GEOSPATIAL MODELLING OF PRAIRIE RIVERS: LINKING PHYSICAL INDICATORS OF FISH HABITAT TO LARGE SCALE GEOMORPHIC PATTERNS IN RIVER SYSTEMS USING GEOMORPHIC RESPONSE UNITS (GRU)

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ABSTRACT

Rivers are inherently dynamic environments with fluctuations in water quality, hydrology, connectivity and geomorphology. Though geomorphology has long been recognized as an important driver defining biological, ecological, and physical habitat characteristics of rivers, a readily applied classification tool that links such characteristics has been lacking. The Geomorphic Response Unit (GRU) method provides a novel approach to identifying large scale patterns in geomorphic character that provide a link between the hydrological regime and different habitat types to which species respond. Specifically, I investigated whether Geomorphic Types and GRUs are related to the distribution and abundance of different fish species, reflecting unique physical habitat characteristics of individual GRUs. The thesis chapters are manuscript based. The second chapter identifies relationships between specific Geomorphic Types, identified using the Geomorphic Response Unit (GRU) methodology, and Lake Sturgeon overwintering locations in the South Saskatchewan and Saskatchewan Rivers. Habitat selection ratios suggest that Lake Sturgeon in the Upper South Saskatchewan River significantly selected for one of seven possible Types for overwintering. Logistic regression results found both Type 0 and Type 4 predicted significantly higher Sturgeon presence than all other Types ($P = < 2e-16$ for both). The third chapter examines relationships between GRUs and abundance of both mature and immature Carmine Shiner in the Birch River, Manitoba. Differences in the median mature Carmine Shiner CPUEs among the GRUs are not statistically different (Kruskal-Wallis test $H = 1.723$; $df = 3$, p value $= 0.632$), though interesting qualitative relationships were identified which may inform further studies. The fourth chapter investigates whether GRUs derived using a large scale network approach are linked to the abundance of specific fish species in the Assiniboine River, Manitoba. A Kruskal-Wallis test identified significant differences in CPUE among GRUs for 10 of 14 tested species. Post-hoc pairwise multiple comparisons using Dunn's Method with Bonferroni p-value correction for multiple paired tests isolated the GRUs that were different from one another. Overall, my findings suggest that Geomorphic Response Units (GRU) are an effective means of identifying patterns in geomorphic structure within Prairie Rivers at both reach and segment scales. Further, I identified links between both Geomorphic Types and GRUs and patterns in abundance of various fish species covering a wide range of life history traits. These findings suggest that GRUs have potential as a valuable fisheries habitat management tool, increasing efficiency of monitoring efforts through quantification of habitat availability, connectivity, and complexity in Prairie River systems.

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1.1 Introduction

1.1.1 Response Unit Theory and Development of GRUs

Response units have been used extensively to organize large scale hydrological and geomorphological processes into smaller, computationally manageable units (Flügel 1997; Becker and Braun, 1999; Cammeraat, 2002; Sidorchuk *et al.*, 2003; Güntner and Bronstert, 2004). Cammeraat (2002) states that such units should be identifiable in a proper and preferably easy way using key indicator variables. Response units are commonly used to delineate areas of similar hydrological response within a watershed based on geomorphological (e.g. soil type, geology), topological (e.g. convexity, concavity, slope and aspect) and biological (e.g. vegetation) landscape characteristics paired with temperature and precipitation data to determine response in an output of interest such as runoff (Flügel, 1997; Becker and Braun, 1999; Devito *et al.*, 2005). Generally, the majority of response unit characteristics can be derived from readily available Geographic Information System (GIS) data layers with moderate effort. In terms of delineating units of similar response within riverine ecosystems specifically, Thorpe *et al.* (2006 and 2008) have developed Functional Process Zones (FPZ). Their Riverine Ecosystem Synthesis (RES) views rivers as longitudinal arrangements of functionally and structurally similar hydrogeomorphic patches formed by flow and geomorphology characteristics. The theoretical framework associated with FPZs is intensive and lacks a well-defined, readily applicable model for identifying such units.

