RELATING FLUVIAL GEOMORPHOLOGY TO MACROINVERTEBRATE DISTRIBUTION

By

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Abstract

Modern rivers undergo constant stress from disturbances such as bank stabilization, channelization, dams, and water expenditures. As these anthropogenic activities persist, efficient methods of characterizing rivers remain essential. Macroinvertebrates are an important feature in evaluating fluvial health, because they are often the first to react to contaminants. These toxins can be transferred through macroinvertebrates to other trophic levels. The purpose of this research was to use a geospatial model to differentiate instream macroinvertebrate habitats, and determine if the model is a viable method for stream evaluation. Through the use of ArcGIS and digital elevation models, the geomorphology of the Qu'Appelle River, Saskatchewan was assessed.

Four geomorphological characteristics of the river were isolated (sinuosity, slope, fractal dimension, stream width) and clustered through a Principle Component Analysis, yielding sets of river reaches with similar geomorphological characteristics, called typologies. These typologies were mapped to form a geospatial model of the river, and grouped into geomorphological response units (GRUs). Macroinvertebrate data were aligned to the model, revealing relationships between macroinvertebrate taxa and fluvial geomorphology. A Kruskal-Wallis analysis and *post hoc* pairwise multiple comparisons pinpointed significant relationships between several genera and typologies. Furthermore, certain GRUs contained more sensitive macroinvertebrate families and healthier levels of diversity than other GRUs. Typologies were better suited to relate geomorphology to macroinvertebrate taxa, because they represented a more direct relationship to localised geomorphological characteristics than GRUs.

Keywords: macroinvertebrates; fluvial geomorphology; fractal dimension; geomorphic typologies; geomorphic response units (GRU); sinuosity; river; instream habitat; Saskatchewan

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Dedication

I dedicate this thesis to my grandpa
for teaching me about bugs in the garden,
to Daisy and my parents
for letting me live in their basement,
and to my brother for losing
the race to finish our masters degrees.
I win.

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List of Abbreviations

Term	Abbreviation
Adjusted P Value	APV
Chironomidae	C
Cumulative Impact Monitoring Program	CIMP
Digital Elevation Model	DEM
Degrees of Freedom	DF
Ephemeroptera, Plecoptera, Trichoptera	EPT
Family Biotic Index	FBI
Geographic Information System	GIS
Geomorphological Response Unit	GRU
Habitat Suitability Criteria	HSC
Principal Component	PC
Principal Component Analysis	PCA
P Value	PV
River Continuum Concept	RCC
Sinuosity	S
Saskatchewan	SK
Slave River Delta	SRD
Slave Watershed Environmental Effects Program	SWEEP
Travelling Kick and Sweep Method	TK & S
Z Value	ZV

1. Introduction to the Study

1.1. Macroinvertebrate Studies

Macroinvertebrates function as a food source for many species in the extended river food chain, including waterfowl and fish. Consequently, macroinvertebrate community metrics are an important source of information for watershed preservation. This study extends the established geospatial model developed by Lindenschmidt and Long (2013) to include macroinvertebrates [1]. This was accomplished through first using the geospatial model to define reaches within the Qu'Appelle River, Saskatchewan. Links between the hydrological regime and aquatic macroinvertebrate habitat preference were then pursued. Macroinvertebrates are routinely analysed to indicate water quality, because certain species are very intolerant to habitats with organic pollution or low levels of oxygen [2,3]. The opposite is also true, with other macroinvertebrates of high tolerance customarily found in less healthy habitats. An effective desktop method can help identify macroinvertebrate habitats more rapidly and inexpensively; therefore, providing a useful tool for communities to complete a preliminary local water quality evaluation. Evaluating macroinvertebrates in the context of a geospatial model can also be useful to better research fish habitat selection, such as investigating migration, spawning, and rearing habitats. Pursuing the relationship between geomorphology and macroinvertebrates herein will further the development of the geospatial model, and make it more effective for future environmental studies.

Whereas many studies and methods focus on riverine macroinvertebrate habitat, they typically rely on sampling, field data, and data processing. In order to research the highly dynamic nature of instream habitats and macroinvertebrate habitat selection, many macroinvertebrate studies also focus on a smaller perspective. Due to the difficulty of studying an entire, dynamic, river basin, macroinvertebrate researchers often use specific parameters, or isolate certain habitat types through qualitative means, such as field observation. One of the most prevalent methods is classifying instream habitats by specific physical biotopes (macrohabitats), such as riffles, runs, and pools [4-7]. Methods used in conjunction with the concept of macrohabitats include the use of habitat preference curves [8-10], the relatively new random forests nonparametric method [6,11], taxa specific methods [12-14], or methods that focus on certain macrohabitats [15]. The Geomorphological Response Unit (GRU) method is a quantitative way of defining smaller habitats within a large river, and is applicable to other river systems [1]. It creates a geomorphological overview of a large river network, and highlights differences throughout the system. The aim of this study was to help eliminate the dependence of researchers on expensive and time-consuming macroinvertebrate research methods, by testing the usefulness of the GRU method, which is a largely desktop approach to assessing river geomorphology.

1.2. Geospatial Model

1.2.1. Past Studies

The geospatial model used in this thesis was a continuation of Lindenschmidt and Long (2013), who developed a means to define the hydro-geomorphological structure of a river system through the use of GRUs, and substantiated the validity of this method [1]. Fluvial geomorphology examines both the hydrological and geological processes that form unique fluvial geomorphological sequences and configurations [1]. These processes subsequently shape instream habitats, thereby influencing the local biota and ecological functioning of the river basin. Geomorphology has long been recognised as a vital driving force behind fluvial habitats and the habitat selection of river organisms [16-17]. Studies into the way aquatic biota interact with instream habitats require immense field work and data processing efforts. Conversely, the geospatial model of Lindenschmidt and Long (2013) is delineated completely through desktop means [1]. This model is a valuable tool for riverine biota studies, in that it eliminates the time and resources traditional methods require.

In order to test the applicability of the model to other river systems and in relation to biota, it was first attempted in the South Saskatchewan River [18]. Here, Lake Sturgeon (*Acipenser fulvescens*) overwintering holes were compared to the geospatial model with several significant relationships identified. Subsequently, the model was applied in the Birch River to a species at risk, the Carmine Shiner (*Notropis percobromus*) [19]. The model did not work as well here, likely due to a loss of connectivity due to drought conditions. The lack of water likely forced the fish to reside in suboptimal habitats [19]. The results of this study imply that the geospatial model is likely more applicable in large river networks with more consistent connectivity. Following the Carmine Shiner study, the model successfully identified geomorphic links to fish habitat within the Assiniboine River [20].

1.2.2. River Models

Several models of the riverine habitat have been presented prior to the GRU model. Vannote's River Continuum Concept (1980) characterized the longitudinal distribution of a normal river, instream habitats, and associated species [21]. The Process Domains model deemed geomorphology and local processes as influential on the function and instream habitats of rivers, while still in a longitudinal viewpoint [22-23]. The River Ecosystem Synthesis referred to patches of instream habitats as functional processes that differ according to local influences [24]. Modern rivers, as affected by anthropogenic activities, do not fit the idealised version of a river as proposed by Vannotte in 1980 [21]. However, for as long as rivers have been viewed as linear, geomorphology has been recognised as vital in the fluvial form. Rodríguez-Iturbe and Valdés (1979) proposed the Geomorphologic Instantaneous Unit Hydrograph, which lauded geomorphology as the driving factor behind hydrological responses [16]. Since then, fluvial geomorphology has been linked to biological responses [25-26] and instream habitat features [17,27]. Geomorphological response units detect and classify river reaches with similar geomorphological structure [1]. They are a representation of local topography and the way the river interacts within it [28]. Geomorphological response units allow for the comparison of reaches within the same river, according to their geomorphology, presenting the true state of the river being studied.

The categorization of a river by GRUs provides a rapid assessment of fluvial geomorphological characteristics. This information is useful and cost-effective when choosing sampling locations by incorporating the model into experimental designs and selecting sites *a* *priori,* by focusing on specific reaches. The model also delivers an enhanced understanding of the similarity of habitats, allowing an improved assessment of habitat compensation requirements in rivers [1]. The model orientates researchers and stakeholders towards reaches with the highest potential to enhance habitat for local biota. It provides stakeholders with the capability to understand instream habitat on the basis of geomorphological characteristics by revealing direct relationships between GRUs and aquatic habitats. The GRU approach of categorizing fluvial geomorphology has the potential to be used as a predictive method, while attempting to pinpoint the ways in which anthropogenic alterations in river morphology may impact fish and macroinvertebrate habitats. It can aid in identifying regions with the greatest potential for fish habitat enhancement and rehabilitation, and identify essential areas that should be conserved to safeguard the preservation of local biota. The model provides a big picture perspective of a river, but includes the vast diversity of habitats found in modern rivers. The fact that it is completed wholly through desktop methods, means that it is a quick and comparatively inexpensive way to gather data. The model can be applied to rivers globally, and expanded to include a multitude of additional variables. The present macroinvertebrate study was completed to try and develop the method further and expand it to trophic levels beyond fish.

1.2.3. Purpose of Research

Practical applications of the study include the potential to increase the efficiency of water resource and fishery management. Since systems, like the Qu'Appelle, are frequently challenged with meeting the demanding withdrawal needs of domestic, industrial, and agricultural uses, methods that may assist in balancing ecosystem needs with anthropogenic interests are beneficial. Using the highly managed Qu'Appelle River system creates a profile of the implications altered flow and connectivity, channelization practices, and high water demands can have on a river within a changing climate. This knowledge will only become more valuable as the effects of climate change worsen, including effects on the riverine species themselves and the overall environmental integrity of the basin. Through pinpointing the relationships between the spatial and ecological aspects of the Qu'Appelle River, an understanding of big picture patterns in trophic relations to instream habitats can be pursued, and potentially recreated on other river systems. This capacity has great potential to be a management device for programs seeking to sustainably maintain the function of the Qu'Appelle river basin. The geospatial model alone can classify the instream habitats that fish and macroinvertebrates inhabit, contributing to the overall understanding of links between geomorphology and fluvial habitats. The identification of these links increases the comprehension of how geospatial data can be applied to better develop methods for increasing the efficiency of fishery and water management. It can be used to recognize spatial patterns within one river system, and also expanded across many different river systems. As the reliance on river waters for anthropogenic pursuits increase, so does the necessity to better understand and manage them. Where many methods rely on data collection and field work, the geospatial model used here can reduce time, labour, and costs associated with traditional methods. The purpose of this research was to investigate the efficacy of the model to relate geomorphology to macroinvertebrate habitat, in the hopes that the model may be used as a tool for sustainable riverine management.

1.3. Transition

1.3.1. Expected Results

The overall goal of this study was to test the validity and efficacy of the geospatial model in the context of riverine macroinvertebrate habitats. The model was previously successful in fish habitat studies, highlighting its potential as a useful tool for watershed management. The objective of investigating the usefulness of the model at the typology level was pursued with a statistical analysis comparing the distribution of macroinvertebrate genera in the Qu'Appelle River to the delineated geomorphological typologies. Expected results of this analysis were that there would be preferences of certain genera towards living in particular typologies. The objective of providing a proof of concept at the GRU level was then pursued with a more qualitative research design. Several common macroinvertebrate indices were completed at the family level for each GRU, and investigated for noteworthy relationships between the macroinvertebrate distribution and the GRUs. The results of this analysis were expected to reveal links between the community distribution and GRU preference.

1.3.2. Thesis Structure

This thesis is composed of four chapters: an introductory chapter, two manuscript chapters, and a final chapter for further discussion and conclusions. Chapter 1, the introduction, presents contextual and background information necessary to provide a framework for the research that follows. It also serves to clarify the rationale behind the study undertaking. A literature review of macroinvertebrate and riverine studies highlights the motivation behind pursuing the application of the geospatial model used in the study.

Chapters 2 and 3 represent published works that have been reformatted for inclusion in the thesis, but largely retain the journal article format. As such, both chapters contain an introduction, methods, results and discussion, and conclusion. These chapters aim to serve as a proof of concept for the geospatial model as viable in riverine macroinvertebrate habitat studies. Chapter 2 evaluated the efficacy of the geospatial model delineated only to the initial geomorphological grouping of river typologies. The macroinvertebrate data set, at the genus level, was assessed to identify significant relationships between macroinvertebrate habitat and the typologies.

Chapter 3 had a similar purpose of validating the usefulness of the model as related to macroinvertebrates, but instead used the model further delineated to the GRU level. The macroinvertebrate data was evaluated, at the broader family level, against eight separate identified GRUs. Three typical macroinvertebrate indices were completed for each GRU, the ratio of Ephemeroptera, Plecoptera, Trichoptera and Chironomidae abundance (EPT/C Ratio), Shannon Diversity Index, and the Family Biotic Index, and qualitatively compared. The community makeup within each GRU was also evaluated for notable patterns and relationships.

The thesis discussion and conclusions are found in Chapter 4, with the two manuscript chapters first summarised. Additional data made available after the publication of Chapters 2 and 3 is briefly discussed, with several figures included. Numerous closing topics are discussed in this chapter, including general conclusions, research limitations, potential for future work, and aspects of sustainability and social relevance.

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2. Genus-Level Relationships with Geomorphic Typologies

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Using a Geospatial Model to Relate Fluvial Geomorphology to Macroinvertebrate Habitat in a Prairie River—Part 1: Genus-Level Relationships with Geomorphic Typologies

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2.1. Introduction

The study of aquatic macroinvertebrates within fluvial systems can reveal information about water quality [1,2], interactions with other trophic levels [3,4], as well as anthropogenic influences on river health [5,6]. Traditional methods used to examine the fluvial benthic community rely on fieldwork and data collection; as such, the methods can be time consuming, labour intensive, and expensive. More efficient methods have emerged for studying macroinvertebrates, but these are often tailored to the interests of specific studies. This could be a result of the sheer vastness of fluvial ecosystems and macroinvertebrates. The dynamic nature of river ecosystems and the highly diverse macroinvertebrate community commonly found in fluvial ecosystems make it difficult to study them as a whole. Therefore, studies often choose to organize macroinvertebrate data collection and analysis by metahabitat metahabitat (*i.e.*, riffle, pool, run) or instream habitats that are classified using physical traits.

Methods used in studies related to analyzing physical habitat include the IndVal method for communities [7–9], analyses using the species-based habitat suitability criteria (HSC) that are subsequently incorporated into habitat simulation models [10–13], the fairly new random forests nonparametric method [9,14], and many more. These methods relate collected macroinvertebrate data back to the river metahabitats for correlation. Other studies focus on certain groups of macroinvertebrates, such as the more sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders [2,4], or macroinvertebrates found in niche stream habitats (e.g., (e.g., rock substrates). Methods for stone substrate macroinvertebrate studies began using labour-intensive field collection, but modern methods, such as surface area estimation, have since been developed [15,16]. Methods used to understand macroinvertebrates within large fluvial systems that do not rely on field data have not been widely developed.

Creating more effective and efficient methods of studying macroinvertebrates is a worthy goal, because a better understanding of macroinvertebrates leads to increased knowledge of the watershed as a whole. Macroinvertebrates are the food source for many trophic levels, are often the first to respond to ecosystem degradation, and can be the point of contaminant uptake [17,18]. In the case of contaminants, macroinvertebrates can pass harmful substances to those that feed on them, like fish and birds, creating a pattern of bioaccumulation. Contaminants can be linked to geomorphology as well; fluvial geomorphology directly influences instream flow and subsequently the distribution of sediment, creating the many instream habitats macroinvertebrates live in [19,20]. Consequently, the sediment type and distribution (driven by geomorphology) directly relates to many dangerous substances that macroinvertebrates may ingest. Clay, for instance, has such a small grain size that it is negatively charged, making bonds with the positively charged metals much easier [19]. The metals derived from industrial processes, such as mining, increase aquatic metal concentrations (*i.e.*, mercury, cadmium, copper, zinc, lead) as they settle and bond to the clay in the river [19,21]. Macroinvertebrates living in this clay can ingest these metals, leading to bioaccumulation in later trophic levels. In the case of the more toxic metals, like mercury, bioaccumulation can reach terrestrial consumers, including humans [21]. Understanding fluvial geomorphology and instream macroinvertebrate habitats is vital to further understanding dangerous bioaccumulation and contaminant relations.

The River Continuum Concept (RCC) exemplifies the notion of viewing rivers as predictable systems assuming that macroinvertebrate habitat is organized by linear location [22]. The RCC has been disputed for not applying to real and complex fluvial environments. Instead of concepts like the RCC, spatial dynamics and geomorphological processes at a local-level are widely accepted as the driving factors behind instream habitats and communities [23,24]. Furthermore, fluvial geomorphology has long been associated with instream biodiversity, meaning that river macroinvertebrates are influenced by river structure [4,25,26]. Aquatic macroinvertebrate habitat selection is influenced by local features, which result from extensive geomorphological and hydrological processes [20,27]. Through classifying reaches of the river with similar geomorphological characteristics (typologies), rather than by metacommunities, patterns in macroinvertebrate habitat can be pursued. This information could then be applied to rivers from which data are difficult to collect, due to their large spatial extent [28]. Therefore, creating a model of geomorphological characteristics within a river is a novel method for identifying macroinvertebrate habitat more broadly.

Unlike the linear RCC, the use of geomorphic typologies acknowledges the fact that diverse instream habitats, resulting from channel morphology interacting with dynamic hydrological processes, are the reality of modern rivers [29]. Four geomorphological characteristics (sinuosity, stream width, fractal dimension, and slope) have been focused on, in the creation of the geospatial model for this study. These characteristics are all affected by anthropogenic influences in modern rivers. Understandably, channelization changes the geomorphology of a river substantially. For the purposes of flood control, land drainage, or erosion mitigation, the channel may be straightened, realigned, or enlarged [30]. Other modifications include dredging, building embankments, bank stabilization, and, of course, dams [30]. These drastic anthropogenic alterations are examples of how the geomorphological characteristics studied here are certain to change with increased societal use of rivers. In this study, valuable macroinvertebrate data were analyzed in relation to a geomorphological model of the Qu'Appelle River, Saskatchewan. It was hypothesized that geomorphic typologies within the river would reveal significant relationships between geomorphology and the benthic macroinvertebrate community in a fluvial system. The study concentrated on macroinvertebrates at the genus level; the data set was tested to determine which genera contain significant relationships to geomorphological typologies. These genera were then the focus of further study.

2.2. Methods

2.2.1. Study Site

The Qu'Appelle River flows in the Saskatchewan plains region of Canada, which is home to sweeping river valleys, wide lake plains, ground moraines, and large spillways prone to flooding

[31]. The Qu'Appelle is a river and lake network; it begins at the Qu'Appelle Dam at Lake Diefenbaker and flows toward the Manitoba border (Figure 1). The basin's dynamic geomorphology provides diverse habitats for many species, including more than 30 rare and endangered animal and plant species. Among these species are bigmouth buffalo fish, loggerhead shrike, and smooth arid goosefoot, all relying on the varied landscape and water within the valley [32]. The Qu'Appelle River Watershed provides water to several municipalities, including two cities (Moose Jaw and Regina), whose combined population could reach half a million by the year 2050 [33].

