected on November 4, 2015 discussed in Chapter 3, a smaller set of aDcp point data collected on July 29, 2015, and additional bathymetric data surveyed throughout the summer of 2015 using the stand-alone RTK-DGPS. All survey data were collected with reference to the NAD83 Ellipsoid shifted by a scaled-down version of the OSU89B geoid model (see NovAtel (2001)); this elevation reference is synonymous with "mean-sea-level" heights. Bathymetry points surveyed using the stand-alone RTK-DGPS were collected at random and point spacing generally varied between approximately 0.5 m and 1.5 m both across-stream and longitudinally. Dry portions of the floodplain within vicinity of the main channel were also surveyed. Further extrapolation of the floodplain data by 10 m on either side of the main channel was conducted in order to produce more realistic floodplain topography in comparison to a hard cut-off. Sufficient survey data were available to extend the alluvial model domain well upstream of the section of interest. However, for the bedrock section, the model inlet had to be manually extended upstream in order to reduce the influence of the upstream boundary condition on the simulation results. Similarly, sufficient survey data were available to extend the bedrock model domain downstream of the area of interest. However, this was not possible for the alluvial domain which terminates at the downstream boundary of the area of interest. A fixed flow was implemented as the upstream boundary condition and a fixed water surface elevation was implemented as the downstream boundary condition for both the bedrock and alluvial models. Boundary conditions were estimated directly from aDcp survey data to recreate the November 4, 2015 flow condition. The discharge, and upstream boundary condition for both models, was 2.25 m^3/s. In the geoid-shifted spatial reference described above, the downstream water level boundary condition for the bedrock and alluvial section was 84.02 m and 82.72 m respectively. However, all elevation data were implemented into the models using an arbitrary spatial reference such that all bathymetry data were entered as negative values.

4.2 Calibration

Both models were calibrated using the November 4, 2015 aDcp data. Measured depth and depth-averaged flow velocity components were compared to simulated values. Measured and simulated data were plotted in Matlab. The Matlab code fits a functional relation through the plotted data as well as regression fit with upper and lower 95% confidence intervals (Rennie and Villard, 2004). The functional slope was used as a calibration metric; a slope of 1 is ideal. The models were calibrated by adjusting boundary roughness, eddy viscosity, and mesh resolution. For the bedrock section, a Manning's n value of 0.014 $s/m^{1/3}$ was used for the main channel and Manning's n values ranging between 0.05 and 0.1 $s/m^{1/3}$ were used for the channel margins and floodplains. For the alluvial section, Manning's n values ranging between 0.02 and 0.05 $s/m^{1/3}$ were used for the main channel and Manning's n values ranging between 0.05 and 0.1 $s/m^{1/3}$ were used for the channel margins and floodplains. For horizontal eddy viscosity, a Smagorinsky coefficient of 0.28 and 0.25 (constant throughout the domain) was specified for the bedrock and alluvial model respectively. A critical Courant-Friedrich-Lévy (CFL) number of 0.5 was specified for both models. A number of computational meshes of varying cell resolutions were evaluated. The cell resolutions described in Chapter 4.1 produced acceptable calibration results and simulation speeds in comparison to other tested meshes. Figure 17 displays the model performance results plotted in Matlab. Although the functional slope was used as the primary metric for model performance, the standard error of the regressions are also displayed to provide a description of the scatter.

The bedrock and alluvial models recreated the measured depth data quite well as indicated by the functional slope. However, simulated velocity data poorly resembled measured data. The low functional slopes of the velocity calibration results indicate that the models tended to underestimate velocity. All calibration results show a lot of scatter, especially velocity. This may be due to the relatively dense point data collection compared to model cell sizes. A single model cell may contain several calibration points as dictated by aDcp point measurements. The models output point data through linear interpolation of cell-centered solutions (DHI, 2011). This approach provides a smoother result in comparison to assigning point values based on discrete cell-centered solutions. However, large measurement fluctuations over short distances are still liable to produce scatter. In order to better understand the variability of measured data, several model cells encompassing three or more measurement locations were selected at random, and the standard deviation of measured values within the model cells was calculated. The typical