In contrast, the Geomorphic Response Unit (GRU) method developed by Lindenschmidt and Long (2012) is an efficient desktop approach for determining areas of similar geomorphological and hydrological response. Geomorphological patterns and trends operate at inter-annual to decadal temporal scales and are associated with long term biological outputs (Lindenschmidt and Long 2012). A GRU essentially represents the structure of a river segment and provides a link between the hydrological regime and physical habitats to which species respond. The planform channel pattern parameters sinuosity, fractal dimension, slope and stream width are extracted from stream network and DEM GIS layers. Variable values are extracted every 50m along the river and principal component analyses (PCA) are preformed to determine orthogonal eigenvalues for each parameter (Lindenschmidt and Long 2012). Eigenvalues are converted to binary values and each unique combination of values across retained components yields a different geomorphic Type that can be linked back to each centerline point. Types then represent unique characteristics of the input variables and identify differences and similarities in geomorphological characteristics along the length of the river or network of interest. Patterns in the associations of Types create emergent patterns at a larger scale and allow the delineation of GRUs.

1.2 Objectives and Thesis Structure

The overall objective of this thesis is to investigate the efficacy of the Geomorphic Response Unit (GRU) method in identifying large scale patterns in river channel pattern that are related to the distribution of fish species in Prairie Rivers. Contributions to the refinement of the original model were: 1) the development of a GIS protocol for river delineation using the ArcMap graphical user interface, 2) testing whether the model relates to significant differences in the distribution and abundance of different fish species, and 3) validating and critiquing the present iteration of the GRU model. This thesis is presented in the ‘dissertation by manuscript’ style and follows the guidelines set out by the College of Graduate Studies and Research. The research complied with ethics requirements for the use of animal subjects. The introductory chapter serves to provide a theoretical basis for the development and application of the GRU method. Following this introductory chapter the thesis is organized into three manuscripts, each of which is presented as a single thesis chapter.

The objective of the first manuscript (Chapter 2), “Development of geomorphic types for identifying Lake Sturgeon (*Acipenser fulvescens*) overwintering habitat in the Saskatchewan River System” was to identify whether Lake Sturgeon overwintering locations in the South Saskatchewan and Saskatchewan Rivers are associated with specific Geomorphic Types identified using GRU methodology.

The objective of the second manuscript (Chapter 3), “Geospatial modelling of the Birch River: Distribution of Carmine Shiner (*Notropis percobromus*) in Geomorphic Response Units (GRU)” was to determine whether specific GRUs are associated with mature or immature Carmine Shiner observations in the Birch River, Manitoba.

The objective of the third manuscript (Chapter 4), “Identifying Links between Geomorphic Response Units (GRU) and Fish Species in the Assiniboine River, Manitoba” was to identify whether GRUs derived using a large scale network approach are linked to the abundance of specific fish species in the Assiniboine River, Manitoba.

The final thesis chapter (Chapter 5), “Conclusions-Understanding links between Geomorphic Response Units and Prairie Fish Species” presents a synopsis of significant findings from the three manuscripts and discusses the contribution of these findings to fisheries management. I also address uncertainty, assumptions, and validation and recommend future research to improve our understanding of relationships between fish habitat and GRUs. Finally, I discuss the potential for GRUs to contribute to the sustainability of Prairie Fishes.

1.3 Background Information

1.3.1 Geomorphological processes

Fluvial geomorphology examines river channel morphology resulting from the interaction of fluid flow and erodible channel boundary materials (Knighton 1998). Such interactions are highly spatially and temporally variable and involve the processes of sediment entrainment, transport, and deposition which occur as the channel boundary maintains coherent structure by withstanding and adjusting to a wide range of forces. Boundary materials may be non-cohesive and readily erodible, or cohesive and highly resistant to erosion. Bedrock channels or those with high silt or clay content are much more cohesive than sand and gravel and therefore adjust more slowly. Flow quantity and timing is intrinsic to the ecological integrity of river systems as these parameters are correlated with many critical physicochemical river characteristics such as channel geomorphology, water temperature, water quality, and habitat diversity (Resh *et al.* 1988, Power 1995, Poff *et al.* 1997). Climate is a primary control influencing river hydrology and geomorphology as it impacts the precipitation timing and quantity which establishes the hydrologic character of a drainage basin (Junk *et al.* 1989, Schumm 2005) as well as the presence of vegetation which stabilizes channel banks and hillslopes (Schumm 2005). Geomorphological features of rivers such as bed form, sediment transport, and the relative position of bed and banks, can be altered by changes in flow regime which influence processes of erosion and deposition (Katopodis 2003). The rate of sediment transport is greatest during dominant or effective discharge, approximately bankfull flood (Allan and Castillo 2007).