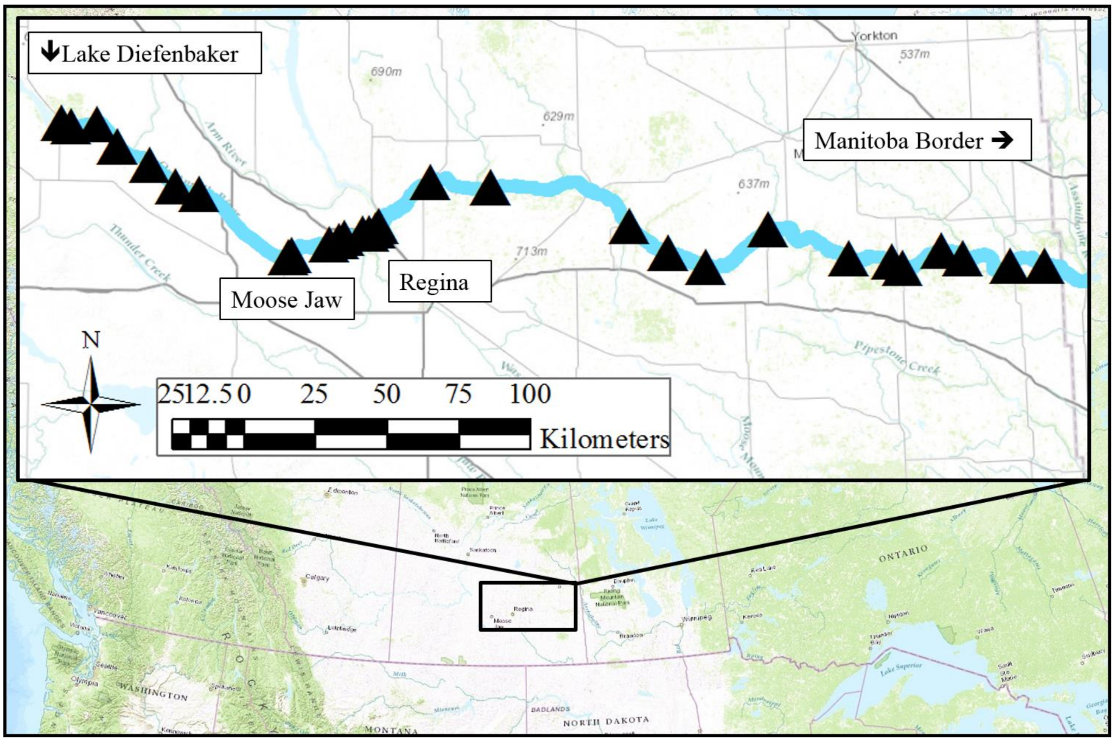
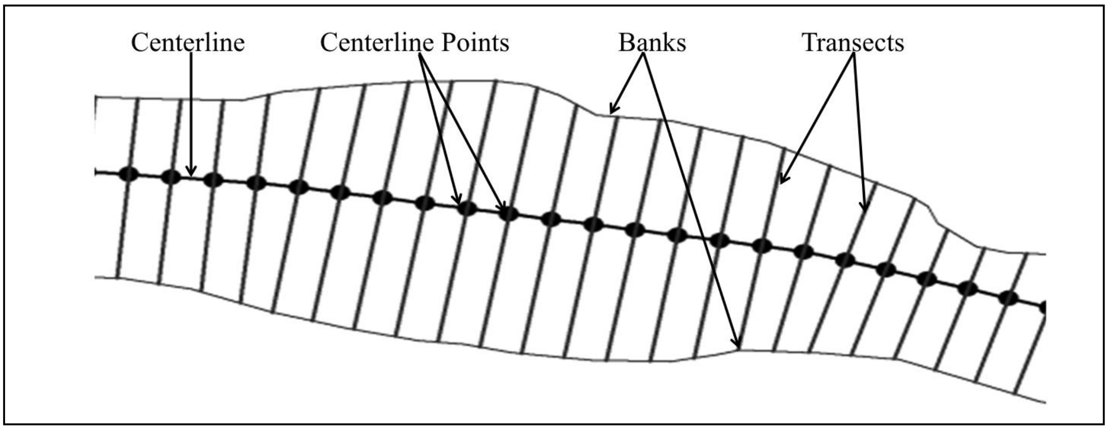


Figure 1. River and Sampling Site Location: The Qu'Appelle River, river centerline, and the 35 macroinvertebrate sampling sites.

Besides municipal water use, the system accommodates many local interests including recreational, agricultural, industrial, and environmental requirements [34]. Water quality and supply are fundamental for the Qu'Appelle system and its residents, as it boasts a diverse fish assemblage and active recreational fishery. The Qu'Appelle River Watershed area also hosts a large amount of Saskatchewan potash production, for which water is essential; demand for water will continue to rise in this region as potash mining and other industrial practices expand [33,35]. Channelization has occurred from the outlet at the Qu'Appelle River Dam to about 32 km downstream; the remaining river stretches' freely-developed and meandering expanses are prone to flooding, erosion, sloughing, silting, as well as water quality and quantity issues [31,33]. Heavy reliance on water by people and industry within the watershed necessitates sustainable and effective monitoring and protection efforts for the Qu'Appelle River.

2.2.2. Geospatial Factors

In order to characterize the geospatial nature of the river, four characteristics were selected as points of comparison; these were stream width, sinuosity, fractal dimension, and slope. These characteristics were chosen because they provide a good representation of the watershed geomorphology. Other studies wishing to use the geospatial model delineated in this study could include a variety of parameters, such as average flow, depth, or water temperature to create a different river profile. First, the centerline of the river was delineated through the use of river polygons, and points placed along the line every 50 m. At each point, transects were placed, crossing the polygon from bank to bank (Figure 2).



<u>Figure 2. River Polygon</u>: Delineation of a river polygon, centerline, points placed on the line every 50 m, and transects through each point that cross the polygon to both banks.

The 1:50,000 digital elevation model (DEM) data (Source: Department of Natural Resources Canada) provided elevation at each bank point using Geographic Information System (GIS) software, and its average elevation linked to the point at the centerline. Finally, at each centerline point, the four geospatial characteristics were extracted [28]. Slope, stream width, sinuosity, and fractal dimension were calculated and extracted at each centerline point delineated. Slope is simply the level of vertical drop in river bed elevation at each 50 m point [30]. Stream width is the length of the transect at each centerline point (Figure 2). The minimum stream width recorded at the centerline points was 6.8 m, the maximum was 2226.9 m, and the average was 168.7 m. The commercial software package Mathcad® v.15 (PTC, Inc., Needham, MA, USA) [36] was used in calculating both the sinuosity and fractal dimension of the river reaches. For the sinuosity, a marginally larger scale was used than for the stream width and slope; 40 adjacent points were used (20 upstream and 20 downstream of each centerline point).

Sinuosity, or how much a river meanders, is a significant fluvial characteristic because it impacts how water flows, how sediment is distributed, and ultimately how local instream habitats form [37]. Sinuosity is also defined as the interchange between the valley slope and the river slope [38], or between the length of the valley (shortest possible distance) and the length of the river. In addition to different definitions of sinuosity, various terms are used to describe the spectrum of sinuosity values (S). These include $S = 1$ for a linear (straight) reach, and in succession of increasing sinuosity, elongated, oscillating, tortuous, and lastly meandering with $S > 2$ [39,40]. Rivers with high sinuosity also have increased bed material of a smaller grain size (*i.e.*, silt, clay) [41]. Where channels meander, augmented bank erosion transpires, thus providing a higher load of easily transferred (fine materials) sediment to the stream [19], with $S > 1.5$ indicating a riverbed containing over 92% fine textured material [38]. Within the Qu'Appelle River, 63% had a sinuosity of $S > 1.5$, suggesting that the riverbed has a share of both coarse and fine materials, corresponding to the till blanket that comprises much of the surficial geology of the river basin. Sinuosity, in this study, was defined as the length of a river reach divided by the shortest distance between the reach end points (a straight path). A sinuosity score of one represented a straight channel, and >1 is a meandering one [37,42].

Analogous to sinuosity, but at a greater scale, fractal dimension represents how much Euclidean space a river reach fills. Different than sinuosity, fractal dimension quantifies form and indicates both the number and amplitude of meander changes within a channel length, at a larger order of magnitude [42–44]. As a tool, fractal dimension is helpful for understanding patterns within fluvial systems at a more expansive, geological scale [28,42]. Fractal dimension is uniquely suited to the complex and irregular nature of a river. It uses a minimum value of one and a maximum of two; in linear river systems, the higher the value is, the more space-filling it is within the drainage area [43]. To calculate fractal dimension, the number of centerline points contained within a 40 km × 40 km window moving along the river was used. These scales were selected, as they were the values where the peak variation was calculated. Once these geospatial characteristics were found, a Principal Component Analysis (PCA) was performed with the statistical package R 2.15.2 [45] to pinpoint groups (typologies) of similar characteristics [28]. The PCA makes a large dataset more manageable by identifying patterns within it and reducing its dimensionality [46]. To improve normality of the dataset while considering the high incidence of zero and minute slope values, the dataset was $\log_{10} + 1$ transformed prior to PCA. The explained variance of principal components (PC) one through four was 49%, 24%, 14% and 13%, respectively. Only the first two principal components (accounting for 73% cumulative variance) were used to derive typologies as, following the Kaiser–Guttman rule, eigenvalues for components 3 and 4 were far less than 1 (0.57 and 0.52, respectively). At each centerline point, binary values were assigned to the scores associated with PCs one and two, 1 for positive PC scores and 0 for negative PC scores. Binary values were then summed, resulting in four unique typologies. Each of the four typologies was designated a colour, which was then matched to the corresponding centerline points (Figure 3).

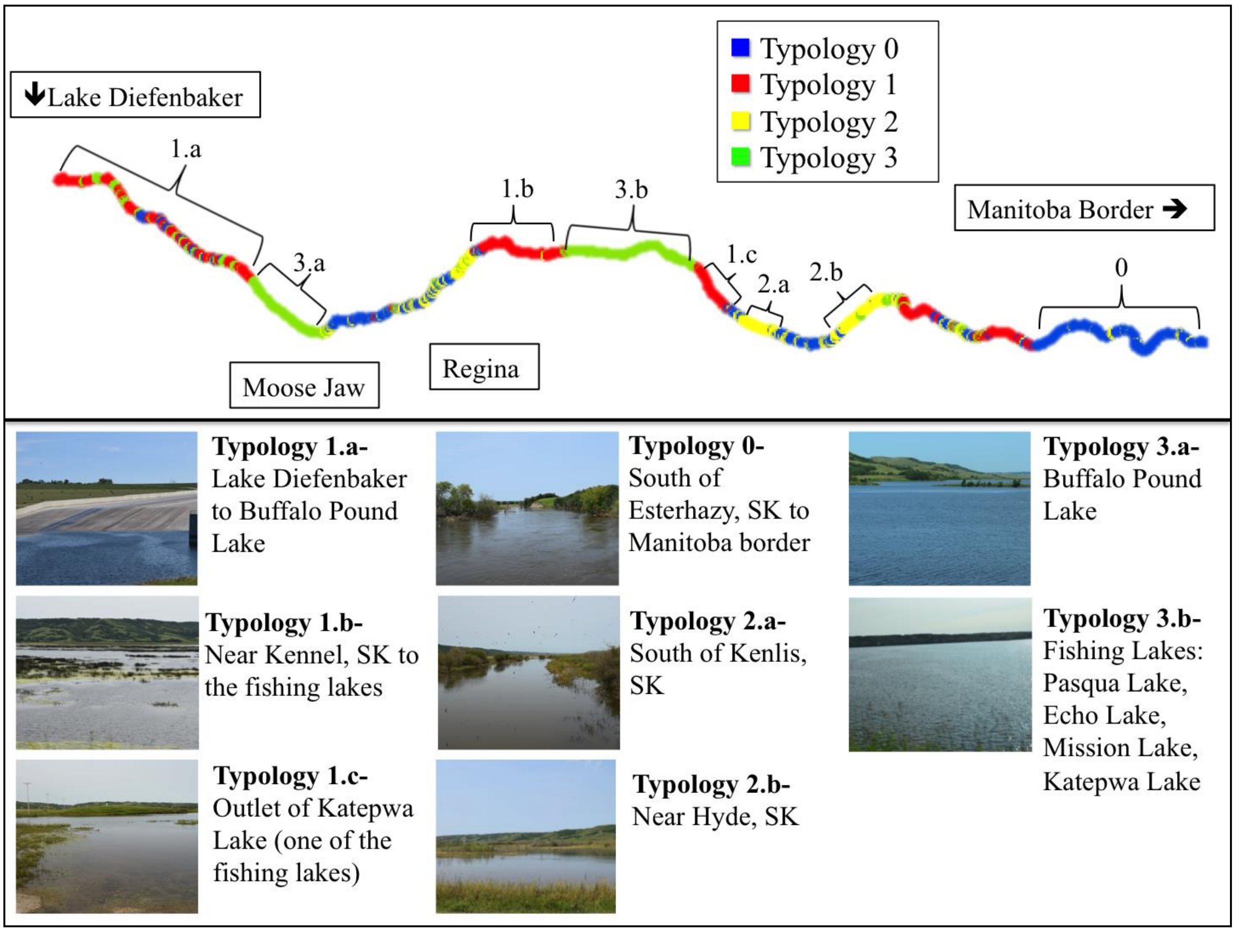


Figure 3. Geospatial Typologies: Delineated Typologies on the Qu'Appelle River centerline, key reaches labeled, site pictures corresponding to the key reaches.

2.2.3. Macroinvertebrate Sampling

Benthic macroinvertebrate collection took place between 2006 and 2009 along the Qu'Appelle River, Saskatchewan. The macroinvertebrate collection and compilation of the database used in this study were completed before the delineation of the geospatial model, and separate from this study. Optimally, the typologies would have been delineated prior to sampling, so that sites could be selected with a more even distribution amongst typologies. The sampling method used was the travelling kick and sweep (TK & S) technique, a standardized sampling method that permits the comparison of communities within similar habitats between sites. Sampling sites were selected to accommodate for road access, at a pre-determined minimum river distance of 10 km between sites. During this process, a bank-to-bank transect is sampled at five different positions and combined into one composite sample. Since the TK & S method involves sampling along transects, the subsequent data set spans an array of habitats found within a reach.

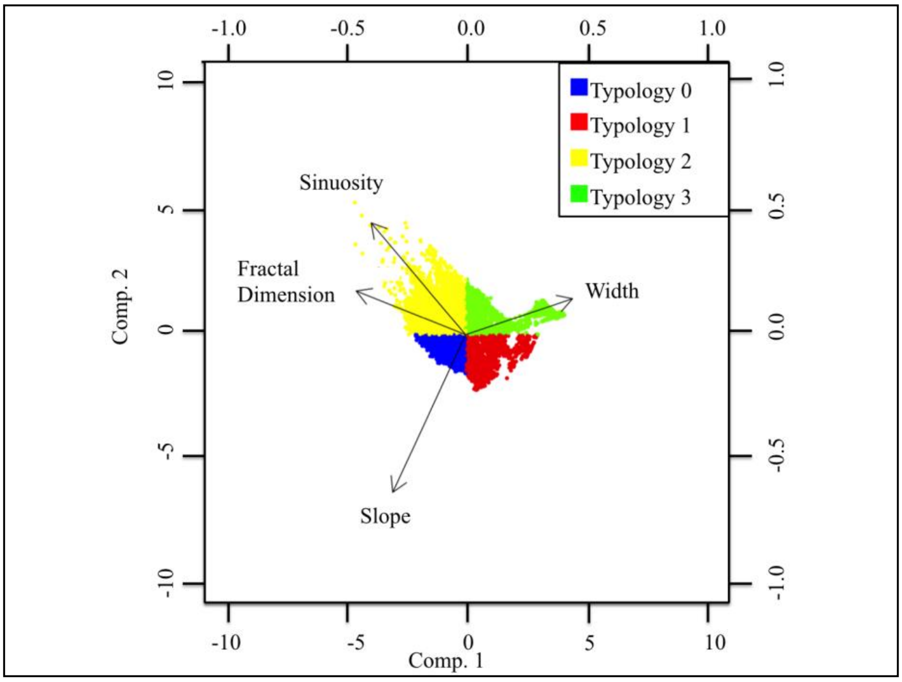
A D-frame net (500 µm mesh), positioned downstream from the person collecting the sample, was used in the present study. As the net is held, the area (~30 cm × 30 cm) was kicked to ~5 cm depth for a 10 s time period at each of the five positions along all transects. All the sampled sites were similar prairie reaches that were straight, slow flowing, and with no riffles. Substrate was generally soft silt, with less frequent and small patches of cobble and vegetation on bank positions. Ultimately, the objective was to employ a standardized method of collecting benthic macroinvertebrates in comparable habitats across all sites, to ensure the dominant communities for major habitat features would be represented. Although the TK & S method does not guarantee that all taxa present at a sampling site are collected, the most dominant assemblages and habitat features were adequately characterized. The collected macroinvertebrate samples were saved in 80% ethanol and subsequently moved to the laboratory, in which 7× magnification was used to separate the macroinvertebrate samples from any organic material. Identification of the macroinvertebrates using keys for North America [17] and Western Canada, when available [47–49], was then completed. The Water Security Agency of Saskatchewan Invertebrate Voucher Collection (Saskatoon, SK, Canada), and the Royal Saskatchewan Museum (Regina, SK, Canada) hold the voucher series from this sample. Taxa occurrence records from the study were submitted to the Saskatchewan Conservation Data Centre with the Ministry of Environment.

2.2.4. Statistical Analysis

Using the R 3.1.2 statistical software [45], a Kruskal–Wallis analysis of variance on ranks was performed on the macroinvertebrate genera, to determine whether their distribution yielded statistical differences between the 4 typologies. In the event of a significant outcome (p value ≤ 0.05), *post hoc* pairwise multiple comparisons were completed. A one-tailed Dunn test with Bonferroni p value correction for multiple paired tests was used, and graphical analyses were accomplished through use of the statistical program R 3.1.2 [45]. The data set was narrowed down for the analysis, to include only genera with ≥30 individuals sampled and collected in >9% (3+) of sampling sites. This test can be used to understand whether the mean ranks are the same or different in all the groups, when dealing with an unequal sampling distribution among typologies.

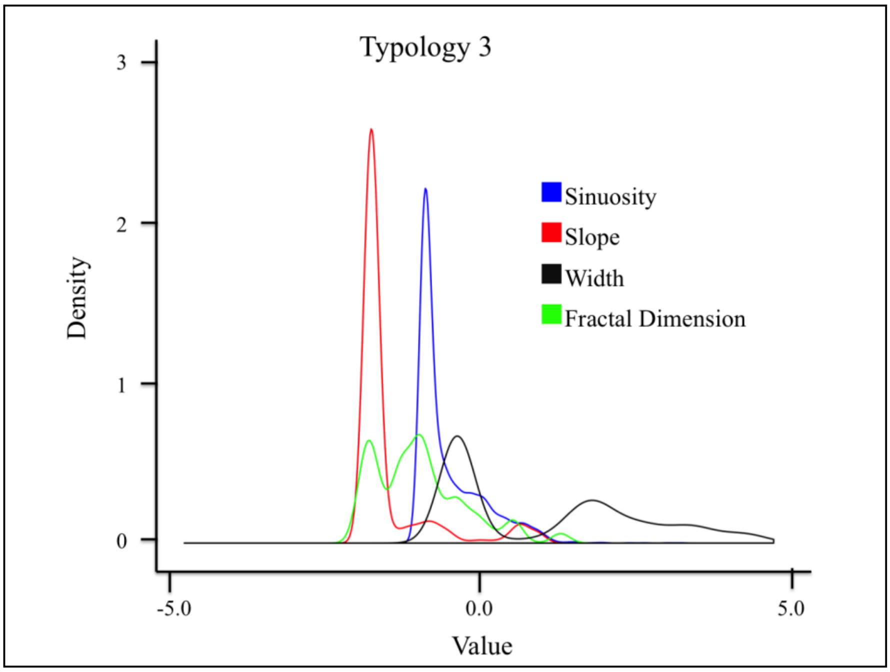
2.3. Results and Discussion

The PCA scores (colour coded by typology) and variable vectors are plotted in Figure 4, with principal component one on the *x*-axis, and component two on the *y*-axis. This biplot is used to surmise the overall relationships between the four geomorphological variables (sinuosity, slope, fractal dimension, channel width), as well as their relationships within the distinct typologies (Figure 4).