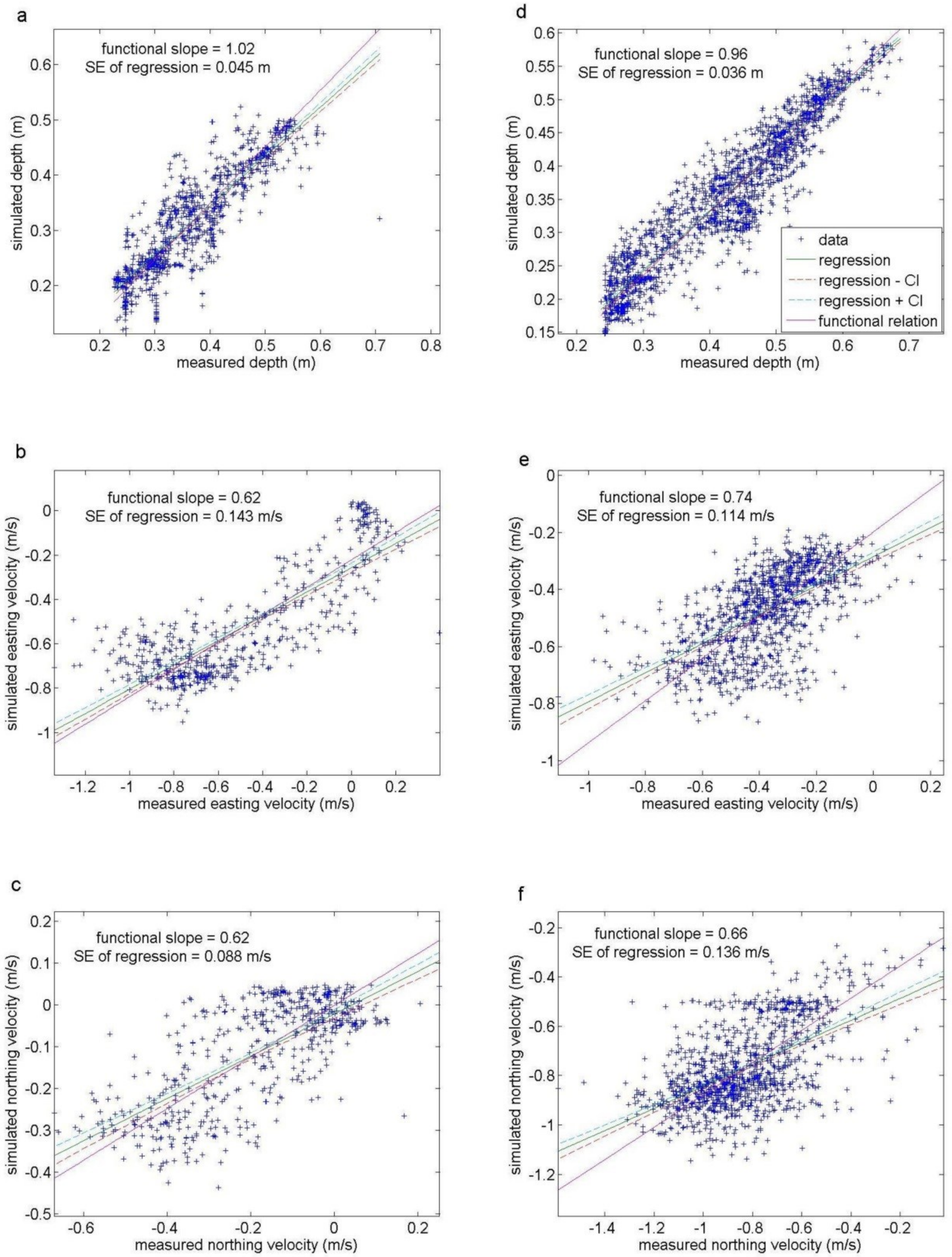

Figure 17. Calibration results for (a, b, and c) the bedrock model and (d, e, and f) the alluvial model. The functional slope and standard error of the regression are displayed for each calibration result. Negative easting velocities represent westward velocity, and negative northing velocities represent southward velocity.

standard deviation of measured depth, easting velocity, and northing velocity within a model cell of the bedrock main channel is 0.003 m, 0.139 m/s, and 0.047 m/s respectively. The typical standard deviation of measured depth, easting velocity, and northing velocity within a model cell of the alluvial main channel is 0.021 m, 0.114 m/s, and 0.151 m/s respectively. These values are comparable with the standard errors reported in Figure 17 and may explain the scatter. Furthermore, there are uncertainties associated with aDcp measurements which may also contribute to the scatter (Rennie and Church, 2010). For reference, Rennie and Church (2010) reported an uncertainty of 0.11 m/s for depth-averaged flow velocity based on aDcp surveys of the Fraser River.