River flood events can occur when bankfull discharge is surpassed due to snowmelt, drainage, extreme weather events, obstructions *etc.* Both drainage basin and channel factors contribute major geomorphic response to flooding and can greatly alter the physical structure of rivers (Schumm 2005). Geomorphic response dictates modifications to the floodplain, channel pattern and channel geometry. Floodplain modifications include scour, fine-grained sediment deposition, coarse overbank gravels and debris flow levees (Kochel 1988). Channel widening, scour, and enchannel deposition modify channel geometry while channel pattern changes such as meander cutoffs, braiding, and chutes may occur (Kochel 1988).

From a geomorphological perspective, Schumm (2005) organizes river variability and complexity into four main categories: Upstream controls, fixed local controls, variable local controls and downstream controls related to gradient change. Upstream controls include tectonics, which influences landscape relief and is an important factor in determining river type, lithology, or physical geological characteristics of the catchment, and climate which is a controlling factor of hydrology (Schumm 2005). Fixed local controls include bedrock, tributaries, active tectonics, and valley morphology. Bedrock can influence river width and meander migrations, while tributaries can potentially introduce large amounts of sediments and flow substantially impacting channel morphology and ecology (Schumm 2005, Knighton1987). Active tectonics can cause local changes in stream gradient which result in stream aggradation or degradation while channel shape, sinuosity and bed material characteristics may also shift (Schumm et al 2000). Variable local controls include floods, vegetation, and accidents (log jams, ice processes, earthquakes *etc.*). Anthropogenic influences can also play a large part in river variability and complexity and depending on the sensitivity of a given river, can incite changes ranging from negligible to drastic (Schumm 2005).

1.3.2 Geomorphology and Ecology

Geomorphology has often been recognized as an important factor in defining biological (Walters *et al.* 2003; D'Ambrosio *et al.* 2009) and ecological characteristics of rivers (Thorpe at al. 2006; Bizzi and Lerner 2012) and ultimately the shaping of aquatic habitat (Bizzi and Lerner 2012, Duncan *et al.* 2011). The term habitat refers to a location or environment where an organism is most likely to be found and can include physical, chemical and biological characteristics that allow the organism to achieve various life history requirements such as spawning, feeding, and overwintering. Throughout this thesis habitats are considered in terms of physical characteristics as they relate to geomorphological features and processes. Retention of particulate organic matter (POM) and course particulate organic matter (CPOM) are influenced by geomorphic features (Allan and Castillo 2007). In large rivers flood plains are often the primary location of POM deposition and storage while studies in smaller order rivers have found that meandering reaches (James and Henderson 2005) and pool features (Hoover *et al.* 2006) retain larger quantities of CPOM in comparison to straightened sections or areas with greater velocities and shallower depths. The ecological significance of geomorphic features is reflected in their associations with habitats of different flora and fauna (Thomson *et al.* 2001). Pools, riffles, and runs have been found to support different algae and macrophytes (e.g. Keithan and Lowe 1985), macroinvertebrate assemblages (Pridmore *et al.* 1985, McCulloch 1986, Hose 2005), and distinct fish habitats (Aadland 1993, Hawkins *et al.* 1993, Braaten and Berry 1997). Geomorphic condition significantly influences fish community diversity and productivity and is of primary importance for river rehabilitation efforts (Chessman *et al.* 2006, Sullivan *et al.* 2006).