<u>Figure 4. Biplot of PCA Scores:</u> Results (colour coded by typology) and the four variable vectors: sinuosity, slope, fractal dimension, and stream width, plotted in relation to principal components 1 (*x*-axis, 49% variation) and 2 (*y*-axis, 24% variance).

Principal components one and two accounted for 73% of the total variation found in the dataset. Normalized values of sinuosity, slope, fractal dimension, and channel width were also charted in density plots. The plots were used to observe the qualitative contribution of these four geomorphological variables to each individual geomorphic typology based on absolute means (Figure 5). The subsequent relationships established for all four typologies to sinuosity, slope, fractal dimension, and channel width were summarized in Table 1.



<u>Figure 5. Density Plot:</u> Normalized values of channel sinuosity, slope, fractal dimension and width exemplified in a density plot of Typology 3.

<u>Table 1. Typology Characteristics:</u> The qualitative contribution of variables to each typology, resulting from the principal component analysis. (–) = negative relationship, (+) = positiverelationship, (0) = no discernable relationship.

Typology	Sinuosity	Slope	Fractal Dimension	Width
0	0	+	+	–
1	–	+	–	–
2	+	0	+	–
3	–	–	–	+

Typology 0 was positively related to both slope and fractal dimension and negatively related to width. Typology 1 was positively related to slope, yet negatively related to all the other variables. Typology 2 was positively related to both sinuosity and fractal dimension, but negatively related to width. Typology 3 was negatively related to all variables, except for width. River stretches designated as Typology 0 were therefore characterized by more narrow regions of high slope and fractal dimension. Typology 1 was associated with narrow areas of high slope, low fractal dimension, and sinuosity. The features related with Typology 2 were highly sinuous regions with high fractal dimension values, yet are still narrow. Finally, Typology 3 was associated with wide reaches that are less sinuous, with low slope and fractal dimension values.

2.3.1. Macroinvertebrate Survey

Macroinvertebrate sampling occurred at 35 sites along the Qu'Appelle River, resulting in a database of 115,696 individual organisms, which were identified to 128 groups at the genus level. It should be noted that some of these 128 taxonomic groups found at the genus level were identified only to class (e.g., Oligochaeta), order (e.g., Amphipoda), or family (e.g., Heptageniidae), in cases where further taxonomic breakdown could not be determined. Sampling occurred prior to delineation of the geospatial model, so an imbalanced 14 of the macroinvertebrate sampling sites corresponded with Typology 0 (blue). In total, these sights contained 14,764 individuals, an average of 1055 per site, with the highest taxa richness of 85. Typology 1 (red) also contained a large portion of sampling sites (11/35), and contained 75 taxa at the genus level. This typology also had the highest macroinvertebrate count (74% of the whole river community) at 85,270 individuals, averaging 7752 per site. With only five macroinvertebrate sampling sites, Typology 2 (yellow) had the lowest community sum (2124), averaging 425 per site. It made up merely 2% of the entire macroinvertebrate survey, and had a taxa richness of 49. Typology 3 (green) was represented by five sites as well, and contained a count of 66 different taxa. This typology had a total of 13,538 individual macroinvertebrates that averaged 2708 individuals per site.

2.3.2. Statistical Analysis of Macroinvertebrate Survey

The 128 genera identified in the macroinvertebrate survey were narrowed down to 50 genera for use in the statistical analyses (Kruskal–Wallis test; Table 2), as the remaining 78 genera were found to be less common. The parameters to designate rare genera were that they occurred at <3 sampling sites and/or they had a sum of ≤ 30 total individuals collected in the macroinvertebrate survey. The Dunn's *post hoc* test provided adjusted p values for each typology comparison of the six genera with significant Kruskal–Wallis test results. If the adjusted p value is ≤ 0.05, the ranking of values was assumed to be significantly different between typologies; therefore, it was inferred that the genus likely favours certain typologies over others.

Table 2. Kruskal–Wallis Test: Results for the 50 common genera, with *H* values, degrees of freedom (df), and *p* values (PV).

Identifier	Order	Genus	*H* Value	df	PV
G1	Amphipoda	Amphipoda	0.25	3	0.97
G2	Ephemeroptera	Baetidae	4.2709	3	0.23
G3	Ephemeroptera	*Baetis*	3.8312	3	0.28
G4	Trichoptera	*Brachycentrus*	4.7699	3	0.19
G5	Ephemeroptera	*Brachycercus*	1.03	3	0.79
G6	Ephemeroptera	*Caenis*	2.2468	3	0.52
G7	Hemiptera	*Callicorixa*	8.4314	3	0.04 *
G8	Diptera	Ceratopogonidae	0.0599	3	1
G9	Trichoptera	*Cheumatopsyche*	2.1279	3	0.55
G10	Diptera	Chironomidae	3.1975	3	0.36
G11	Hemiptera	*Coenocorixa*	1.9423	3	0.58
G12	Hemiptera	Corixidae	3.5733	3	0.31
G13	Lepidoptera	Crambidae	3.8277	3	0.28
G14	Coleoptera	*Dubiraphia*	8.0284	3	0.05 *
G15	Odonata	*Enallagma*/*Coenagrion*	5.0571	3	0.17
G16	Ephemeroptera	Ephemeridae/Polymitarcyidae	2.9232	3	0.4
G17	Ephemeroptera	Ephemeroptera	3.6787	3	0.3
G18	Ephemeroptera	*Ephoron*	1.7929	3	0.62
G19	Amphipoda	*Gammarus*	0.915	3	0.82
G20	Gastropoda	*Gyraulus*	2.907	3	0.41
G21	Coleoptera	*Haliplus*	7.9122	3	0.05 *
G22	Ephemeroptera	*Heptagenia*	9.5818	3	0.02 *
G23	Ephemeroptera	Heptageniidae	8.0369	3	0.05 *
G35	Decopoda/Malacostraca	*Orconectes*	4.4706	3	0.21
G36	Gastropoda	*Physa*	7.1221	3	0.07
G37	Gastropoda	Physidae	0.9604	3	0.81
G38	Pelecypoda	*Pisidium*	2.0397	3	0.56
G39	Gastropoda	Planorbidae	3.8277	3	0.28
G40	Gastropoda	*Probythinella*	7.5965	3	0.06
G41	Hemiptera	*Sigara*	8.0465	3	0.05 *
G42	Diptera	*Simulium*	6.5807	3	0.09
G43	Pelecypoda	Sphaeriidae	3.1967	3	0.36
G44	Pelecypoda	*Sphaerium*	6.9774	3	0.07
G45	Gastropoda	*Stagnicola*	3.7902	3	0.29
G46	Ephemeroptera	*Stenacron*	2.6016	3	0.46
G47	Ephemeroptera	*Stenonema*	2.2751	3	0.52
G48	Hemiptera	*Trichocorixa*	0.9051	3	0.82
G49	Ephemeroptera	*Tricorythodes*	2.5764	3	0.46
G50	Gastropoda	*Valvata*	7.3756	3	0.06

Note: * Significant results are denoted with an asterisk.

The outcomes of the Kruskal–Wallis test (Table 2) revealed significant differences in genus distribution among typologies for six of the 50 tested genera. These were *Callicorixa*, *Dubiraphia*, *Haliplus*, *Heptagenia*, Heptageniidae (identified to family), and *Sigara*. Subsequently, *post hoc* pairwise multiple comparisons were carried out using Dunn's Method on these six genera. A Bonferroni *p* value correction for multiple paired analyses pinpoints the typologies that were different from each other (Table 3).

Table 3. *Post hoc* Dunn Test: Results for each typology comparison for each genus that had a significant Kruskal–Wallis result, including the Genus Identifier, *Z*-Value (ZV), *p* Value (PV), Adjusted PV (APV).

Genus	3 vs. 1			0 vs. 3			2 vs. 0		
	ZV	PV	APV	ZV	PV	APV	ZV	PV	APV
G7	2.246216	0.0124	0.0741	−1.677963	0.0467	0.2801	1.785511	0.0371	0.2225
G14	−1.430855	0.0762	0.4574	0.868452	0.1926	1.0000	1.662240	0.0482	0.2894
G21	−0.469371	0.3194	1.0000	1.963520	0.0248	0.1488	0.253711	0.3999	1.0000
G22	−2.831301	0.0023	0.0139 *	2.202077	0.0138	0.0830	−1.148641	0.1254	0.7521
G23	−2.634423	0.0042	0.0253 *	0.671864	0.2508	1.0000	−0.407633	0.3418	1.0000
G41	−0.778480	0.2181	1.0000	1.138817	0.1274	0.7643	1.390046	0.0823	0.4935
Genus	**0 vs. 1**			**2 vs. 1**			**2 vs. 3**		
	ZV	**PV**	**APV**	**ZV**	**PV**	**APV**	**ZV**	**PV**	**APV**
G7	0.000000	0.5000	1.0000	2.167528	0.0151	0.0906	0.415734	0.3388	1.0000
G14	−0.207490	0.4178	1.0000	1.810392	0.0351	0.2107	2.817601	0.0024	0.0145 *
G21	1.669768	0.0475	0.2849	1.977762	0.0240	0.1439	2.261024	0.0119	0.0713
G22	0.090114	0.4641	1.0000	−1.304284	0.0961	0.5764	0.855175	0.1962	1.0000
G23	−1.341801	0.0898	0.5390	−1.836650	0.0331	0.1988	0.193871	0.4231	1.0000
G41	0.576929	0.2820	1.0000	2.264381	0.0118	0.0707	2.768790	0.0028	0.0169 *

Note: * Significant results are denoted with an asterisk.

After the post hoc test, it was found that four genera had significant differences between typologies (Figure 6). Typology 3 and Typology 1 were significantly different for two genera, and Typology 2 and Typology 3 were significantly different for two genera. Typology 0 had the highest total counts of all four Dubiraphia, Heptagenia, Heptageniidae, and Sigara genera. Typology 3 had the second highest total for both Dubiraphia and Sigara. Typology 2 was the second highest for Heptageniidae and Heptagenia (Figure 6).

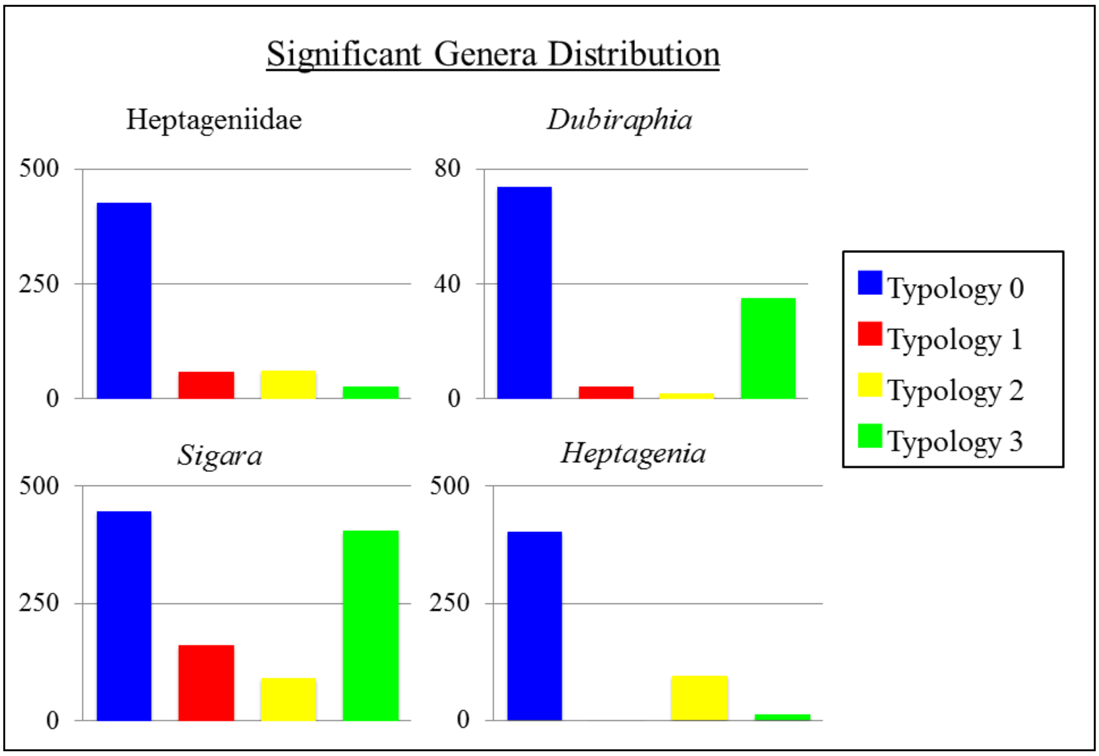
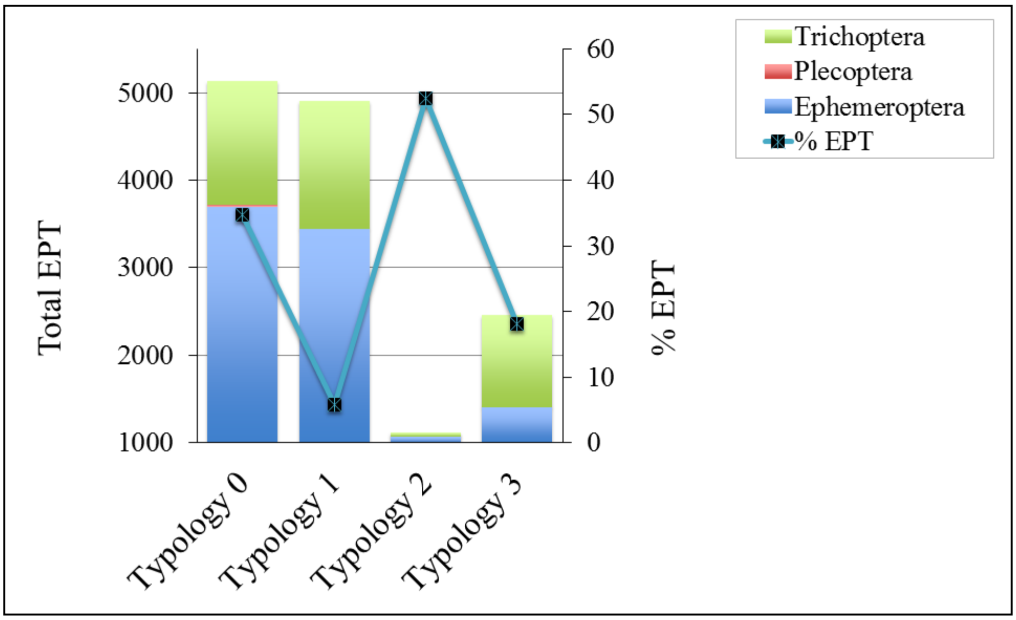


Figure 6. Significant Genera: Bar charts depicting population distribution for the four genera found significant in Table 3, as related to the typologies.

2.3.3. Ephemeroptera, Plecoptera, Trichoptera (EPT)

The mayfly (Ephemeroptera), stonefly (Plecoptera) and caddisfly (Trichoptera) orders (EPT) are commonly used together to indicate the overall water health at a site. The groups are often sensitive to water condition and have specific habitat preferences [3,50,51]. The presence of a healthy EPT population indicates a healthy and well-oxygenated ecosystem, as opposed to one dominated by macroinvertebrates more tolerant to pollution (e.g., Chironomidae midges), which may indicate poor water quality [17,52]. The total EPT individuals, percent of the total population they represent (% EPT), and EPT taxa richness were calculated for each typology (Figure 7). Typology 0 (blue) contained the largest total EPT population, followed closely by Typology 1 (red), while Typology 2 (yellow) contained the smallest sum. However, Typology 2 had the highest % EPT at 52%, followed by Typology 0 (35%), and Typology 3 (18%), with Typology 1 only containing 6% EPT (Figure 7). Typology 0 had the highest EPT richness (39) of its total 85 genera. Of the 75 genera found in Typology 1, only 25 are EPT. Typology 2 had an EPT taxa richness of 18, and 49 genera overall. Typology 3 had 22 EPT taxa, and a richness of 66 genera total.



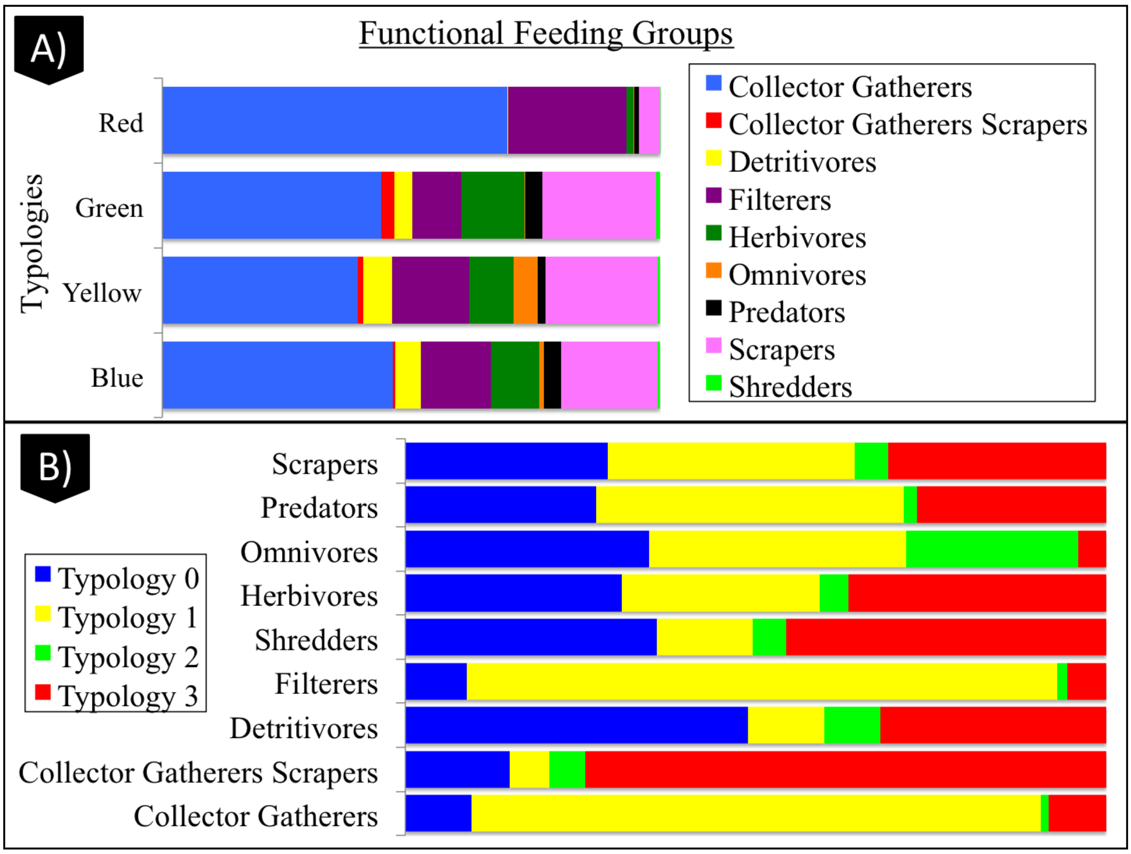
<u>Figure 7. EPT Distribution:</u> Total Ephemeroptera, Plecoptera, and Trichoptera (EPT) populations, and percent EPT in each typology.