Convergence was evaluated by calculating the average percent difference between model simulations 30 seconds apart at the point locations coinciding with aDcp measurements (i.e. the same point locations used for calibration were used to evaluate convergence). The bedrock and alluvial models converged reasonably well after one hour of simulation time. The bedrock model produced depth, easting velocity, and northing velocity solutions with 0.006%, 0.037%, 0.122% fluctuation respectively. The alluvial model produced depth, easting velocity, and northing velocity solutions with 0.012%, 0.031%, and 0.028% fluctuation respectively. These degrees of variability were considered satisfactory for the application at hand, interpreting fish habitat suitability.

4.3 Implementing HSIs into ECO Lab Module

The HSIs developed for juvenile white sucker, adult longnose dace, and juvenile yellow perch (Figures 14 and 15) were implemented into the models using the MIKE ZERO ECO Lab module. The ECO Lab module allows modellers to use a number of built-in “forcings” to calculate desired results from hydrodynamic simulations (DHI, 2009). The term “forcing” is used to describe a parameter which may be used as an argument in a mathematical expression (DHI, 2009). As discussed in Chapter 3, the univariate HSIs represent habitat suitability based on depth and flow velocity, both of which are available as built-in “forcings” in ECO Lab. Unique “processes” were created in ECO Lab for each HSI. “Processes” enable the modeller to enter mathematical expressions using “forcings” as variables (DHI, 2009). The habitat criteria displayed in each HSI were entered into respective “processes” as a series of if-statements using “forcings” as expression variables. Unique “processes” were created for the overall habitat suitability of each species and life-stage in which habitat suitability at a point is calculated as the product of depth and velocity suitability. It is worth noting that the ECO Lab module will not operate without specifying a “state variable”. Since a “state variable” was not required for this analysis, a dummy variable was specified.

4.4 Results

Figure 18 displays the modelled depth and depth-averaged flow velocity results for the November 4, 2015 flow condition and Figure 19 displays the corresponding habitat suitability distributions for juvenile white sucker, adult longnose dace, and juvenile yellow perch. The hydrodynamic simulations resembled the same patterns observed in the interpolated depth and flow velocity data displayed in Figure 11. Accordingly, the modelled habitat suitability distributions resembled the same patterns interpreted from the interpolated data displayed in Figures 16a, c, e, and g. However, as discussed in Chapter 4.2, the models generally underestimated flow velocity. The discrepancies in the hydrodynamic simulations are reflected in the resulting habitat suitability distributions. Furthermore, the model results showed wetted areas extending beyond the region in which aDcp data were collected as displayed by the outline of the fishing sectors. This is especially apparent along the north bank of the bedrock section