Riverine fish exhibit complex life cycles and habitat use patterns associated with variations in body size as they grow from embryo to adult (Schlosser 1991). Geomorphological processes are directly and indirectly linked to the formation and maintenance of different habitat areas used during these stages of development. Physical habitat conditions can directly impact distribution of species as well as act indirectly by determining type and abundance of food resources (Rabeni and Minshall 1977) and influence the roles of competition or predation (Peckarsky and Dodson 1980). Often, species have different habitat requirements for foraging or summering, spawning, rearing, and overwintering. For example, consider the foraging and spawning habitats of a variety of species examined in the following chapters: Lake Sturgeon (*Acipenser fulvescens*), Common Carp (*Cyprinus carpio*), Sauger (*Sander Canadensis*), and Carmine Shiner (*Notropis percobromus*). These species cover a range of sizes, lifespans, and guilds, reflecting the diversity of Prairie fishes.

Foraging habitat is essentially defined by the presence of food items. In this sense, foraging habitat for fish can be considered the habitat of food items themselves as well as the areas where feeding mechanisms the fish possess are most successful. Substrate is closely correlated with many fluvial process variables such as water level, flow velocity *etc.* and is considered the primary condition for the survival of benthic animals (Allan and Castillo 2007, Pan *et al.* 2012). Lake Sturgeon feed over fine substrates of sand, mud and gravel suggesting areas of lower velocities that allow deposition of such substrates. Similarly, Common Carp prefer slower moving waters in streams, ponds, rivers and lakes, and are typically benthic feeders, preferring shallow water and soft substrates for feeding (Stewart and Watkinson 2004). Upstream sediment and particulate organic matter sources must also be maintained in order to replenish these soft substrates. Silty substrates are generally nutrient rich with greater amounts of fine particulate organic matter, thus collector-gatherers predominate in soft substrates with densities and biomass increasing with increasing total phosphorous, while collector-filterers and scrapers are more dominant in gravel substrates (Allan and Castillo 2007, Pan *et al.* 2012). The migratory nature of Lake Sturgeon allows them to take advantage of an array of foraging areas that have relatively low velocities and a range of substrates supporting different macroinvertebrate assemblages and large invertebrates such as crayfish. Carmine Shiner are typically found near riffles in creeks and small rivers over clean gravel or rubble substrates during summering and spawning (COSEWIC 2006). Their diet is mainly comprised of aquatic and terrestrial insects though vegetation, diatoms, and filamentous algae are also consumed (Pfeiffer 1955, Watkinson and Sawatsky 2013). Carmine Shiner feed based mainly on sight, relying on flows to bring food items past them, either within the water column or at the surface, so that they can locate them by sight and catch them with their terminal mouths. This species is also very sensitive to turbidity and though the exact effects are not known it possibly interferes with visual feeding (Zamor *et al.* 2007). More stable substrates such as gravel and cobble also allow the production of biofilms and filamentous algae (Allan and Castillo 2007). Sauger are most often associated with rocky substrates though they have been found on substrates ranging from clay and silt to rubble and boulders (Stewart and Watkinson 2004). This species feeds on a variety of invertebrates and small fishes depending on the size of the Sauger and season.

For spawning, Carmine Shiners and Lake Sturgeon are both often associated with swift currents and larger-size substrates. Lake Sturgeon spawn in larger rivers at riffles or beneath rapids over heterogeneous substrates with high proportions of gravel (LaHaye *et al.* 1992 and 2004, Manny and 2002, Chiotti *et al.* 2008). Eggs scatter, adhering to substrate and debris, and hatch after 7-10 days. The larvae are negatively buoyant and move relatively little within the water column until they begin to drift downstream after about 11 days (LaHaye et al 2006, USFWS 2006). Though little information exists on the spawning habits of Carmine Shiner in Canada they are likely similar to those of the Rosyface Shiner (*Notropis rubellus*) (Watkinson and Sawatsky 2013). The Rosyface Shiner has been observed spawning in riffles over depressions in clean gravel (Pfeiffer 1955) which are often nests constructed by other cyprinids (Baldwin 1983). The eggs hatch after 2.5 days and larvae remain in the bottom gravel presumably until the yolk is absorbed (Pfeiffer 1955). It has been suggested that larger-sized substrates such as gravel and cobble provide interstitial spaces that protect eggs from predation and relatively high velocities reduce sedimentation which can cause suffocation (Kempinger 1988). Similarly, Sauger spawn over gravel to rubble or rocky substrates but in deeper water rather than riffles (Scott and Crossman 1973, Stewart and Watkinson 2004). These spawning habitats are dependent upon lithology, which can dictate which substrates are present, as well as substantial flows and effective stream gradient to prevent deposition of fine sediments or exposure to desiccation. Mature Common Carp move to vegetated shorelines or flooded areas to spawn, their adhesive eggs attaching to submerged vegetation and hatching after 4 days (Stewart and Watkinson 2004). Like Lake Sturgeon, adult Common Carp often have to make considerable spawning migrations to find suitable backwaters and flooded vegetation.