2.3.4. Geomorphological Typologies

Six of the common genera tested were found to have significant differences in distribution between typologies, signifying the predilection of several macroinvertebrates for specific geomorphic typologies in this river. These six significantly different genera were the water boatman *Callicorixa*, the riffle beetle *Dubiraphia*, the water beetle *Haliplus*, the water boatman *Sigara*, the flathead mayfly only identified to the family Heptageniidae, and those Heptageniidae further identified to the genus *Heptagenia* (Table 2). Four of these genera (excluding the *Callicorixa* and *Haliplus*) ranked as significant, according to Dunn's *post hoc* test (Table 3).

2.3.4.1. Typology 0 (Blue)

The blue typology occurred throughout the system but dominated in a few areas, most notably a large expanse south of Esterhazy, SK, stretching to just before the Manitoba border (Typology 0; Figure 3). Typology 0 was characterized as being relatively narrow, with high bank slope and fractal dimension, and no relationship with sinuosity (Table 1). Narrower reaches such as these tend to have more vegetation falling into the water, creating an ideal habitat for herbivores and detritivores [19]. Although this typology consisted primarily of the functional feeding group collector gatherers (46%), when compared to the others Typology 0 contained the most detritivores, housing 49% of the total detritivorous individuals (Figure 8).



<u>Figure 8. Functional Feeding Groups:</u> Proportional bar charts depicting (**A**) functional feeding groups contained in each typology; and (**B**) functional feeding group distribution amongst typologies.

The predominance of collector gatherers in this typology could be attributed to the high abundance of Chironomidae (midges) and Amphipod *Hyalella*, which accounted for 19% and 15% of the population respectively (Figure 9). It should be noted that Typology 0 contained the most EPT, highest EPT richness, and the second highest % EPT of the sample (Figure 7). The population distribution ws highest in Typology 0 for all four of the genera with significant links to typologies according to the statistical analysis; thus, all four demonstrated a preference for Typology 0 (Figure 6). Of the four genera, one was a water boatman, one was a riffle beetle, and two were Heptageniidae mayflies. The mayflies (Heptageniidae; *Heptagenia*) were nearly exclusively found in Typology 0, followed by Typology 2 at a distant second (Figure 6).

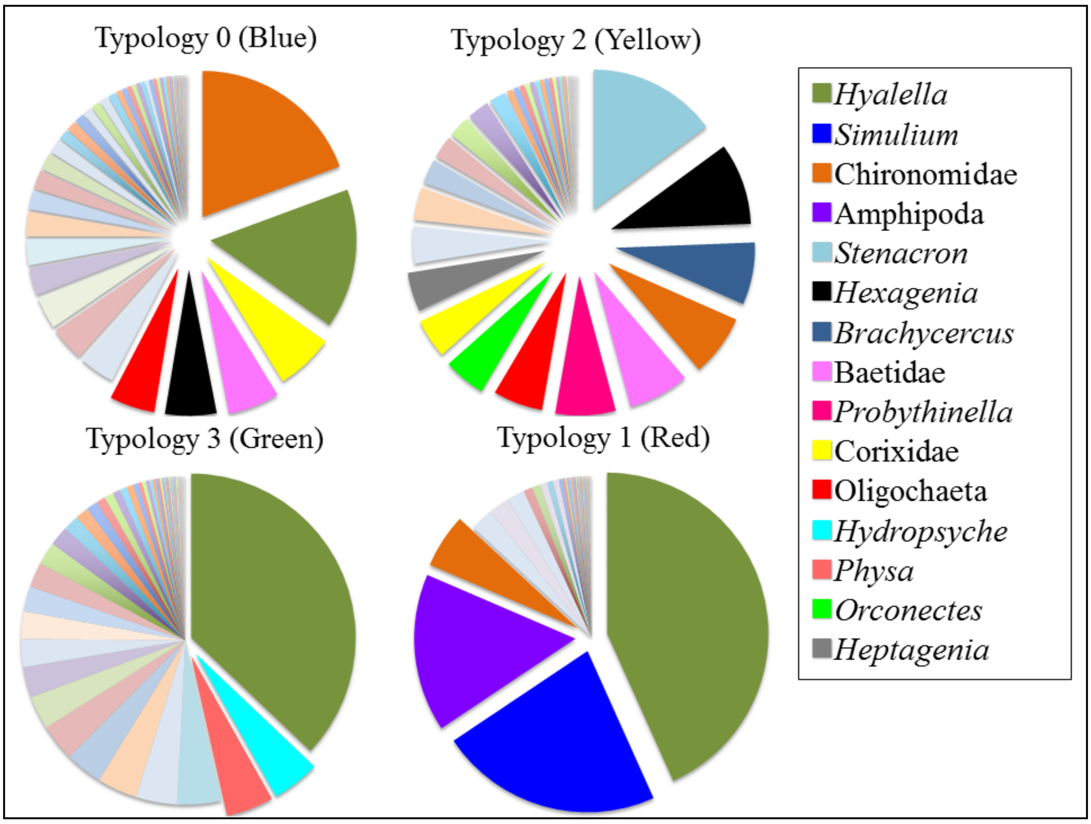


Figure 9. Community Makeup of Typologies: A breakdown of the macroinvertebrate community in each typology, with the most abundant genera (≥5% of the community) named in the legend.

Sometimes known as flat-headed mayflies because of adaptive general flattening and streamlining of the body, they cling to substrate in lotic streams [17,19]. All four of the genera showing preference to Typology 0 succeed in lotic environments. The mayfly Heptageniidae belongs to the scraper functional feeding group, which made up 19% of the community in Typology 0. They thrive in habitats where sunlight can reach, scraping biofilm and periphyton as their food source [19,50]. The highest concentration of the two other significant genera (*Dubiraphia*; *Sigara)* was also found in Typology 0, followed by Typology 3. The water boatman *Sigara* are herbivores and swimmers; they prefer areas with ample vegetation and use their modified mouthparts to pierce plant tissue [21]. The narrow reaches of Typology 0 are apt to provide access to vegetation for these herbivores. The riffle beetles *Dubiraphia* are collector gatherers, who cling on to substrate in lotic environments, similar to the Heptageniidae mayflies, collecting organic matter for food.

2.3.4.2. Typology 1 (Red)

Typology 1 dominated first at the culmination of the river until Buffalo Pound Lake (Figure 3; 1.a), then again from near Kennel, SK to the fishing lakes around Fort Qu'Appelle (Figure 3; 1.b), and again for a short stretch at the outlet of Katepwa Lake (Figure 3; 1.c). Geomorphological characteristics associated with Typology 1 were high bank slopes that are narrow with low sinuosity and low fractal dimension (Table 1). The channelized areas at the onset of the river were dominated by the red typology. It had the lowest percent of the sensitive EPT individuals, representing only 6% of the local community, yet housed the highest total EPT population at 74% of the community sample (Figure 7). Correspondingly, this typology had a high taxa richness of 75, and merely 25 of them were EPT genera. Further examination of the expansive Typology 1 community at the genus level revealed that it was dominated by the amphipod *Hyalella*. This amphipod genus represented 43% of the total community held in Typology 1. The *Hyalella* here mark the highest portion represented by one genus in any of the typologies (Figure 9).

Following *Hyalella*, by population size, in the red typology was the black fly larva *Simulium* (22%), and those only identified to the Amphipoda order (16%). *Simulium* can be found in almost any lotic water body, as they have many mechanisms to adapt to selective pressures [53,54]. Amphipods are very tolerant as well; *Hyalella* in particular has been found in extremely different climates, from Guatemala to the Northwest Territories [55]. Out of all four typologies, Typology 1 appeared to have the most imbalanced distribution and least complex community, dominated by the tolerant amphipods and black fly larvae (Figure 9). Typology 1 also consisted mostly of the collector gatherer functional feeding group (69%), followed by filterers (24%), and scrapers (4%), with very few representatives of the other groups relative to its large community (Figure 8). As compared with the other typologies, Typology 1 contained the majority of the collector gatherers (81%) and filterers (84%), as well as the most predators (44%), omnivores (37%), and scrapers (35%) of any typology. This is not surprising due to the large community held within this typology, as compared to the other three. The second highest EPT population was found here; nevertheless, it had the lowest % EPT (Figure 7). It also contained few of the four genera found to be statistically linked to typology choice, indicating these specialized genera preferred geomorphic regions different to that of Typology 1 (Figure 6). In combining all of these indices, Typology 1 seemed to house the least healthy macroinvertebrate community. It was dominated by less sensitive genera, which could result from nearby anthropogenic influences on the geomorphology.

2.3.4.3. Typology 2 (Yellow)

Typology 2 dominated the most in two separate stretches, first south of Kenlis, SK and again at Hyde, SK (Figure 3; 2.a; 2.b) It had high sinuosity and fractal dimension, with a negative relation to width, and no relation to slope (Figure 3; Table 1). Although Typology 2 housed the smallest community at merely 2% of the macroinvertebrates sampled in the Qu'Appelle River (and only five sample sites), it had the highest % of EPT individuals. The intolerant EPT orders represented a notable 52% of the Typology 2 community, indicating healthy water and habitat quality (Figure 7). At the genus level, the yellow typology consisted mostly of *Stenacron* (mayfly; 15%) and *Hexagenia* (mayfly; 9%), followed by 7% each of *Brachycercus* (caddisfly), Chironomidae (midge), Baetidae (mayfly), and *Probythinella* (snail). With a fairly proportional distribution of the remaining genera, Typology 2 appeared to have the most even taxa makeup of all four typologies; no single genus took obvious dominance over the others, as was the case with *Hyalella* in Typology 1 (Figure 9). It contained predominantly collector gatherers (39%), scrapers (29%), and filterers (16%). Within its small community, Typology 2 had 25% of the total omnivores (Figure 8).

2.3.4.4. Typology 3 (Green)

The green typology was characterized by large stream width (Table 1), and correspondingly consisted mostly of the large water bodies (Buffalo Pound Lake, Pasqua Lake, Echo Lake, and Mission Lake) as well as areas scattered throughout the system (Figure 3; 3.a; 3.b). Typology 3 contained 12% of the total Qu'Appelle River macroinvertebrates collected, within its five sampling sites, 18% of which were EPT. When examining Typology 3 at the genus level, it contained mostly the amphipod *Hyalella* (37%), followed by a fairly proportional distribution with *Hydropsyche* (caddisfly) and *Physa* (snail) at 5%, and *Valvata* (snail), Chironomidae (midge), Corixidae (water boatmen), Baetidae (mayfly), and Oligochaeta (worms) at 4% each. Besides a large amount of *Hyalella*, this typology had one of the more even taxa distributions, second to Typology 2 (Figure 9). In regards to functional feeding groups, the green typology had mostly collector gatherers (44%), followed by scrapers (23%), and herbivores (13%; Figure 8). When compared to the other typologies, Typology 3 contained the most collector gatherer scrapers (74%), shredders (46%), and herbivores (37%); it also had the least omnivores (4%). Two of the four genera that were revealed to be significantly linked to the typologies (*Dubiraphia*; *Sigara)* shared population distribution attributes, with the highest amount of both found in Typology 0, followed by Typology 3 (Figure 6). The water boatman *Sigara* had very similar numbers within both typologies, indicating it prefered both Typology 0 and 3 (446 individuals were collected in Typology 0, and a close 406 in Typology 3). As herbivores, *Sigara* need access to plants, and as swimmers, they would do well in the wide streams found in Typology 3. The riffle beetles *Dubiraphia* more heavily favoured Typology 0 (74 individuals), with Typology 3 holding second place with 35 individuals.

2.4. Conclusions

A need for rapid and visual methods of river assessment has been identified, especially those capable of reflecting and adjusting to local stream variability [56]. Within current systems of understanding fluvial macroinvertebrates, there is a lack of comprehensive watershed approaches. The geospatial model here fills the gap in understanding river typologies and benthic macroinvertebrate distributions. The use of typologies in this study resulted in the successful classification the Qu'Appelle River by similarities in geomorphology and provided a useful model to be used as a reference for these geomorphic characteristics. Geospatial models have the potential to be applied to larger rivers, and to be a predictive method for macroinvertebrate habitat. The geospatial model here was further used as a means to reveal relationships between macroinvertebrate distribution and geomorphology. The effectiveness of geomorphology as a potential means of identifying macroinvertebrate habitat in a more efficient manner has been proven in this way. Certain genera in the Qu'Appelle River were significantly linked to specific regions with similar geomorphic characteristics, showing potential for the use of this geospatial model as a means of pinpointing where certain macroinvertebrates can be found. This research has been an important step in revealing significant relationships between geomorphology and benthic macroinvertebrate community in a fluvial system. Additional data would help the analysis and complement the results discussed in this study. Whereas in this study, the geospatial data was extracted at a very fine resolution of 50 m intervals along the river, faunistic sampling was carried out only at certain stations. Future studies will include not only geomorphological variables but also biological and physical variables extracted using different methods. A water quality model of the Qu'Appelle River is currently being developed, which will provide water temperatures and dissolved oxygen concentrations at 50 m intervals along the river.

Bathymetric surveys of the river are also planned, which will provide water depths and substrate types at the same fine-scale resolution.

The model would be valuable to use prior to, or in lieu of field data collection. Through gaining understanding into the basic geomorphic makeup of the river before sampling, choosing sampling sites can be a more informed process. Since geomorphology drives sediment and contaminant transport, geomorphic typology maps could be a valuable tool to strategically locate new monitoring stations. Macroinvertebrates are established as indicators of environmental health, because they often respond more quickly than other groups, like fish, to ecosystem degradation and contaminants [17,18]. Understanding how geomorphology influences macroinvertebrates can be applied further up the food chain as well, as energy and contaminants move bottom up. Geomorphic structure and instream habitats are key limiting factors for freshwater fish, but it can be hard to pinpoint habitat preferences throughout their life stages [57]. Macroinvertebrates are important food sources for fish, and are also heavily influenced by geomorphic variables; incorporating macroinvertebrates may help to refine fish studies [2,57]. The geomorphic model used in this study is valuable for the sustainable preservation and management of rivers, which requires an understanding of the geomorphological factors that drive species distributions.

Author Contributions: Anna Meissner performed data analysis and prepared the manuscript; Meghan Carr delineated the model and contributed to some figures; Iain Phillips collected and provided macroinvertebrate data and contributed to the editing of the manuscript; and Karl-Erich Lindenschmidt contributed to the development of the model and editing of the method and manuscript.

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3. Article 2: Matching Family-Level Indices to Geomorphological Response Units (GRUs)

Published in 2016, Figure 10 has been converted from miles to kilometers, but the manuscript does not differ in content from the published version.

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Using a Geospatial Model to Relate Fluvial Geomorphology to Macroinvertebrate Habitat in a Prairie River—Part 2: Matching Family-Level Indices to Geomorphological Response Units (GRUs)

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3.1. Introduction

The fluvial environment is influenced by factors such as climate, vegetation, and geology, geology, which leads to the formation of many different instream habitats [1,2]. Since the geomorphological structure of a river basin is a driving factor affecting biological responses, it plays a vital role in the functioning and habitat selection of many species within the river [1,3]. Changes in river geomorphology influence the hydrological and ecological processes within the river ecosystem by creating these diverse instream habitats [4]. In order to thrive in dynamic river ecosystems, aquatic organisms must adapt to regional conditions. Food source availability, interactions with other species, and trophic levels are important as macroinvertebrates select a suitable instream habitat [2]. Taxa of Hydropsychidae (Trichoptera) larvae, for instance, are common in the running waters suited to their use of catchnets for feeding [5].

Other than food availability, some benthic macroinvertebrate families have sensitivities to organic pollution that can also influence habitat selection [6]. Due to this variation in tolerance levels to organic pollution, macroinvertebrates are used as indicators of present, cumulative, and overall water integrity within river systems [1]. As a result of the many habitat requirements of fluvial macroinvertebrates, studying their habitat in relation to geomorphology can provide valuable information about the river ecosystem. Most riverine macroinvertebrate habitat studies are organized by niche physical traits suited to the study (*i.e.*, rock substrate dominant) metahabitats (*i.e.*, run, riffle, pool) [7–9]. As opposed to these methods that pick out habitats and are based on field observations, the method proposed in this study is completed through solely desktop means. The method allows habitats to be characterized in a nonpartisan manner, and saves time and money because it does not require field work to be completed. The geospatial model can be adjusted to fit rivers in a variety of locations and climates; it can be used as base data before a study and to monitor changes in geomorphology within a river basin over time. With the information the model provides, local communities, industries, and researchers benefit. For instance, geomorphology drives water, sediment, and contaminant transfer, so information from the model can better inform the decision process of where to build new monitoring stations [2]. In combining the model with biotic data, even more useful information can result. Part 1 in this two-part series focused on macroinvertebrates at the genus level, and their relationships to the geomorphic typologies delineated for the Qu'Appelle River. In Part 2, the typologies were further sorted into Geomorphic Response Units (GRUs), which are river reaches with similar geomorphological features (e.g., sinuosity, channel width, *etc.*) and compare them to macroinvertebrate distribution at the family level.

GRUs can be useful in describing the structure of a river network; the GRU model provides helpful geomorphological information, entirely gathered through desktop analysis [10]. Once determined for a water body, GRUs can be used for selecting sample sites, predicting the effects of man-made changes in river structures, and identifying vital habitats for conservation. When provided with a GRU model of the river beforehand, field sampling efforts can be more focused and useful, with GRUs being sampled more evenly, avoiding oversampling in areas with similar geomorphological characteristics. Thus, the gathered field data can be paired with pertinent geomorphological data to work with during analysis [10]. The GRU method was found to be effective in a previous study carried out for the South Saskatchewan River, as related to Lake Sturgeon and overwintering holes [11]. It was then attempted for the Birch River, Manitoba and the Carmine Shiner (*Notropis percobromus*), a species at risk. This study had more limited success, perhaps due to drought conditions which led to a loss of connectivity during the sample period. The fish may have been forced to use sub optimal habitats [12]. This study reveals that the GRU method is likely more applicable to larger rivers with a more connected network. The method was also carried out for the Assiniboine River in Manitoba, which was successful in identifying relationships between different fish species and GRUs [13].

Since macroinvertebrates are a food source for many fish species and are often the first to react to contaminants, understanding how they are influenced by geomorphology can help to refine fish studies [14–16]. Gaining knowledge pertaining to the effects fluvial geomorphology has on macroinvertebrates can therefore be useful for other trophic levels, and the flow of energy and contaminants through the food chain. It can also aid in pinpointing important habitats for preservation, and maintenance of natural food sources for fish, including species at risk. Macroinvertebrates, a lower trophic level and food source for many fish, were pursued in Part 1 of this study, in relation to geospatial typologies. Several genera were identified as significantly linked to geospatial typologies in the Qu'Appelle River, using the Kruskal-Wallis analysis and *post hoc* pairwise multiple comparisons [17]. These positive results revealed the potential of the model, and GRUs as a means of relating macroinvertebrates to geomorphology.

Due to the success of linking fish species and the GRU model as well as macroinvertebrates and geospatial typologies, in this study macroinvertebrates were tested with the GRU model. Macroinvertebrate data were superimposed on a GRU network of the Qu'Appelle River, Canada. Various standard macroinvertebrate analyses were completed and compared within the parameters of GRUs, to test for relationships between the macroinvertebrates and GRUs. The three different diversity indices completed here (Shannon diversity, family biotic Index, EPT/C ratio) are commonly used in macroinvertebrate studies, and are pertinent tools for comparison to the GRUs as a means to reveal relationships to macroinvertebrates. The purpose of this study was to carry out a complete desktop assessment, as a proof of concept, to determine whether the GRU method is valid for differentiating macroinvertebrate habitats in rivers. The objective was to show the usefulness of the GRU model as a means of gathering important data, as applied to fluvial macroinvertebrate habitats. Part 1 revealed several significant relationships between geomorphic typologies and certain macroinvertebrate genera [17]. By further categorizing the typologies into GRUs, and comparing them to the broader family classification of macroinvertebrates, the goal was to find additional significant relationships. Due to the success of Part 1, it was hypothesized that GRUs will explain some of the variation in benthic macroinvertebrate community characteristics and habitat selection.