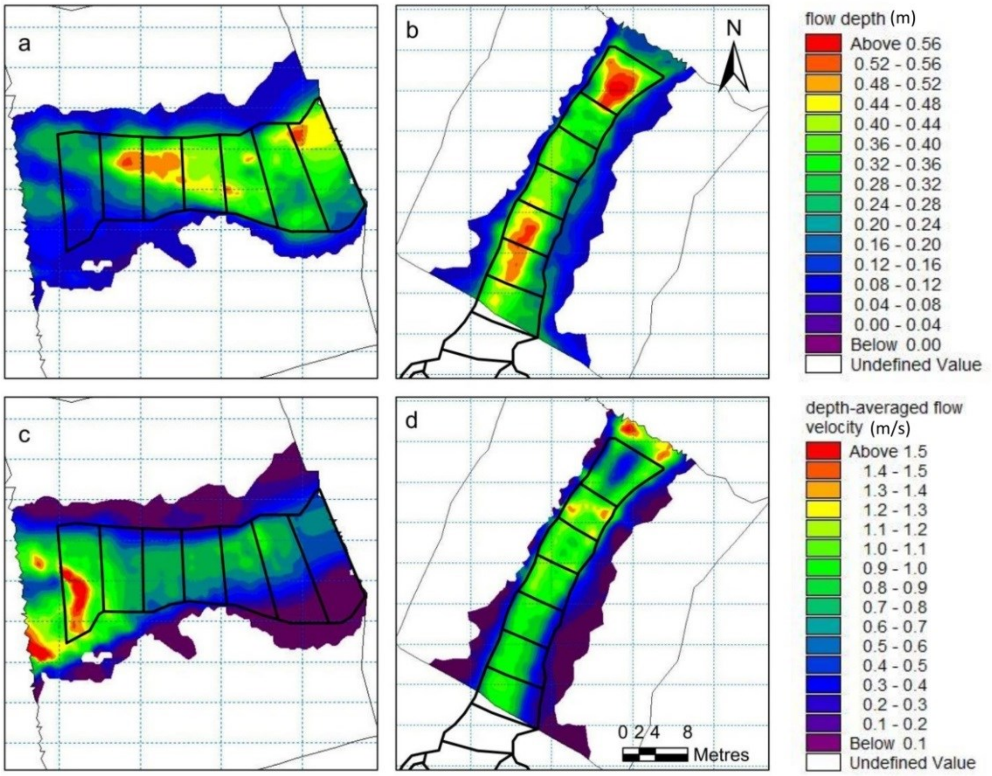

Figure 18. Simulated (a) depth in the bedrock section, (b) depth in the alluvial section, (c) flow velocity in the bedrock section, and (d) flow velocity in the alluvial section. Fishing sectors are displayed for reference.

and the south-east bank of the alluvial section. These locations correspond with relatively low-lying wetland. Pooled water was in fact observed in portions of these locations during the November 4, 2015 survey. However, shallow depths and dense wetland macrophytes prohibited data collection with the aDcp. The bedrock model also showed wetted areas extending past the region in which aDcp data were collected at the south-west portion of the bedrock section. This location corresponds with an exceptionally planar extent of limestone bedrock. Similarly, shallow depths prohibited data collection with the aDcp at this location. Furthermore, it is difficult to accurately depict the true extent of inundation in this location due to the flat nature of the rock. With the exception of extreme flow events, it is reasonable to assume that these locations are generally unable to support fish habitat.

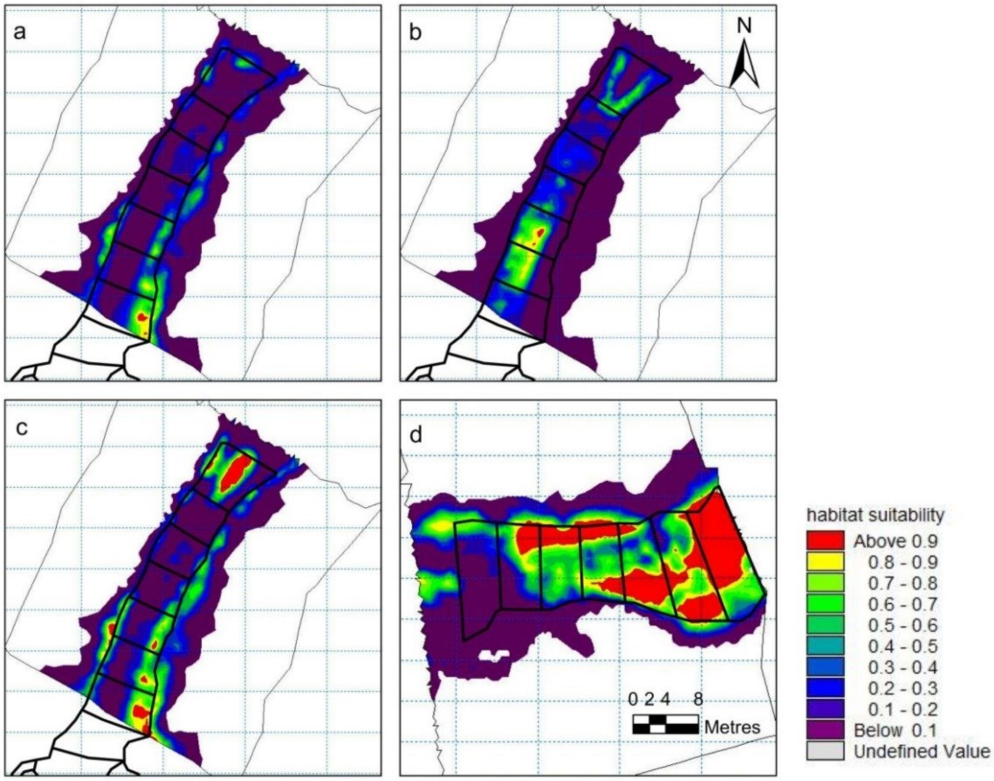

Figure 19. Simulated habitat suitability distributions for (a) juvenile white sucker in the alluvial section, (b) adult longnose dace in the alluvial section, (c) juvenile yellow perch in the alluvial section, and (d) juvenile yellow perch in the bedrock section. Fishing sectors are displayed for reference.

The main benefit of incorporating HSIs with hydrodynamic models is the ability to simulate habitat suitability during different flow events. This was not pursued for Wilton Creek since limited aDcp data were available from other flow conditions for validation. Although other flow events could be simulated with the models, presented simulations were reserved to the November 4, 2015 condition for which model performance could be evaluated. To simulate different flow events, users should be aware that upstream flow boundary conditions and downstream water surface elevation boundary conditions must be adjusted accordingly. Additionally, users should be aware of the uncertainty in the selected channel roughness distribution to produce accurate depth and flow velocity distributions at different discharges.

4.5 Conclusion

Hydrodynamic-habitat modelling was conducted using the MIKE 21 flexible mesh flow model in conjunction with the ECO Lab module. The models were calibrated by adjusting boundary roughness, eddy viscosity, and mesh resolution such that hydrodynamic simulations resembled surveyed aDcp data. The HSIs were implemented into the ECO Lab module using a series of if-statements which use simulated depth and depth-averaged flow velocity as input variables. The models adequately reproduced the spatial distributions of flow depth, depth-averaged flow velocity, and habitat suitability interpreted from measured data.

5 Conclusions

The articles presented in this thesis are valuable contributions to river research and present new findings which expand upon existing literature regarding semi-alluvial bedrock rivers. The thesis provides insight on the form and adjustment characteristics of semi-alluvial bedrock channels and discusses fish habitat in a freshwater semi-alluvial bedrock river. As a whole, the thesis contributes to the fields of fluvial geomorphology and freshwater fish ecology.

Discharge-based channel width scaling relationships were developed for bedrock, mixed, and alluvial channels. The widths of all three channel types scaled at similar rates with respect to flow. However, bedrock channels were statistically wider than mixed channels and alluvial channels. The widest channels were formed in sedimentary bedrock channels in low-relief settings. For low-relief channels, near-vertical rock banks were only observed where alluvial cover was present suggesting that vertical incision is only possible where sufficient abrasive tools are available to erode the bed (Gilbert, 1877; Finnegan et al., 2007; Turowski et al., 2008). However, results suggest that vertical incision in high-relief settings is possible even under conditions low sediment supply. Additionally, bedrock and mixed channels were categorized based on rock type to evaluate the influence of lithology on channel form. Channels influenced by igneous/metamorphic bedrock produced a much stronger scaling relationship with discharge compared to channels influenced by sedimentary bedrock. This may be attributed to differences in bedload transport pathways produced by the different rock types. Channels influenced by igneous/metamorphic bedrock tended to produce identifiable thalwegs. Consequently, bedload transport, and thus erosion, is likely most concentrated in the thalweg of these channels. Channels influenced by sedimentary bedrock had much more planar beds. Bedload likely moves overtop of flat sedimentary bedrock in a much more sprawling and complex manner (Inoue et al., 2016).

Fish habitat was evaluated in proximate bedrock and alluvial sections of Wilton Creek. Statistical methods were used to evaluate substrate selectivity of eight fish species and life-stages. Adult logperch, juvenile white sucker, adult round goby, and adult longnose dace demonstrated preference toward alluvial substrate, whereas juvenile logperch and adult banded killifish demonstrated preference toward bedrock. Juvenile silver shiner and juvenile yellow perch were indifferent to substrate type. The results suggest that the distribution of bedrock and alluvium correlate with, and possibly govern, the distribution of fish species throughout the stream. Furthermore, Category III HSIs were developed for each fish species and life-stage using habitat utilization data obtained via electrofishing and habitat availability data obtained through a survey of physical flow parameters. Habitat suitability predictions based on the HSIs developed in this study were compared to predictions based on HSIs from literature. The HSIs developed in this study provided a better description of the habitat suitability distribution throughout the study area. This result was to be expected since the study HSIs were employed to predict the data from which they were developed. However, the comparison illustrated the potential implications of using HSIs from literature without considering applicability to the study location. The HSIs developed in this study represent the first habitat suitability criteria developed from a small semi-alluvial bedrock stream. In comparison to existing HSIs from literature, the study HSIs may be more applicable to other semi-alluvial bedrock streams similar to Wilton Creek.