3.2. Methods

3.2.1. Study River

The Qu'Appelle River watershed is located in the Saskatchewan plains region of Canada, which encompasses many different topographical features such as ground moraines, lake plains, and river valleys [18]. The length of the river is 430 km, originating at the Qu'Appelle Dam at Lake Diefenbaker (located at 550m above sea level) and flowing into the Assiniboine River, just beyond the Manitoba-Saskatchewan boundary (Figure 10). The system contained a number of lakes, broad floodplains, and sweeping meanders. There are several existing threats to the sustainable functioning of the aquatic ecosystem, including disrupted flow regime, loss of connectivity, channelization, climate change, and amplified anthropogenic use. The watershed area contained industrial, urban, and agricultural development, resulting in an ever-increasing water demand [19]. Irrigation and potash mining are two main sources of increased water demand in the area, which will only intensify; together, these two activities could account for three-quarters of the water use in the river basin by 2060 [19]. For the environment, society, and economy of the Qu'Appelle area to thrive under these strains, long-term solutions must be found [19].

The gross drainage area of the Qu'Appelle River at the outlet station (Station #05JM001 near Welby) is 50,900 km^2. This station is just past the 35th and final macroinvertebrate sampling site used in this study, and is located at 394.57 m above sea level. Highest flows were 7 July 2014 at 454 m^3/s, and flows have been as low as 0.0 m^3/s, several times between 1987 and 1988, which were very low flow years. The average between 1974 and 2014 was 12 m^3/s. The minimum stream width recorded at the centerline points was 6.8 m, the maximum was 2226.9 m, and the average was 168.7 m. The lowest monthly mean discharge at the station (1975–1993) happens in February (2.6 m^3·s^{-1}) and the monthly mean discharge upsurges abruptly from March to April (3.7 to 17 m^3·s^{-1}), resulting from the prairie snowmelt period [20]. Following the spring freshet, the monthly mean discharge declines abruptly, maintaining low levels throughout the remainder of the season with the exception of a minor upsurge in autumn, serving to draw down lake levels for the subsequent year's spring runoff [20].

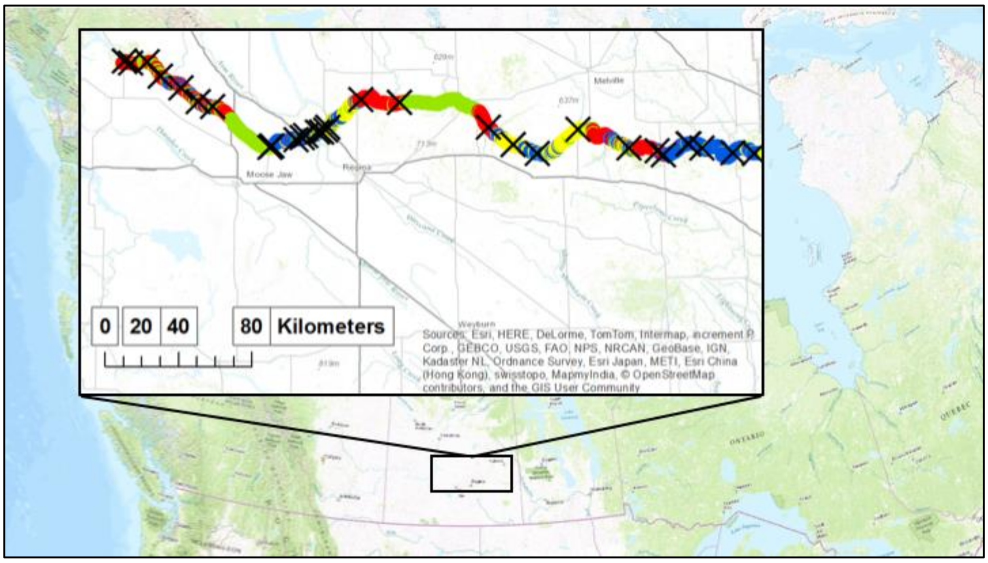


Figure 10. Site Location: The Qu'Appelle River in Saskatchewan, Canada. The 35 macroinvertebrate sampling sites are denoted by a triangle shape. The centerline of the river is made up of the colour coded geospatial typologies as described further in Chaper 3.2.2.

3.2.2. Creating the Geospatial Model

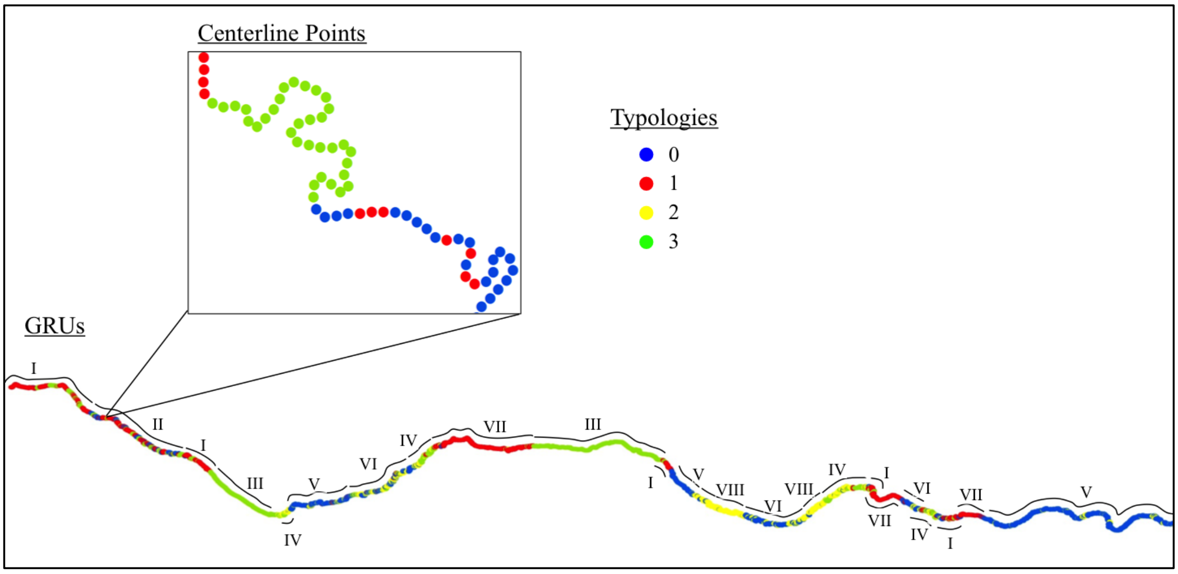
As the study focussed on the geospatial characteristics of the river, several characteristics (sinuosity, slope, fractal dimension, stream width) were chosen to be the points of comparison in the model. These characteristics were selected because they provide a satisfactory overview of the local fluvial geomorphology. The model has the potential to be expanded for other studies or in different river basins to include a variety of features, such as the average water temperature, dissolved oxygen concentration, depth, or flow. To create the geospatial model of the Qu'Appelle River, sinuosity, slope, fractal dimension, and stream width were extracted from a combination of Lidar (Water Security Agency) and 1:50,000 CanVec digital elevation model (DEM) data (Department of natural resources Canada), using Geographic Information System (GIS) software (ESRI 2013). Given the accessibility of this information to researchers, the model is flexible and could be completed for fluvial watersheds all over the world. A river polygon was first delineated, and a river centerline was added along the entire length of the river. Points were placed along the centerline at 50-meter intervals, followed by a transect (bank to bank) at each centerline point (Figure 2). Average bank point elevations were extracted from the DEM, and for each 50 m section, the river's sinuosity, slope, fractal dimension and stream width could then be determined [10].

Sinuosity measures the intensity of river windiness and is defined as the ratio between the centerline length of a river stretch to the straight-lined distance between its endpoints [21–23]. Sinuosity can also be understood as a relationship between the slope of the valley to the slope of the river [23], or between the river length and valley length (shortest possible distance). Different terms are used to describe the spectrum of sinuosity values (S), including $S = 1$ for a straight-lined (linear) stretch, and in order of increasing sinuosity, elongated, oscillating, tortuous, and finally meandering with $S > 2$ [24,25]. Very sinuous rivers have a higher silt and clay content in their bed material [26], with $S > 1.5$ pointing to a riverbed consisting of over 92% fine textured material [23]. Sixty-three percent of the Qu'Appelle River's stretch has a sinuosity of $S > 1.5$, suggesting that its bed has a balance of both coarse and fine materials, coinciding with the till blanket constituting most of the surficial geology of the Qu'Appelle River basin. Sinuosity in this study is the length of a river reach divided by the shortest distance between the reach end points, with a sinuosity score of 1 being a straight channel, and >1 a meandering one. The determination of a river's sinuosity is an important goal, as the meandering of a system can influence sedimentation and various hydrological and ecological processes in the nearby environment [22].

The fractal dimension of a channel is a measurement of how much of the river length fills a certain Euclidean space. It is similar to sinuosity but quantifies an order of magnitude larger than sinuosity; it is indicative of the amplitude of meander change, within a river reach [21,27]. Fractal dimension can be helpful when examining complex meandering river patterns in the context of larger, geological viewpoints [10,22]. Both sinuosity and fractal dimension were calculated using the commercial software package Mathcad® v.15 (Parametric Technology Corporation; PTC, Inc., Needham, MA, USA) [28]. Sinuosity was calculated at a slightly larger scale than width and slope, using 40 adjacent points (20 upstream and 20 downstream of each centerline point). Fractal dimension was calculated based on the number of centerline points that fell within a 40 km × 40 km square window moved along the course of the river. These scales were chosen because they were the values at which peak variation was calculated, giving the greatest range and, therefore, the most information about each variable. As described in Lindenschmidt and Long (2012), geomorphic typologies were identified by performing a Principal Component Analysis (PCA) of these four variables (sinuosity, slope, fractal dimension, stream width), using the statistical package R 2.15.2

[10,29]. The PCA was chosen because of its capacity to reduce the dimensionality of a data set with a large number of descriptors, and subsequently identify patterns within it [30].

The dataset of the four geomorphic characteristics calculated at each centerline point was $\log_{10} + 1$ transformed to improve normality while accounting for the high incidence of zeros and very small positive values. The explained variance of principal components (PC) one through four was 49%, 24%, 14% and 13%, respectively. Following Jolliffe's (1972, 2002) modified Kaiser's rule, the eigenvalues for components 3 and 4 were both less than 0.7 (0.57 and 0.52, respectively); therefore, only the first two principal components (accounting for 73% cumulative variance) were used to derive typologies [31,32]. The sum of binary values assigned to PCs at each centerline point, 1 for positive PC values and 0 for negative PC values, identified different geomorphic typologies, resulting in four unique geomorphic typologies (Figure 11). River typologies were each given an identifying color and assigned to the corresponding 50-meter centerline points. Patterns within the typology distribution were visually assessed to identify spatial groupings (GRUs); eight different GRUs were identified along the Qu'Appelle River (Figure 11). An example of repetitive typology patterns being identified as a GRU occurred in GRU I, which was composed of Typology 1 and 3, as compared to GRU II that was a mix of typologies 0, 1 and 3 (Figure 11). As the objective of this study was to identify geomorphologically similar reaches along the river, GRUs were assigned to reaches that exhibited repetitive patterns in typology associations, separating such units in transition zones where large patterns gradually or abruptly changed (Figure 11).



<u>Figure 11. Map of GRUs:</u> Colour-coordinated centerline points and corresponding typologies, with resultant GRUs labelled.

3.2.3. Macroinvertebrate Sampling

Macroinvertebrate sampling was carried out prior to and separate from the delineation of GRUs, taking place between 2006 and 2009. With the GRU model, it would be ideal to delineate the geomorphological typologies before data collection instead, so that the sampling sites could be decided in light of the model and with a more even distribution amongst the GRUs. Benthic macroinvertebrate samples were collected at a total of 35 sites along the Qu'Appelle River, from Lake Diefenbaker at its headwaters to its termination at its confluence with the Assiniboine River at the Manitoba border (Figure 10). Sites were selected for road access and with a pre-determined minimum 10 km river distance between sites. At each site, samples were collected in a 500 µm mesh D-frame net using a time and space standardized travelling kick and sweep (TK & S). This is a standardized method of sampling, which allows for the comparison of communities in similar habitats, between sites. Specifically, each sample comprised five evenly spaced positions along a transect from bank to opposite bank. These five samples were then integrated into one composite sample for each site. The transect sampled was perpendicular to the river channel and, at each position, an area ~30 cm × 30 cm was kicked to a depth of ~5 cm, for 10 s.

In each collection, the net was swept downstream of the collector. All sites had similar features of straight, slow flowing reaches with no riffles. Substrate was typically soft silt, but did include small patches of cobble and vegetation on the bank positions. Ultimately, the objective of this study was to use a standardized method of benthic macroinvertebrate collection in comparable habitats across all sites, so that the dominant communities of the major habitat features would be represented. Although this method does not ensure that all taxa present at a site are represented, most dominant assemblages and habitat features were adequately characterized in this way. All benthic macroinvertebrate samples were preserved in 80% ethanol in the field, and sorted from the organic material under 7× magnification in the laboratory. Benthic macroinvertebrates were identified to family designations using keys for North America [15] and western Canada where available [33–35]. Voucher series were deposited in both the Water Security Agency of Saskatchewan Invertebrate Voucher Collection (Saskatoon, Saskatchewan), and the Royal Saskatchewan Museum (Regina, Saskatchewan). Further, taxa occurrence records were submitted to the Saskatchewan Conservation Data Center with the Ministry of Environment.

3.2.4. EPT/C Ratio

Although many sensitive benthic macroinvertebrates can be found in water with organic pollution, polluted stretches are often dominated by Chironomidae and freshwater Oligochaeta worms [2]. Chironomids can thrive in a wide variety of habitats due to physical adaptations and high tolerance levels; as such, they are commonly held to be indicators of poor water quality [15,36]. Conversely, Ephemeroptera, Plecoptera, and Trichoptera (EPT) do not thrive in compromised water conditions due to their low pollution tolerance [6,14,37]. A high proportion of sensitive EPT at a site should therefore indicate higher water quality [38]. By comparing the population of EPT to that of Chironomidae, a metric of community health can be established for the site [38]. A habitat in good condition will have a more even distribution among these groups, rather than an overwhelming abundance of chironomids above EPT. Finding the sum of individual organisms in the Ephemeroptera, Plecoptera, and Trichoptera orders and dividing that total by the aggregate number of chironomids calculates an EPT/C ratio. A higher number is a positive result, meaning the chironomids are outnumbered by the EPT. A lower number shows possible environmental stress, as the EPT are greatly surpassed by chironomids.

3.2.5. Shannon Diversity Index

The Shannon diversity index is a biological index indicating biodiversity; this value increases as the number and distribution of taxa within the community increases [38]. As a measure of diversity, it includes both evenness and richness to evaluate community health [14]. A Shannon diversity index value was determined for each macroinvertebrate sample site in this study. The percent relative abundance for each family was first determined within each sample site by dividing the total number of individuals in each family, by the total number of individuals of all the families together. The natural logarithm of each of these family proportion values was then found. The negative sum of these values for all families at a site represents its Shannon diversity index value. A higher Shannon diversity index value indicates a more diverse community, in this case at the family level, within the study site.

3.2.6. Family Biotic Index

An additional metric of ecosystem health commonly used to assess the impact of organic pollution, is the family biotic index (FBI) [39]. Hilsenhoff (1988) developed the index by designating tolerance values of organic pollution to benthic macroinvertebrates by family, ranging from 0 (very intolerant) to 10 (very tolerant) [38,39]. These values are based on family distribution in pollution; for instance, a family only found in pristine waters would be given a lower value like 0 or 1 [14]. Specifically, the number of benthic macroinvertebrates in each family is recorded, and then the FBI is calculated by multiplying the abundance per family by that family's respective tolerance value. These family abundances adjusted to tolerance are then summed and divided by the total number of organisms in a sample and multiplied by 10. The resulting FBI value between 0 and 10 can indicate a level of water quality and corresponding degree of organic pollution present at the site (Table 4) [39].

Table 4. Biotic index Scores: Results and associated water quality in the Qu'Appelle River [38,39]. Far right column displays results from the 35 Qu'Appelle River sampling sites.

Biotic Index Score	Water Quality	Degree of Organic Pollution	Percent of Sites
0.00–3.50	Excellent	No apparent organic pollution	0% *(0)*
3.51–4.50	Very Good	Possible slight organic pollution	6% *(2)*
4.51–5.50	Good	Some organic pollution	31% *(11)*
5.51–6.50	Fair	Fairly significant organic pollution	34% *(12)*
6.51–7.50	Fairly Poor	Significant organic pollution	26% *(9)*
7.51–8.50	Poor	Very significant organic pollution	3% *(1)*
8.51–10.00	Very Poor	Severe organic pollution	0% *(0)*

3.2.7. Comparing GRUs to Macroinvertebrate Data

Each of the macroinvertebrate indices (EPT/C, Shannon diversity index, family biotic index) were calculated separately for each sampling site. The data collected at each of the 35 macroinvertebrate sampling sites was sorted into the eight GRUs for comparison. Qualitative analysis of these results was carried out to identify any patterns. Separate from these indices, the macroinvertebrate community was combed through within each GRU at the family level, to pinpoint any family–GRU relationships. This study focused on the comparison of GRUs to family-level macroinvertebrate data only.

3.3. Results and Discussion

The purpose of the study was to complete an assessment of the GRU method applied to macroinvertebrate habitats, as a proof of concept. This was accomplished completely through desktop means, including the creation of the model to identify relationships between macroinvertebrates and GRUs. Therefore, the objective was to demonstrate the worth of the GRU model as a method of collecting useful geomorphological data, and as a tool to be applied to macroinvertebrate habitat in rivers. The methods first detailed the making of the geospatial model and identification of the GRUs; these were further explained and discussed below. Once the model was created, the provided macroinvertebrate data were superimposed on the GRU network of the Qu'Appelle River. The standard macroinvertebrate indices described in the methods were completed and related within the parameters of GRUs, to reveal relationships between the macroinvertebrates and the GRUs. It was hypothesized that GRUs would relate to some of the variation in macroinvertebrate community features as well as in macroinvertebrate habitat selection.

3.3.1. Geospatial Factors

Figure 4 shows PCA scores (color coded by typology) and variable vectors plotted in terms of principal component one on the *x*-axis, and component two on the *y*-axis. Principal components one and two accounted for 73% of the total variation in the dataset. In general, sinuosity and fractal dimensions tended to be more positively related to one another, while relationships between other variables differed depending on the typology of interest (Figure 4). General relationships between the four geomorphological variables (sinuosity, slope, fractal dimension, and channel width), as well as their relationships within different typologies, can be inferred from the biplot in Figure 4. Density plots of normalized values of sinuosity, slope, fractal dimension, and channel width were also used to examine the qualitative contribution of each of these variables to each unique geomorphic typology based on absolute means (Figure 5). General relationships for all four typologies are summarized in Table 1.