The utility of the MIKE ZERO ECO Lab module as a tool for fish habitat modelling was demonstrated. ECO Lab was used in conjunction with MIKE 21 hydrodynamic modelling to simultaneously interpret fish habitat suitability from hydrodynamic simulations. The presented methodology may be of interest to researchers or fisheries professionals interested in automating fish habitat evaluations, especially if a variety of flow conditions must be investigated.

5.1 Recommendations for Future Work

There are a number of possibilities to expand upon the research presented in the thesis. The surveyed channels influenced by sedimentary bedrock were primarily located in low-relief settings and the channels influenced by igneous/metamorphic bedrock were primarily located in high-relief settings. As such, it was difficult to elucidate the relative influence of lithology and topography on channel width. Augmenting the database with additional channel dimensions surveyed from high-relief sedimentary bedrock channels and low-relief igneous/bedrock channels could help explain the relative influence of the two parameters.

As discussed, the HSIs presented in this thesis were developed using small fish observation samples and relatively coarse averaging techniques. Furthermore, the HSIs were developed from data collected from a single stream during a single flow condition. Re-developing the HSIs with additional data collected from Wilton Creek during different flow conditions, or collected from other similar streams, would make the habitat criteria more robust and would likely improve transferability amongst small semi-alluvial bedrock streams (Groshens and Orth, 1994; Conallin et al., 2010).

The model presented in Chapter 4 was used to simulate only the November 4, 2015 flow condition. It would be interesting to evaluate the performance of the model for different flow conditions. The hydrodynamic simulations could be evaluated using additional aDcp survey data and the habitat suitability simulations could be evaluated using additional fish sampling data.

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Appendix A – Procedure for Tying-in Archer/SurvCE Survey Data with aDcp Survey Data

For the benefit of future users, this appendix outlines the procedure for tying in Archer/SurveCE survey data (stand-alone RTK-DGPS) with aDcp survey data. Some information of SurvCE project setup is also discussed.

In the Field:

- **Base setup**
    - Setup the base and allow time for a fixed position to be achieved
    - Measure the height of the antenna above your benchmark
    - As per the lab's typical protocol, connect with the base receiver via BBTalk and save the output as a text file on your computer (i.e. In BBTalk: File -> Log to File). The output data should look similar to the following:

```
SOL_COMPUTED FIXEDPOS 44.22268570893 -76.86278558618 88.0013
-35.3000 WGS84
```

-
    - In the above output example, the latitude, longitude, mean sea level elevation, and undulation value are 44.2227, -76.8627, 88.0013, and -35.30000 respectively. **The mean sea level height (88.0013) is equivalent to the geoid. The ellipsoid height is the sum of the mean sea level height and the undulation value: ellipsoid height = 88.0013 + (-35.3000) = 52.7013.**
    - Note that the undulation value is spatially variable ("changes roughly every 1x3 degrees square on earth"). Basically, the NovAtel equipment determines an undulation value based on your xy position. For more information see the NovAtel Manual: Geodetic Principles APN-026 Rev 1

- **Archer setup**
    - Setup the rover (antenna, rod, rtk, receiver)
    - Connect receiver to the Archer Field PC
    - Start a new project in SurvCE and enter the appropriate project data
        - For spatial reference and projection, select a reasonable spatial reference. For instance, if we are surveying near Ottawa, the "CANADA/NAD83/UTM zone 18N" or the "UTM/WGS 84/UTM zone 18N 72-78W" spatial references are recommended.
    - Once the project has been created, navigate to the "Equip" tab
        - Select "GPS Base" and enter necessary information (See following paragraph below dot-jot list for further explanation)
            - "Current" tab
                - Manufacturer: NovAtel
                - Model: DL-V3

  - “Comms” tab
    - Port: COM 1
    - Baud: 115200
  - “Receiver” tab
    - Select NOV702GG from dropdown menu
    - Enter base antenna height (See following paragraph: Although it is not essential for the base antenna height to be entered into SurvCE, it is still recommended)
  - “RTK” tab
    - Device: Pacific Crest PDL”
    - Port: COM 2
    - Baud: 9600
    - Message Type: RTCA
  - SurvCE will then prompt to average base position. I usually select “Read From GPS”.

Upon completion of the base averaging, SurvCE will display an average base position. It will likely be close to, but different than, the base position recorded on BBTalk (ellipsoid elevation will be displayed). **The base position displayed in SurvCE is irrelevant**. **The base position recorded in BBTalk should be used for base correction amongst different survey dates.** However, the SurvCE base setup is still required to ensure that the equipment is functioning properly.

- Select “GPS Rover” and enter the necessary rover information
  - “Current” tab
    - Manufacturer: NovAtel
    - Model: OEM6
  - “Comms” tab
    - Port: COM 1
    - Baud: 115200
  - “Receiver” tab
    - Select NOV600 from dropdown menu. **Note that the software automatically displays an antenna offset value** (90.5mm for NOV600)
    - For “Antenna height”:
      - <u>Recommended:</u> Enter the height from the ground to the rubber ring of the rover antenna minus the antenna offset (2.06m-0.0905m~1.970m). No post-processing will be required. Or,
      - <u>What was done for my thesis surveys:</u> Enter the height from the ground to the rubber ring of the

antenna (~2.06m). Post-processing is required; the magnitude of the antenna offset (90.5mm) will have to be added the elevation of each survey point.

- “RTK” tab
  - Device: Pacific Crest PDL
  - Port: COM 2
  - Baud: 9600
  - Message Type: RTCA

- Select “Tolerances” and enter the desired information. This can be changed mid-survey should satellite availability or GPS quality become an issue
- Select “Configure” and select the desired information. This can be changed mid-survey as well.
  - Store fixed verified only
  - No. Recordings to Average: I usually use 20 for single cross-sections and 5 for large spatial surveys. The software measures at 1Hz (i.e. a 20 reading average will take 20 seconds)

- Navigate to the “Survey” tab
  - Select “Store Points” and begin survey
  - Make sure GPS quality if “fixed”

Exporting Archer/SurvCE Survey:

- Open SurvCE project
- Navigate to “File” tab
- Select “Import/Export”
- Select “Export Ascii File”
- Enter desired settings and export the file
- Connect Archer Filed PC with computer and copy/paste file onto computer

Base Correction Post-Processing:

- Use the base information from BBtalk to tie-in surveys. Do not use the base information from SurvCE
- Tying Archer/SurvCE data and ADCP data together
  - ADCP elevation data are referenced to the mean sea level (geoid) height and Archer/SurvCE data are referenced to the ellipsoid height.
  - Simply subtract the undulation value from the SurvCE points to tie into the ADCP survey (all points will be referenced to geoid)

  - Alternatively, add the undulation value to all of the ADCP points (all points will be referenced to ellipsoid)
  - For all of my surveys, I also had to add the built-in rover antenna offset (0.0905m) to each Archer/SurvCE point (See SurvCE GPS Rover setup)
- Tying different survey dates together
  - Simply use the BBTalk base position information for each survey day to tie surveys together as usual.

Example – Consider a spatial survey which is conducted over two days. Each survey day consists of an ADCP survey and an Archer/SurvCE survey.

July 29 Base Output:

```
SOL_COMPUTED FIXEDPOS 44.22266700394 -76.86279278541 85.2724
-35.3000 WGS84
```

July 30 Base Output:

```
SOL_COMPUTED FIXEDPOS 44.22269200048 -76.86280166460 89.8047
-35.3000 WGS84
```

Procedure:

1. Tie July 29 Archer/SurvCE and ADCP data together. Add 35.3m to the elevation of each Archer/SurvCE point

2. Tie July 30 Archer/SurvCE and ADCP data together. Add 35.3m to the elevation of each Archer/SurvCE point

3. Tie the two survey days together using the UTM base positions and the base antenna heights

	latitude	longitude	utm east	utm north	elevation	Elevation of antenna	ground elevation		correction e	correction n	correction el
Date	[decimal degrees]	[decimal degrees]	[m]	[m]	[m, a.m.s.l.]	[m]	[m, a.m.s.l.]		m	m	m
TRUE			351211.169	4898291.681			83.8164				
29-Jul-15	44.22266700394	-76.86279278541	351211.169	4898291.681	85.2724	1.456	83.8164		0.000	0.000	0.000
30-Jul-15	44.22269200048	-76.86280166460	351210.522	4898294.474	89.8047	1.456	88.3487		0.647	-2.793	-4.532