Typology 0 was positively related to slope and fractal dimension and negatively related to to width, implying more narrow regions of a higher fractal dimension and slope (Table 1). Typology 1 was positively related to slope but has a negative relationship with all other variables, associating it to narrow areas with a low fractal dimension and less meanders, and a high slope. (Table 1). Typology 2 was positively related to sinuosity and fractal dimension and negatively related to width, associated to highly sinuous and narrow reaches, with a high fractal dimension. Typology 3 had a negative relationship with all variables except width, meaning it was comprised of wide and straight reaches with low slope and fractal dimension values (Figure 4, Table 1). The typologies were grouped into eight different GRUs, by identified patterns within the typology distribution (Figure 11). Table 5 provides a summary of what these GRUs were composed of, as well as how many macroinvertebrate sites were available within each of them. For example, GRU III was characterized by Typology 3 exclusively, which was positively related to stream width (Tables 5,6). Correspondingly, the GRU consisted of large water bodies (*i.e.*, Buffalo Pound Lake, Pasqua Lake, Echo Lake, Mission Lake) within which no macroinvertebrate data was collected (Table 5, Figure 11). Some of the smaller reservoirs (*i.e.*, Eyebrow Lake, Katepwa Lake, Crooked Lake, Round Lake) were not a part of this GRU.

Table 5. GRU Characteristics: Summary of typology makeup, and the number of macroinvertebrate samples contained within each GRU.

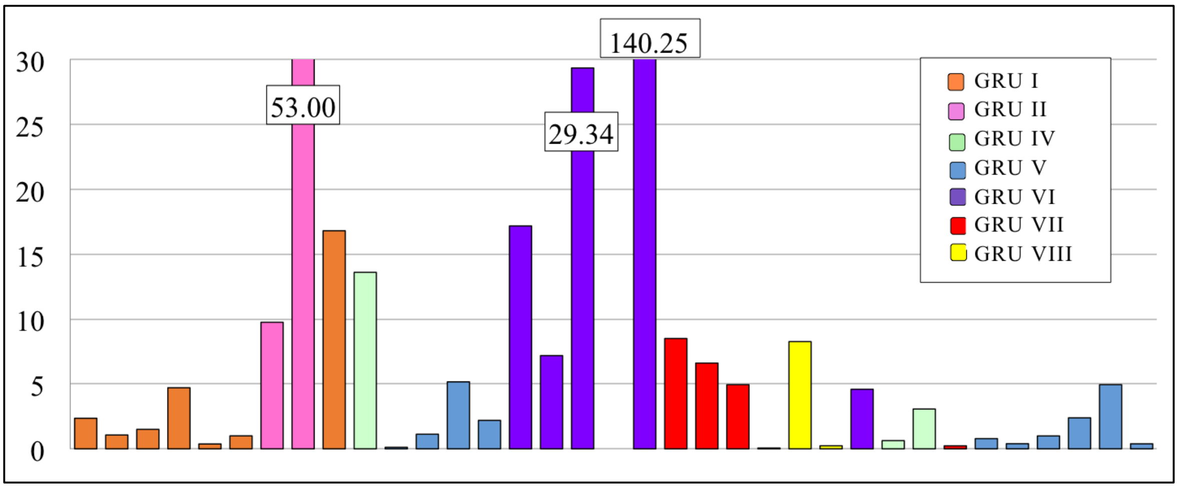
GRU		**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**
Typology Makeup	*Most*	1	1, 0, 3	3	3, 2	0	0, 2	1	2
	Other	3	-	-	1	1, 2, 3	3, 1	0, 2	0, 3
Macroinvertebrate Sample Sites		8	2	0	4	9	6	4	2

3.3.2. Overall Macroinvertebrate Indices Results

The three macroinvertebrate indices used here (EPT/C ratio, Shannon diversity index, family biotic index) were chosen because they are often used in macroinvertebrate community evaluations. Upon calculating the indices for each of the 35 sampling sites, it became clear that variation from site to site was high, and relationships to the GRUs were minimal. As a result, the focus shifted towards macroinvertebrate family distribution, as a more qualitative evaluation. The results of all three macroinvertebrate indices are recorded and displayed graphically below. The relationships discovered between specific macroinvertebrate families and GRUs are also detailed below.

3.3.2.1. EPT/C Ratio

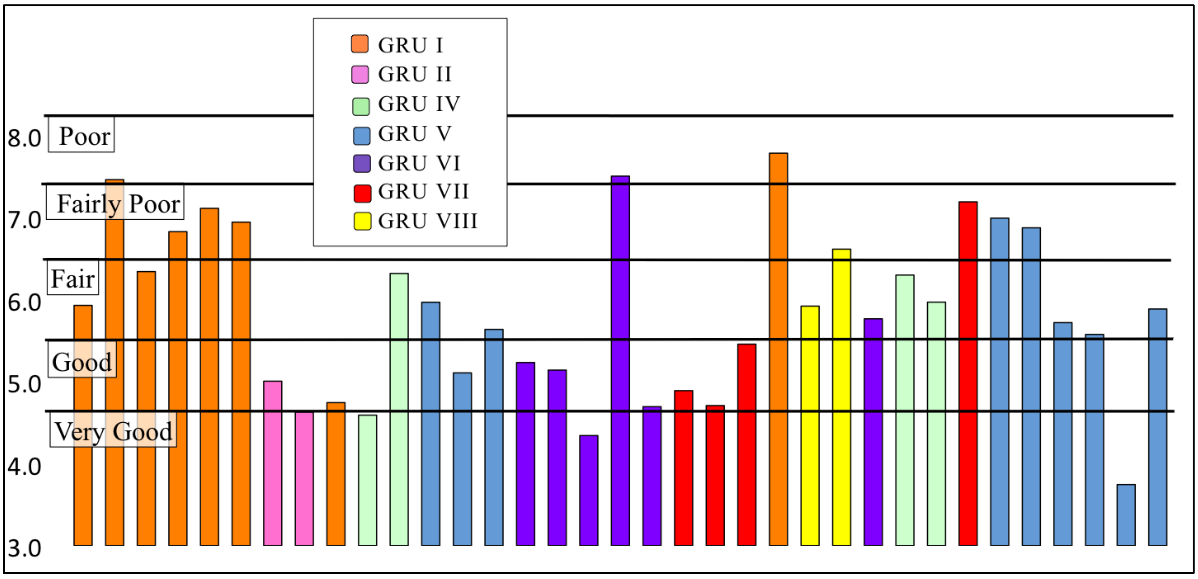
Minor relationships could be observed between the GRUs and the EPT/C ratio results; for instance, some of the highest EPT/C scores were recorded in GRU VI. GRU I and GRU V had lower average EPT/C ratios than other regions. However, the site to site variation was undeniable, and no obvious patterns could be identified. GRU I had an average EPT/C of 3.48 (Figure 12). GRU II had an average EPT/C of 31.38, GRU IV had an average EPT/C of 4.35, and the average EPT/C ratio in GRU V was 2.04. GRU VI had an average EPT/C of 33.09 and 39.71 without site 53. The lowest EPT/C score was calculated at site 53, with a ratio of 0 (0 EPT and 3 chironomids). GRU VII had an average EPT/C of 5.07. GRU VIII had an average EPT/C ratio of 4.25.



<u>Figure 12. EPT/C Ratio Results:</u> Scores for each sampling site in the Qu'Appelle River. The sampling sites are in order of upstream to downstream. The GRU of each site can be found in the legend.

3.3.2.2. Family Biotic Index

Similar to the EPT/C results, the high variation between sites hindered the ability to pinpoint specific GRU patterns in this analysis. GRU I had the worst average results in the family biotic index analysis. GRU VI generally seemed to have the best average, aside from the two sites contained in GRU II. GRU I had an average biotic index value of 6.64 (*fairly poor*; Table 4, Figure 13).



<u>Figure 13. Biotic Index Scores:</u> Results for each sampling site, displayed in river order, for the Qu'Appelle River. Bar-colours indicate the GRU each site is located in.

GRU II had an average biotic index value of 4.82 (*good*), GRU IV had an average biotic index value of 5.79 (*fair*), and GRU V had an average biotic index value of 5.72 (*fair*). GRU VI had an average biotic index value of 5.44 (*good*), and 5.03 (*good*) without site 53. Site 53 received the second-worst biotic index value of 7.50. GRU VII had an average biotic index value of 5.56 (*fair*), and GRU VIII had an average biotic index value of 6.27 (*fair*). The undeniable disparity of FBI scores between sites as opposed to between GRUs points to the necessity of including local influences (*i.e.*, agriculture, industry) in future studies.

3.3.2.3. Shannon Diversity Index

The Shannon diversity values found in this study ranged from 0.71 to 2.46 (Figure 14). As with the other macroinvertebrate indices, most of the GRUs did not show an obvious relationship to the Shannon diversity index. For instance, the sites within GRU V all fell within similar Shannon diversity ranges, whereas GRU I contained a high variety of results. Studies with a more even site distribution amongst GRUs may obtain more useful Shannon diversity results.

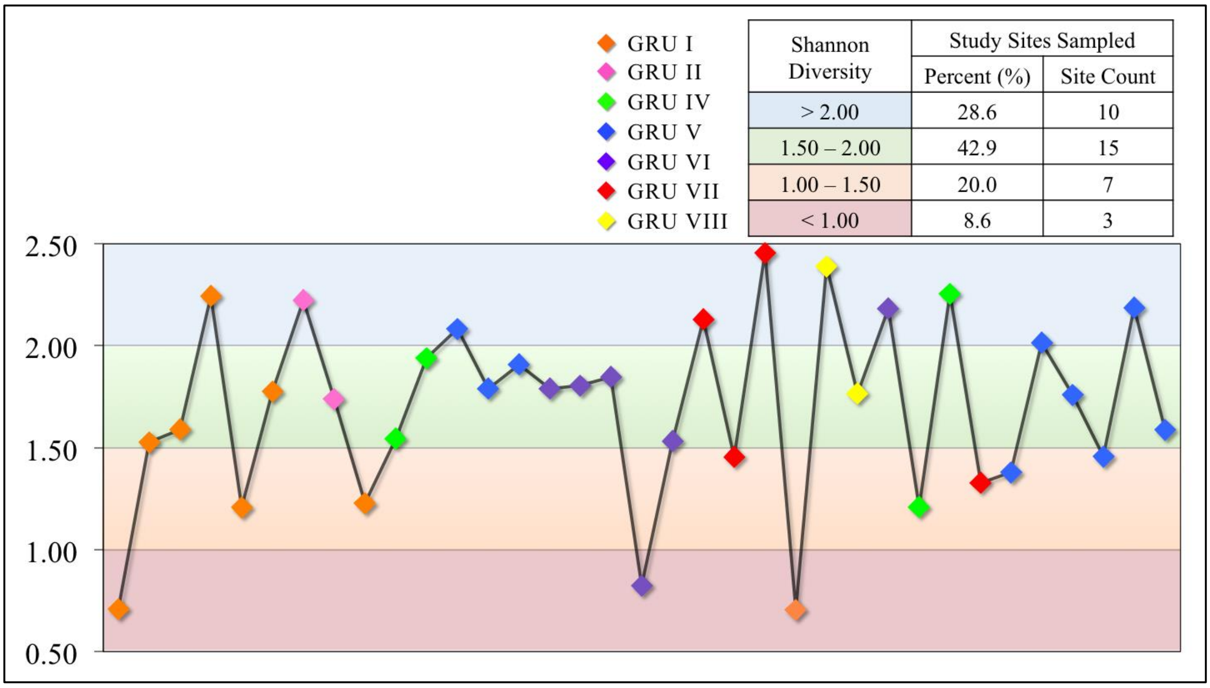


Figure 14. Shannon Diversity Index Scores: Results for each sampling site, displayed upstream to downstream, along the Qu'Appelle River. The GRU of each site can be found in the legend.

GRU I had an average Shannon diversity score of 1.37 (Figure 14). GRU II had an average Shannon diversity of 1.98, GRU IV had an average Shannon diversity of 1.74, and GRU V had an average Shannon diversity of 1.80. GRU VI had an average Shannon diversity of 1.66 and 1.83 without site 53. Site 53, within GRU VI, received the penultimate Shannon diversity score of only 0.82. GRU VII had an average Shannon diversity of 1.84, and GRU VIII had an average Shannon diversity of 2.08.

3.3.3. Comparing GRUs to Macroinvertebrate Data

Overall community makeup shifted highly from site to site; the lowest total individuals recorded was 12 at site 53 and the highest was 40,227 at site 35. The complete data set contained 115,696 individuals from 63 families. The initial qualitative examination of this vast data set was accomplished through examining the family abundance within each GRU. The westernmost stretch of the Qu'Appelle River, immediately downstream of Lake Diefenbaker, consisted mainly of GRUs I and II (Figure 11). All of the GRU I sites contained Chironomidae, Corixidae, and Oligochaeta. Most (6/7) sites also contained Dogielinotidae, which was the second highest family by relative percentage for GRU I (Figure 15). The family Simuliidae (black fly larvae) had the highest abundance in GRU I. Both GRU II sites contained Baetidae, Cambaridae, Chironomidae, Coenagrionidae, Corixidae, Ephemeridae, Heptageniidae, Hydroptilidae, Oligochaeta, and Pisidiidae. The highest abundance in GRU II was the family Ephemeridae, followed by Baetidae, Corixidae, and Oligochaeta. GRU IV occured in 5 relatively small stretches throughout the river (Figure 11). Each of these sites contained Oligochaeta, and the families Chironomidae, Ephemeridae, Cambaridae, and Pisidiidae. The most abundant family in GRU IV was Hydropsychidae; following this family by abundance were Corixidae, Chironomidae, and Baetidae.

GRU V appeared throughout the river. All nine sites within GRU V contained Chironomidae and Dogielinotidae, and most (8/9) contained Baetidae and Heptageniidae. The most abundant family in GRU V was the Dogielinotidae, followed by Simuliidae, and those identified only to the Amphipoda order. Besides site 53, all five other sites within GRU VI contained the families Cambaridae, Chironomidae, Corixidae, Ephemeridae, Heptageniidae, and those identified as being in the Oligochaeta class. The most abundant family was Heptageniidae, followed by Hydropsychidae, Baetidae, Ephemeridae, and Oligochaeta. Site 53, within GRU VI, contained the smallest total, at only 12 individuals, eight of which were the aquatic worm taxa Oligochaeta, which is known to be highly tolerant to adverse environments and is often used as an indicator of polluted systems [14]. This site also had a family richness of only 3; besides the aforementioned Oligochaeta (only identified to class), it contained just Corixidae and Chironomidae.

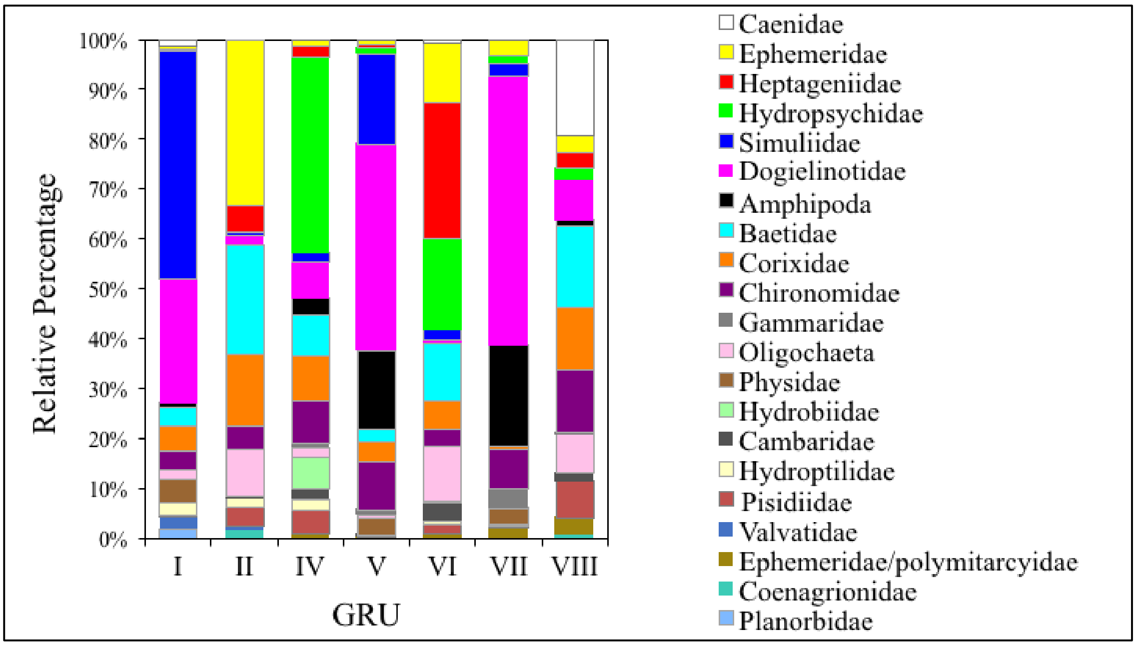


Figure 15. Abundance by Relative Percentage: The 10 most abundant families in each GRU are included here, with a total of 22 families.

All four sites within GRU VII contained the families Chironomidae, Corixidae, Hydropsychidae, and Pisidiidae. The most abundant family was Dogielinotidae, followed by those only identified as Amphipoda. GRU VIII was made up of three small reaches, all in the eastern half of the Qu'Appelle River, and two sample sites. Both sites contained the families Caenidae, Cambaridae, Chironomidae, Corixidae, Ephemeridae, Gammaridae, Heptageniidae, Hydropsychidae, Leptoceridae, Notonectidae, Physidae, Pisidiidae, and Dogielinotidae. The most abundant family in GRU VIII was the Caenidae, followed by Baetidae (Figure 15). Due to the vastness of the data set, simply observing the relative abundance by GRU did not point to any obvious significant relationships. However, through comparing the family abundance within each GRU, certain families stood out as important within the system. The qualitative examination, seeking relationships between the GRUs and macroinvertebrate families, continued then by focusing on certain family distributions.

3.3.3.1. EPT Families

Hydropsychidae net-spinner caddisflies composed 2.38% of the total river community (the sum of individuals within all sampling sites) with 2748 individuals (Table A1 in Appendix). They have tolerance levels of 4 or 5. They are filterers and clingers, preferring lotic environments. These caddisflies spin nets to catch food (organic matter) in flowing water [6]. Physical adaptations allow them to attach to stones and stabilize themselves in swift currents [15]. These lotic insects prefer more rapid water flow, as it aids in food collection [5]. Sedimentation can cause tearing or burying of their nets, or can cause the nets to get clogged, both of which lessens food capture and increases energy expenditure [40,41]. They have been found to be especially intolerant of fine substrates near agricultural sites and could therefore be used as indicators of habitat degradation as a result of increased sedimentation [5]. Few of these Hydropsychidae were found in GRUs I, II, and VIII. Totals ranged between 0 and 21 individuals; however, they were fairly evenly distributed throughout the rest of the GRUs (IV, V, VI, VII), ranging from 401 to 885 individuals, even ranking as the most abundant family in GRU IV (Figure 15). The limited representation of Hydropsychidae in these GRUs seemed to indicate the presence of an unsuitable habitat for them. In comparing only the GRUs and the macroinvertebrate data in this instance, perhaps the lack of Hydropsychidae in GRUs I, II, and VIII could be due to increased suspended sediment, unsuitable for their catchnet-method of food collection. This could be further collaborated in future studies that include sediment data, local land use information, and water chemistry data.

GRU VII contained many burrowing families, including the majority of the Ephemeridae/ Polymitarcyidae burrowing mayflies (775/891). It also contained almost half (1316/2667) the population of the burrowing mayfly family Ephemeridae, designated with a tolerance level of 6. This family selects finer sediments in which to build tunnels, such as soft, firm clay or clay-silt [41,42]. It can cope with low oxygen levels by beating its gills to create a current through its burrow [2]. Sand, gravel, and detritus stemming from leaves and twigs are unsuitable for this mayfly's burrowing [42]. Sometimes, stream currents disturb and mix the sediments, which has been known to interfere with maintenance of Ephemeridae burrows [42]. All four sample sites within GRU IV contained Ephemeridae, as well as 5/6 (excluding site 53) in GRU VI. The comparison of GRUs to macroinvertebrate family data in this case indicated that GRU VII must have a habitat compatible with burrowing families. Perhaps, the sediment common in GRU VII is finer, such as silt or clay, and not sand. This could be further confirmed in future second-tier studies that include field data, such as water and sediment, as well as information about regional terrestrial practices.

All the Plecoptera (stoneflies) were found in GRU V, at the two sample sites farthest east. One of these, the stonefly Pteronarcyidae, was the only species collected that has the lowest tolerance of 0. Likewise, the other stoneflies were found to be sensitive, with an assigned tolerance of 1. Stoneflies are generally associated with low pollution, well-oxygenated, healthy running water, and are therefore useful in water quality and biotic integrity analyses [14]. GRU V also contained all of certain Trichoptera and Ephemeroptera families. One of the most sensitive Trichoptera families, Brachycentridae, was exclusively found in GRU V. It is a filterer preferring the lotic environment, with a tolerance of 1. It also contained all of two Ephemeroptera families, Leptohyphidae (tolerance 4) and Leptophlebiidae (tolerance 2). Through the comparison of GRU and macroinvertebrate family data only, it could be inferred that GRU V is a fairly healthy environment. It contained many sensitive species, and scored fairly well in the macroinvertebrate community indices. Further studies, including additional data, and more specific species data, could further corroborate this.

3.3.3.2. Dipteran Families

The Dipteran black fly larva family Simuliidae appeared at only 4/8 sites in GRU I, yet this GRU contained the majority (12,573/19,958) of this family and it ranked as the most abundant family of the GRU (Figure 15). A total of 6086 Simuliidae were found in GRU V, and 1153 in GRU VII. The bulk of these individuals in GRU I were found at the first sample site (Site 45; 12,236 individuals), immediately downstream of Lake Diefenbaker. These black fly larvae have a tolerance of 6, and comprise 15.67% of the total benthic macroinvertebrate community sampled here. Black fly larva are not selective consumers, and can adapt to selective pressures [41,43]. They spread silk webs to attach to substrate, stones or vegetation, for stabilization in currents, and motility [15]. These adaptations also include a wide range of behaviors such as those for avoiding predators, moving across substratum, and adapting to different flow conditions [43]. They are most often found on rocks, submerged wood, and stream bottom substrates, preferring relatively clean surfaces to which they can stick and remain stationary [41,44]. The disturbance of the Diefenbaker dam right before site 45 could explain the dominance of this insensitive family; however, this hypothesis needs further data to be validated. This cannot be attributed as a GRU characteristic, as the extremely high abundance of Simuliidae was only found at site 45.

A large number of Chironomidae midges (used in EPT/C) were collected in GRUs V (3260) and VII (3358). A total of 8189 Chironomidae were in the sample (Table A1). As burrowers, they often prefer the finer sediment in which tunnels can be formed [41]. In general, these taxa can survive in diverse habitats; the larvae are not atmospheric respirators, so they can live in large deep waters [15]. As their sensitivity of 6–8 indicates, chironomids can often withstand low oxygen levels and organic pollution [38]. GRUs V and VII had fairly good EPT/C scores and Shannon diversity scores; however, the large number of Chironomidae may have affected them in some instances. Dominance of Chironomidae is generally a negative indication of community health; more specific taxa information, as to what type of Chironomidae were comprising these numbers, could aid in determining the condition of these GRUs.

3.3.3.3. Lepidopteran Families

All 820 individuals in the order Lepidoptera were found within GRUs I and II. Lepidoptera were obtained in six out of 10 sample sites within GRUs I and II. The Lepidoptera were identified as either juvenile Grass Moths (family: Crambidae) or Owlet Moths (family: Noctuidae). Crambidae have been found to be polyphagous, meaning they feed on more than four different species of plant within at least three families [45]. Lepidopterans presiding in fluvial systems commonly graze on diatoms and periphyton [14]. They are believed to be more influenced by abiotic factors, such as food availability and geomorphology, than by biotic factors, such as trophic interactions and competition, in regards to their community structure and habitat selection [45]. The presence of these families exclusively in the first GRUs could be an indication of high plant presence, which could be substantiated in future studies that include more location-specific data. In lieu of this data, through the comparison of GRUs to macroinvertebrate family data only, the presence of Lepidopterans as indicators of stable macrophyte habitat could be further corroborated by other herbivorous species being abundant in these GRUs as well. In fact, these first typologies also contained nearly all (642/643) Valvatidae snails. Consistent with the herbivorous Crambidae and Noctuidae, Valvatidae snails have been found to prefer high vegetative cover and diversity of floating vegetation. These snails rely on gills for gas exchange and are vulnerable to anoxia [46]. GRUs I and II also contained 674/770 representatives of the caddisfly family Hydroptilidae, found in 5/10 sites. Hydroptilidae case-building caddisflies are herbivores, with a tolerance level of 4, mainly feeding on periphyton or dead leaves [14]. They both feed on and use filamentous algae to build their cases [5]. The indication of stable macrophyte coverage, and relationship between these GRUs with herbivorous families revealed a link between the model and macroinvertebrate habitat distribution.

3.3.3.4. Amphipoda Families

GRU VII contained 33,646/60,606 Amphipoda, and site 35 (GRU VII) contained 33,637 of them. This site also had half of the total amphipod family Dogielinotidae in the sample; these have a high organic pollution tolerance of 8. Due to their often-high abundance, Dogielinotidae are commonly used as test organisms in toxicology studies [14]. They are an important food source for fish, waterfowl, salamanders, and large invertebrates [47]. Site 35 housed a majority of the amphipod family Gammaridae as well. GRU V contained 19,524/60,606 Amphipoda and, within it, site 39 (GRU V) contained 16,928 of them. Site 35 was situated directly downstream from the Round Lake reservoir and site 39 was the next site downstream, which could factor into the dominance of Amphipoda at these sites. The dominance of Amphipoda at site 39 could have been caused by drift from site 35. A future study including local influences, such as reservoirs, could aid in further verifying this hypothesis and revealing more about the health of sites 35 and 39. Again, this finding points more to site variation than GRU relationships.

3.4. Conclusions

The GRU method has functioned in revealing similar geomorphological stretches along the Qu'Appelle River (Figure 14). Taxa were related to the geomorphic typologies delineated in this study. Applying GRUs in benthic macroinvertebrate habitat identification has proven to be a difficult task. Relationships between the GRUs and macroinvertebrate distribution were challenging to find, given the high site to site variation recorded. Part 1 of the study yielded more significant results than Part 2. Although direct relationships between the GRUs and macroinvertebrates were minimal, the GRU model presents valuable geomorphological information. It provides a rapid and visual method to assess any unique river basin, by classifying the river into similar geomorphological characteristics. Subsequently, the GRUs further classify them into clusters and patterns in geomorphology. This process provides a sound basis and starting point for any number of studies. It provides a useful reference point to lead informed studies as well as to monitor any future shifts in local geomorphology. The findings within the study reported here could be used to design a more effective study in the future. The delineation of GRUs before sampling (as was not done in this study) could provide a more even sampling site distribution, and more even data collected for each GRU.

The GRU model has the potential to be an effective tool to use while managing fluvial systems, and better developing field sampling campaigns. The use of the GRU model saves time and money because it can efficiently categorize river reaches, and can greatly improve the process of selecting sample sites. The findings recorded here indicate the need for additional data to be combined with the GRU model. The GRUs could be the primary step in evaluating the river, with subsequent steps including additional field data, and local influences. The delineation of the typologies themselves could include additional geospatial characteristics, to provide even more information to researchers.

The efforts demonstrated in this study were intended to use macroinvertebrate indices as a proof of concept of the GRU model. The study succeeded in showing that instream habitats can be pinpointed and related to the GRUs, but the GRUs proved to be too large to capture the high variability of the macroinvertebrate community. The GRU model has worked well in relation to more mobile fish species [11–13], but GRUs may be too coarse a resolution for the more sessile macroinvertebrate community. Part 1 of the series focused on the typology scale, which seemed to be a better fit for macroinvertebrates [17]. Future second tier studies should be able to substantiate the effectiveness of using GRUs to identify benthic macroinvertebrate habitat by further relating the two through a more comprehensive study. Such an analysis may consider the inclusion of river depth, sediment, vegetation, and local influences (*i.e.*, nearby reservoirs, industry, municipalities). Studies could also focus on geomorphic typologies as related to macroinvertebrates, rather than the clustered GRUs, as was carried out in Part 1. Additional studies may also consider comparing these geospatial factors to more specific macroinvertebrate data, identified to genus or species. More data, collected in line with the GRU model and after it has been delineated, would be a great asset and aid in the quality of analysis. The highly dynamic nature of both the river and macroinvertebrate community make it difficult to create a simple method to link the GRUs to the macroinvertebrates.

The Qu'Appelle River will further be studied with a water quality model currently being developed to provide water temperatures and dissolved oxygen concentrations at the centerline points used in the model. Through doing so, the objective is to find a practical and useful way to use the macroinvertebrate data discussed here, in light of geomorphology and climate change. This has been purely a desktop study comparing macroinvertebrate family data to GRUs; the desktop research is well suited as a basis for future studies to further understand the Qu'Appelle River system. Additionally, these findings reveal potential for the GRU model to be applied to other river systems as an efficient resource management method. The use of GRUs can be a valuable precursor for more detailed habitat studies. Through categorizing fluvial systems by geomorphological characteristics, GRUs can provide insight into instream habitat complexity, availability, and connectivity as a whole.

Author Contributions: Meghan K. Carr and Karl-Erich Lindenschmidt conceived and delineated the Geospatial Model; Iain D. Phillips contributed Macroinvertebrate data; Anna G.N. Meissner analyzed the data and wrote the paper, with editing and contribution from all the authors.

Appendix A

<u>Table A1. Macroinvertebrate Taxa List:</u> Qu'Appelle River macroinvertebrate taxa, including order, family, functional feeding group, and count.

Qu'Appelle River Macroinvertebrate Taxa List							
Order	**Family**	**Functional Feeding Groups**	**Total**	**Order**	**Family**	**Functional Feeding Groups**	**Total**
Acari	*Acari*	Predators	15		*Ancylidae*	Scrapers	14
	Amphipoda	Collector Gatherers	14269.91		*Gastropoda*	Scrapers	1
Amphipoda	*Gammaridae*	Collector Gatherers	2046.05		*Hydrobiidae*	Scrapers	165
	Dogielinotidae	Collector Gatherers	44289.81	Gastropoda	*Lymnaeidae*	Scrapers	140
Total			60605.76		*Physidae*	Scrapers	3825.57
	Dytiscidae	Predators	106		*Planorbidae*	Scrapers	506
	Elmidae	Collector Gatherers	122.82		*Valvatidae*	Scrapers	643
	Gyrinidae	Predators	70	Total			5294.57
	Haliplidae	Shredders	43		*Corixidae*	Herbivores	3021.56
Coleoptera	*Hydraenidae*	Scrapers	4	Hemiptera		Predators	586.02
	Hydrophilidae	Collector Gatherers	10		*Notonectidae*	Predators	14
		Herbivores	1	Total			3621.58
		Predators	1	Hydrachnidia	*Hydrachnidia*	Predators	53
		Shredders	1		*Crambidae*	Herbivores	546
Total			358.82	Lepidoptera	*Lepidoptera*	Herbivores	10
Collembola	*Collembola*	Collector Gatherers	1		*Noctuidae*	Herbivores	264
Decopoda	*Cambaridae*	Omnivores	166	Total			820

Table A1. *Cont.*

Order	Family	Functional Feeding Groups	Total	Order	Family	Functional Feeding Groups	Total
	Athericidae	Predators	2	Malacostraca	*Cambaridae*	Omnivores	257
	Ceratopogonidae	Predators	167.04	Nematoda	*Nematoda*	Predators	15
	Chironomidae	Collector Gatherers	7747.06		*Coenagrionidae*	Predators	165
		Predators	442.26	Odonata	*Gomphidae*	Predators	16
	Diptera	Collector Gatherers	18		*Lestidae*	Predators	16
Diptera	*Empididae*	Predators	39	Total			197
	Leptoceridae	Shredders	22	Oligochaeta	*Oligochaeta*	Detritivores	1514.70
	Simuliidae	Filterers	19958	Ostracoda	*Ostracoda*	Filterers	8
	Stratiomyidae	Collector Gatherers	1	Pelecypoda	*Pisidiidae*	Filterers	691.10
	Tabanidae	Predators	12	Pharyngobdellida	*Erpobdellidae*	Predators	24
	Tipulidae	Predators	10		*Perlidae*	Predators	5
				Plecoptera	*Plecoptera*	Shredders	1
Total			28418.35		*Pteronarcyidae*	Shredders	10
				Total			16
	Baetidae	Scrapers	3088.10				
	Caenidae	Collector Gatherers Scrapers	491	Rhynchobdellida	*Glossiphoniidae*	Predators	20
		Filterers	279				
	Ephemeridae	Collector Gatherers	2666.82		*Brachycentridae*	Filterers	238
	Ephemeridae/ polymitarcyidae	Collector Gatherers	891		*Hydropsychidae*	Filterers	2748.02
	Ephemeroptera	Scrapers	353.27		*Hydroptilidae*	Herbivores	770
Ephemeroptera	*Heptageniidae*	Collector Gatherers	437		*Leptoceridae*	Collector Gatherers	54
		Scrapers	1189.82			Herbivores	16
	Isonychiidae	Filterers	4	Trichoptera		Shredders	92.02
	Leptohyphidae	Collector Gatherers	79		*Phryganeidae*	Shredders	31.02
	Leptophlebiidae	Collector Gatherers	52.85		*Polycentropodidae*	Filterers	8
		Scrapers	2			Predators	20
	Polymitarcyidae	Collector Gatherers	82		*Trichoptera*	Shredders	6
Total			9615.86	Total			3983.05
			Grand Total				**115695.80**

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4. Discussion

4.1. Summary of Chapter 2

In the first manuscript (Chapter 2), Qu'Appelle River macroinvertebrate genera data were compared to the geospatial model at the typology classification. The model provided a colour coded map of the river, with each colour signifying one of four total typologies. These four typologies were the result of a Principal Component Analysis (PCA) that clustered geomorphological data and identified patterns within it. The geomorphological data that was inputted to the PCA included the stream width, slope, fractal dimension, and sinuosity at every 50m point along the river centerline. In sum, the typologies (denoted by colour) represented reaches with similar fluvial geomorphology. Chapter 3 takes this model to the next step, by further classifying the typologies into Geomorphic Response Units (GRUs). The macroinvertebrate data (sampling took place independently and prior to the delineation of the geospatial model) was collected at 35 sites along the Qu'Appelle River. The resulting data set from this field collection comprised of 128 classifications at the genera level; this data was then compared with the geospatial model. Since the data collection was completed before and separate from the identification of typologies, sample sites were not evenly distributed amongst them. Typology 0 contained 14 sites, Typology 1 had 11 sites, while Typology 2 and Typology 3 have 5 sites each. According to the PCA, Typology 0 corresponded to narrow regions of the river with high slope and fractal dimension, but showed no relationship to sinuosity. Typology 1 was associated with narrow reaches of high slope, but low sinuosity and fractal dimension. Typology 2 indicated narrow areas of high sinuosity and fractal dimension, with no relation to Slope. Typology 3 contained many of the Qu'Appelle lakes; likewise, it corresponded to high stream width with low sinuosity, slope, and fractal dimension.

As the Ephemeroptera, Plecoptera, and Trichoptera (EPT) macroinvertebrate orders are often grouped for comparison in aquatic communities, these were compared amongst the Qu'Appelle typologies as well [1,2]. Typology 0 contained the highest total number of EPT, representing 35% of the total community within the typology. Typology 1 housed the second highest total of EPT; however, these only represented 6% of the total community within the typology. Typology 2 contained the lowest total EPT, but they represented the highest percent (52%) of any typology. Typology 3 contained 18% EPT, with the second lowest total.

In order to explore the macroinvertebrate genera distribution amongst the four typologies, a Kruskal-Wallis analysis of variance on ranks was completed using the R 3.1.2 statistical software [3]. The large data set was narrowed down for this analysis, with the criteria of the genera being represented by ≥ 30 individuals sampled, and collected in > 9% (3 or more) of sampling sites, indicating more common genera. Where significant outcomes resulted (P Value ≤ 0.05), *post hoc* pairwise multiple comparisons were executed, with a one-tailed Dunn test and Bonferroni P Value correction for multiple pair tests. Graphical analyses were accomplished through the R 3.1.2 statistical software as well [3]. The Kruskal-Wallis test revealed significant distribution differences for 6/60 genera tested. Subsequently, the *post hoc* pairwise multiple comparisons identified 4 of these genera to have significant differences between typologies. These were *Dubiraphia* (riffle beetle), Heptageniidae (flat headed mayfly identified to family level only), *Heptagenia* (flat headed mayfly genus), and *Sigara* (water boatman). All four of these groups showed a preference to Typology 0.

The community distribution within Typology 0 appeared to be quite healthy and evenly distributed. At the genus level, Chironomidae represented 19% of the community, followed by *Hyalella* (15%), Corixidae (6%), Baetidae (6%), *Hexagenia* (6%), and Oligochaeta (5%), and the grouped EPT within typology represented 35%. Typology 0 was dominated by the collector gatherer functional feeding group (46% of the typology community), and housed 49% of the total Qu'Appelle River detritivores. Typology 0 corresponded to narrow reaches of high slope and fractal dimension. The flat headed mayflies (Heptageniidae; *Heptagenia*) with significant predilections to Typology 0 were found nearly exclusively there, followed distantly by Typology 2. These mayflies are suited to lotic habitats, and can be found clinging to substrates as suited by their flat and streamlined appearance [4,5]. As scrapers, they thrive where sunlight can penetrate and encourage the growth of biofilm and periphyton for food sources [1,5].

The water boatman (*Sigara*) with significant preference to Typology 0 were not as exclusively found there, with a secondary preference to Typology 3. These are herbivorous swimmers, favoring areas with vegetation readily available to consume [2]. The riffle beetle (*Dubiraphia*) mostly prefers Typology 0, also followed by Typology 3. They are collector gatherers; similar to the flat headed mayflies, Dubiraphia cling to substrate, but differ in their reliance on organic matter as a main food source [2]. The only positive relationship within Typology 3 was towards stream width, and includes many large water bodies. The community within this typology was dominated by *Hyalella* (37%) followed by a more proportional distribution of other genera, including 18% grouped EPT.

In conclusion, Chapter 2 identified four benthic macroinvertebrate genera with significant tendencies towards certain geomorphic typologies within the Qu'Appelle River. Although only 4/60 genera showed this relationship, the potential for this geospatial model to be used as a means to pinpoint macroinvertebrate habitat has been shown.

4.2. Summary of Chapter 3

As a continuation of the first article, the second article further classified the geomorphic typologies into geomorphological response units (GRUs) and compared them with the family level (63 families) macroinvertebrates data. The geospatial typologies were visually evaluated for spatial patterns, resulting in 8 GRUs within the Qu'Appelle River depicting various repetitive groupings of typologies. Instead of using a statistical evaluation method, like in Chapter 2, the macroinvertebrate analysis focused initially on three common indices. These were the EPT/C Ratio, Shannon Diversity Index, and the Family Biotic Index (FBI). All three indices were completed for each macroinvertebrate site. The EPT/C ratio measures the aforementioned Ephemeroptera, Plecoptera, Trichoptera (EPT) orders as compared to the Chironomidae (C). Where the EPT are often considered more sensitive and indicate a healthy system, the Chironomidae (midges) can survive in many environmental conditions [4,6]. The EPT/C ratio measures the evenness between these two groups, as an indication of general community health [7]. The Shannon Diversity Index indicates biodiversity, including evenness and richness, to measure community health at a site [2]. The Family Biotic Index, developed by Hilsenhoff (1988), uses designated tolerance values of macroinvertebrate families towards organic pollution, to indicate water quality and degree of organic pollution at a site [8].

With the aim of testing the GRU model against macroinvertebrate data only, no tertiary data (i.e. sediment, local influences) were included. Sample sites available within each GRU varied significantly, with 0 sites within GRU III and up to 9 sites in GRU VI. Community makeup from site to site shifted considerably as well, ranging from 12 to 40,227 individuals at one site. Consequently, the macroinvertebrate indices results varied substantially from site to site as well, revealing minimal patterns in the context of GRU distribution. For this reason, the study was shifted to include more qualitative evaluations of each GRU. The community (by family) of all the sites in each GRU were examined, with the aim of pinpointing noteworthy relationships between certain families and corresponding GRUs; several such relationships were found.

Hydropsychidae (net spinning caddisflies) were quite rare within GRUs I, II, and VIII (0 to 21 individuals), but were abundant (401 to 885 individuals) in the rest. Without considering local influences, it was difficult to pinpoint why this might be. As net-spinners, some studies suggest high total suspended sediment may interfere with the nets they use to gather food [1,4,9-11]. Other researchers say that these caddisflies can be adaptive (cleaning, moving, rebuilding) towards these types of environmental intrusions, depending on the water velocity, net mesh sizes, spatial microhabitat characteristics, particle size, type, and load, as well as the duration of particle exposure [12,13]. GRUs I, II, and VIII together included all the typologies, so the Hydropsychidae distribution was likely due to other influences, besides the GRU impact. The Simuliidae (black fly larva) family is highly adaptive and tolerant, subsequently making up 15.67% (19,958 individuals) of the total community found within the Qu'Appelle River [14-16]. The very first site, just downstream of the dam at Diefenbaker, was found to contain 12,573 of these Simuliidae pointing to the importance of local influences as well. The Amphipoda order (scuds) are also rather tolerant, abundant, and adaptable organisms [1,2]. Site 35, directly downstream of the Round Lake Reservoir, was home to 33,637 out of the total 60,606 amphipods present in the total sample. Accordingly, it also contained the highest total (40,227) found at any sampling site. The following site contained another 16,928 of the amphipods, indicating possible drift effects. These sites lie in different GRUs, and the populations do not compare within other samples in the GRUs, indicating the need to include site-specific information as well.

Families within the Lepidoptera order held a stronger relationship to GRUs than most other macroinvertebrate taxa. All the Lepidoptera were found within GRUs I and II, which held a similar typology makeup and river locations. The Lepidopterans are all herbivores, relying on vegetative presence for food [2,17]. Other families, which were nearly exclusive to these GRUs as well, including Valvatidae (snails) and Hydroptilidae (caddisflies) rely on plant presence as well. Valvatidae prefer vegetated areas, as they rely on gills and are vulnerable to anoxia [18]. The Hydroptilidae are herbivorous case-makers that both feed on and use filamentous algae to build their cases [2,9].

Although the macroinvertebrate indices did not seem to correlate to the GRUs, relationships were found qualitatively between GRUs and macroinvertebrate families. Due to the high site variation, additional data would be valuable in order to seek and strengthen said relationships. The lack of evenness of sampling site distribution amongst GRUs may have also negatively influenced these results. Geomorphological response units at the very least provided a valuable first step, by mapping geospatial data that can then be applied to further data points.

4.3. Additional Data

Following the completion of the preceding papers, some Qu'Appelle River field observation vegetation and sediment data became available. Site 45 (Typology 1, GRU I) was notable for containing 12,236/19,958 Simuliidae (black fly family), and for being the first sampling site, downstream from Diefenbaker. This site contained about 80% mud, 10% sand, and 10% cobble. The site also contained 100% submerged macrophytes, and 80% vegetated banks (Figure 16). GRUs I and II dominated the first stretch of the river; they contained mostly mud as well, and highly vegetated banks. GRU I contained the highest amount of submerged macrophytes by far, at an average of 36%. GRUs I and II held the most notable relationship to several herbivorous macroinvertebrates in Part 2, indicating the presence of vegetation. All of the Lepidopteran order were found in these GRUs, as well as nearly all the Valvatidae (snails) and Hydroptilidae (caddisflies). This observation insinuated there might be a high vegetative presence in these GRUs.

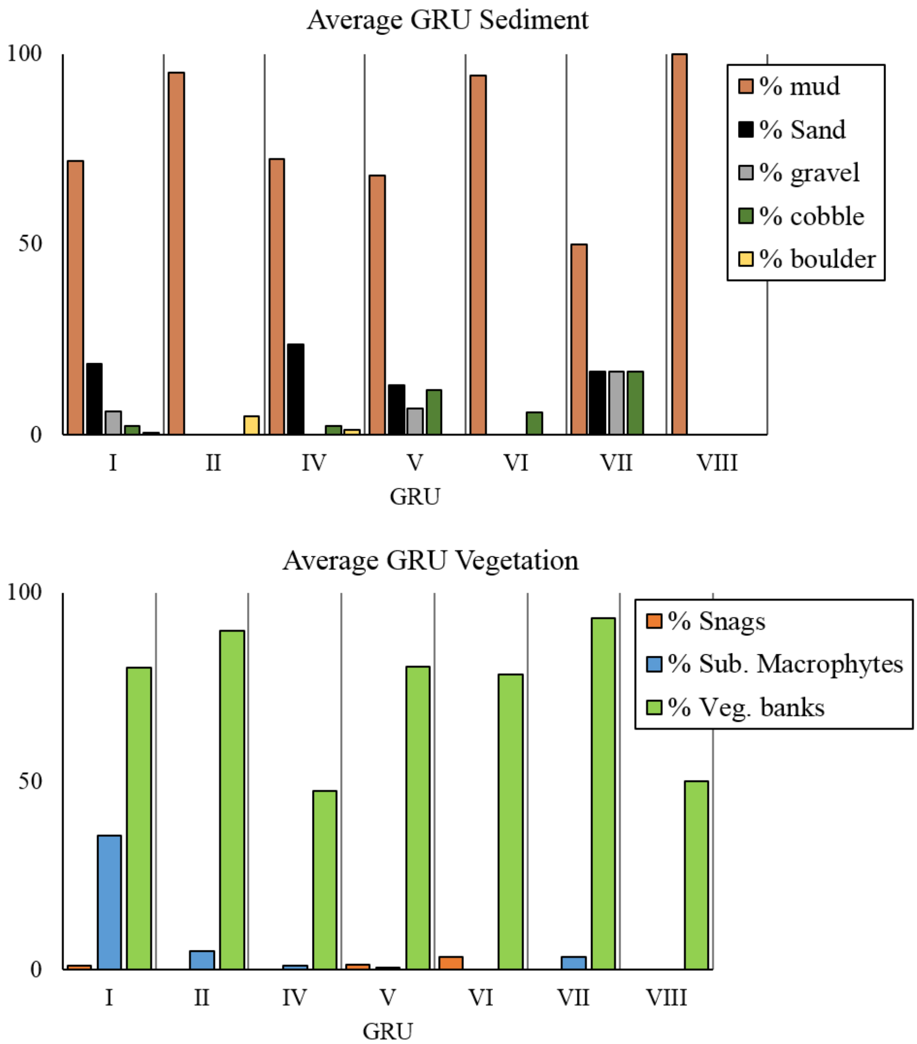

Figure 16. GRU Habitat Types: Observed at macroinvertebrate collection sites, as sorted by Geomorphological Response Unit (GRU) designation in the Qu'Apelle River.

According to Newman (1991) aquatic Lepidoptera, as aquatic herbivores that are related to terrestrial groups, prefer to feed on aquatic macrophytes, whereas aquatic herbivores from predominantly aquatic groups are detritivores [4,19]. Furthermore, aquatic lepidopteran larvae are believed to feed nearly entirely on live macrophytes [20]. The Qu'Appelle Dam likely increases opportunity for aquatic macrophyte growth in these regions, since flowing water is advantageous to aquatic plants as a source of oxygen [21].

Site 35 (Typology 1, GRU VII) contained the highest total individuals (40,227) and contained 33,637/60,606 of the total Amphipoda families. This site was downstream of the Round Lake Reservoir, and was followed by site 39 (Typology 1, GRU V). Site 39 contained another 16,928 Amphipoda; together the two sites accounted for 83% of the total Amphipoda. Site 35 contained 50% sand, and 50% gravel, whereas site 39 had 100% sand (Figure 17). Dams influence the biological and physical nature of the habitats surrounding them. The complexity of instream habitats is depleted by the existence of dams, which prompts the homogenization of fluvial habitats and a decline in taxa richness [5]. In fact, Lehmkuhl (1972) observed drastic community differences surrounding the Qu'Appelle dam, with only nine Chironomidae present at their sampling site below a dam outlet and a decline in macroinvertebrate richness still evident 70 miles downstream [5,22]. It is a common occurrence for the benthic macroinvertebrate community downstream of a dam to demonstrate a reduced community [5].

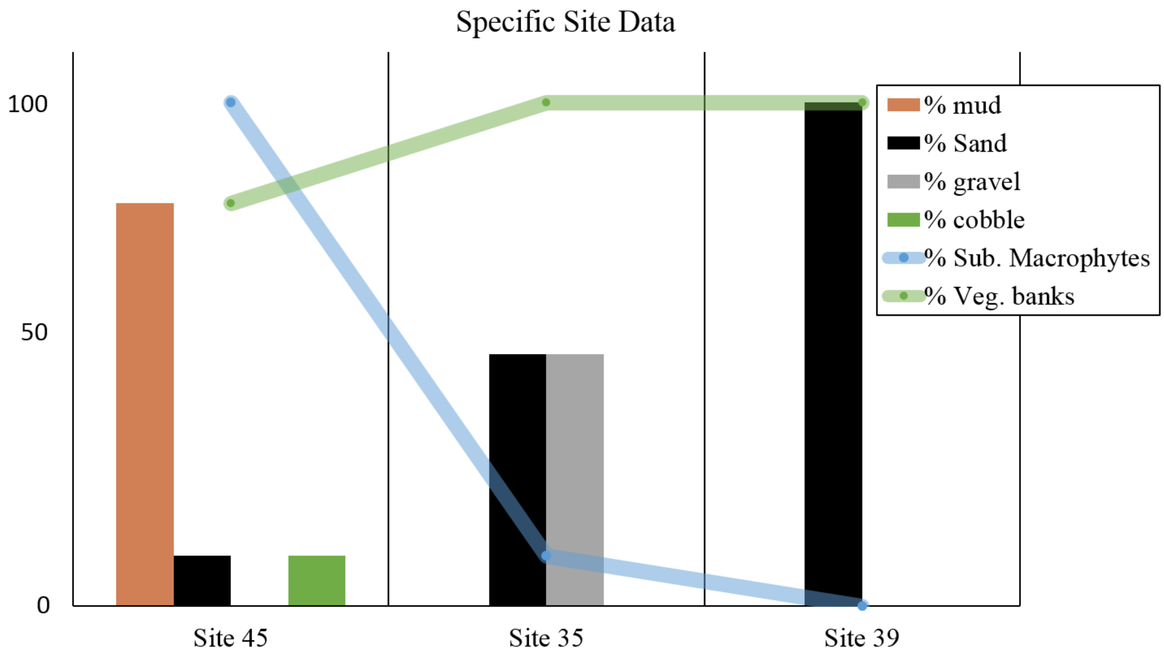

Figure 17. Habitat Types at Specific Sites: Observed at three specific macroinvertebrate collection sites of interest in the Qu'Apelle River.

Both sites 35 and 39 had 100% vegetated banks, and site 35 had 10% submerged macrophytes. Typology 1, in which both of these sites were found, indicated more straight and narrow reaches with high slope and low fractal dimension. Typology 2 was the only group indicating high sinuosity; correspondingly, it had the highest average percent of muddy sediment (Figure 18). Regions with high sinuosity tend be predominantly composed of small grain size bed material (i.e., mud) [23].

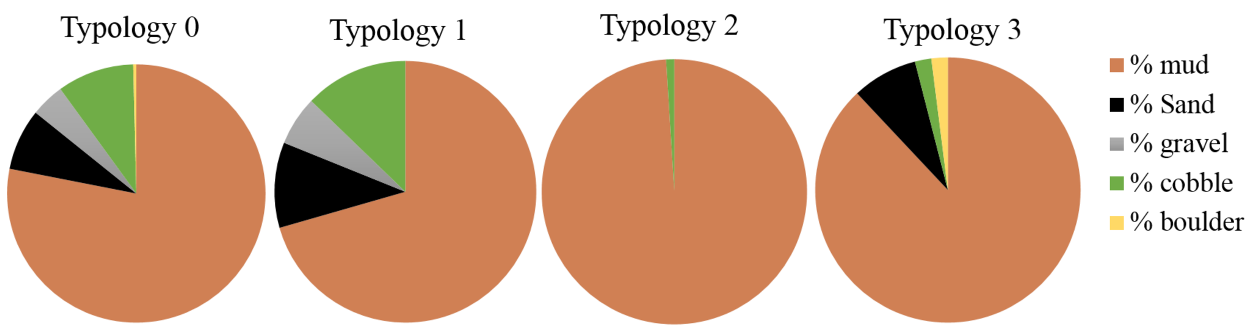

Figure 18. Typology Sediment Makeup: Average sediment makeup within each geomorphic typology of the Qu'Appelle River.

4.4. Conclusions

4.4.1. Limitations

The geospatial model seemed to fit macroinvertebrate data better at the typology designation level, rather than with GRUs, although neither revealed simple or perfect relationships. It is not surprising that this was the case, as ratifying the characteristically erratic relationship between benthic macroinvertebrates and the vast geomorphological patterns they exist within is a difficult task. Nevertheless, this study has shown that the geospatial model can aid in the identification of these patterns and macroinvertebrate habitat preferences. Seeking a method of better understanding the relationship between macroinvertebrates and geospatial pattern will fill a hole in current water resource management standards. The GRU method has succeeded in relating fish species to geomorphology [24-26]; perhaps the GRU classification provides too coarse of a resolution for macroinvertebrates, as a more sessile community than fish.

Supplementary data, collected in coordination with the model delineation would greatly enhance the quality of analysis for instream habitat studies. Furthermore, the highly dynamic nature of fluvial systems, as well as macroinvertebrate distribution, make the goal of linking fluvial geomorphology to macroinvertebrates more challenging. The manuscripts presented here, particularly in Chapter 3, show the necessity of additional data to be combined with the geospatial model. Habitat studies, especially towards macroinvertebrates, do not succeed when comparing only the desktop model to the data set. The inclusion of additional information, such as presence of reservoirs and nearby industry, would be helpful additions. Tertiary data points, such as sediment data, would also be useful.

The geospatial model used here would be most effective when it is the first step of a research project, meaning the remaining exploratory steps would be taken in the context of the typologies or GRUs. For example, macroinvertebrate sampling sites could have been distributed evenly amongst the different geomorphological classifications, eliminated the disparity amongst sample sites and thereby encouraging a comprehensive and clear results. If it were possible, researchers could also sample in the context of seasonality, in order to better understand every aspect of what may be influencing the macroinvertebrate community's distribution among the GRUs or typologies. Increasing the parameters inserted to the PCA might help to better understand the distribution as well.

4.4.2.. Future Work

The geospatial map provides researchers with a time efficient and affordable means of information sharing. As a rapid and visual assessment of the geomorphology of a channel, it delivers a basis of valuable information from which to expand upon. Possibilities to expand on the model span far beyond just the instream habitat studies pursued so far. It could also be used as a tool for researchers to model a study after, and to choose sampling sites in relation to the varied geomorphology of the region. For water management, the GRUs or typologies could aid in selecting locations for new monitoring stations, and as a visual baseline to monitor the region's future shifts in geomorphology. These papers, the model, and macroinvertebrate data will be used in a future study that will use a water quality model to try and predict the effects of climate change on instream communities. A second Principle Component Analysis will combine the four geomorphological characteristics (Sinuosity, Slope, Fractal Dimension, Stream Width) with the average water temperature and dissolved oxygen levels at each 50 m centerline point. The model will then be used to predict how a site of like geomorphology (same typology or GRU) would react to a temperature increase. This will be accomplished by comparing the instream community of two reaches in the same GRU or typology that have differing temperatures.

The model has already been used in river ice jam studies in the Slave River Delta (SRD) [27] as well as in the pursuit of the Slave Watershed Environmental Effects Program (SWEEP), which is a monitoring program with the aim of creating effective tools for the local communities amid present and future environmental distress [28]. The model has also been used in the SRD in collaboration with the Northwest Territories Cumulative Impact Monitoring Program (CIMP), which aims to improve on local cumulative impacts monitoring. The delta region has an amplified need for effective monitoring tools, as industry (mining, oil and gas, proposed pipelines) pressures increase [29]. The geospatial model provides a baseline of data, which can be used in combination with present data and as a tool to monitor the geomorphology of the region in the future. Within these projects, the model is being combined with isotope data, and used to research contaminants and food web interactions in the delta. There, the model is contributing to the pinpointing of instream habitats crucial to the various lifecycle points for fish species, as well as locations where dangerous contaminants may settle.

4.4.3. Sustainability

The geospatial model presented here is a valuable tool for fisheries and watershed management. The Qu'Appelle River basin is home to several species at risk, including the federally protected Bigmouth Buffalo (*Ictiobus cyprinellu*). This species maintains low population numbers throughout Canada with the exception of the Qu'Appelle River, which has a commercial fishery [30]. Bigmouth Buffalo live in benthic aquatic regions, prefer slow currents, and feed on plankton and benthic aquatic invertebrates [30,31]. Not only can the model help to pinpoint key habitats for species such as this, but pursuing macroinvertebrate studies will aid in the management of this threatened species as well. Benthic macroinvertebrates are a critical dietary staple for many fish and waterfowl and as such, are a crucial part of riverine ecology as a whole. A good example of this is the white-winged scoter, which has been found in Saskatchewan to prefer a diet consisting nearly exclusively of the amphipod *Hyalella azteca* [32]. Identifying and retaining reaches that are conducive to the macroinvertebrates other trophic levels feed on may help to sustain the vulnerable population. Determining key habitats for aquatic biota is vital for effective and sustainable long-term management goals.

The use of a GRU or typology map is an easy and quick method of assessing fluvial systems, and could be incredibly beneficial to communities. The geomorphology of the river is disseminated into a colour-coordinated map of the instream habitats, which is easy for all stakeholders to understand and read. It is also incredibly effective for modern rivers that generally have altered geomorphology due to human activities. As a flexible method, the model is adaptable to a variety of fluvial systems. Local stakeholders can then use the geospatial model to gain initial information as to the current state of their local stream. Subsequently, communities can carry out their own primary analysis of watershed quality, with the addition of geospatial data. In the Slave River Delta projects, the geospatial model is combined with both isotope data and traditional ecological knowledge [28,29]. Community members are involved in every aspect of the project, such as decision making, field collection, and even the identification of sampled macroinvertebrates. Traditional ecological knowledge is collected and included in the projects as well. This collective view of river studies is a more sustainable approach because it places more power in the communities, garnering a sense of respect, thus strengthening the overall analysis and understanding of the watershed.

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