Other physical habitat variables have been linked to geomorphic characteristics of rivers. Baxter and Hauer’s (2002) multiscale study identified three different scales of habitat associations for Bull Trout (*Salvelinus confluentus*) redds (nests) in tributaries of a Montana river. At a 5-10 km scale redds were associated with low-gradient bounded alluvial valley segments (BAVS). Groundwater upwellings within BAVS created thermal refugia for incubating eggs preventing freezing during winter months and at an even finer scale, sites with localized downwelling were chosen likely to ensure adequate oxygenation of the eggs. The large scale geomorphological context of these habitats acted as a filter for smaller, local scale patterns in redd sites (Fausch *et al.* 2002).

1.3.3 Channel Planform and physical habitats

The majority of existing studies investigate relationships between fish habitat and geomorphology in relatively small, often wadeable streams (order 1-5), where monitoring protocols tend to be well established and geomorphological variables can be measured with relative ease (Bizzi *et al.* 2012, D,Ambrosio *et al.* 2009). Such thorough data collection becomes less attainable in larger rivers where greater depths, widths, discharge and flow velocities impede both active and passive data collection methods. The increase in study area also increases the time and effort required to collect data which is often at odds with financial and temporal constraints of a given study or monitoring program. There are also boundless hydraulic and geomorphic variables that can be measured in an effort to describe the fluvial geomorphic character of rivers. These parameters vary in spatial and temporal scales and some are more readily measured than others. For example, flow velocity is an instantaneous variable often used to describe aquatic habitats (Brewer *et al.* 2006). Although velocity ranges are valuable descriptors of known habitat areas, identification of possible habitat areas using such a parameter is not feasible because local velocities are constantly in flux and most sampling and monitoring methodologies reduce this highly variable parameter to an average value that does not accurately reflect the heterogeneity present in a given cross section or reach. Two streams or river reaches may have similar mean velocities yet exhibit disparate velocity profiles (Beebe 1996, Rhoads *et al.* 2003). A larger scale understanding of the relative differences in flow velocities within or between reaches is likely to be more informative for the characterization of habitat patches in large river systems. Many of these possible hydro-geomorphological variables are correlated and often their influence is reflected in measures of higher order variables. The most readily acquired geomorphological data for large rivers are variables describing the planform channel morphology. Planform variables describe the configuration of the river channel and include measurements such as channel width, meander length, sinuosity, fractal dimension, and radius of curvature. Although relationships between the spatial distribution of different species, assemblages, or communities and various abiotic and biotic factors are often complex, planform channel variables representative of geomorphic character can act as higher order proxies for myriad possible predictors. Identifying patterns in channel planform can provide insight into the physical features present in different reaches and allow us to infer which are likely to coincide with different habitats.

Different planform shapes and types are influenced by discharge, sediment caliber and availability, and the dominant type of sediment transport occurring in a given reach. Channel size is influenced by discharge, though how a river responds to changes in discharge depends upon the hydrologic regime (Yu and Wolman 1987) and bank material. Rivers with flashier regimes tend to increase in width much more rapidly than those with smaller peak flows, and channels with less cohesive bank materials like sand tend to be more susceptible to the influence of discharge variability (Osterkamp and Hedman 1982, Knighton 1998). Channel planform is related to habitat hydraulics and has been found to influence the distribution of cross-stream and vertical velocities with more sinuous reaches exhibiting more complex flow habitats as measured by three-dimensional geometry and motion of flow (Rhoads *et al.* 2003). Channel slope and sinuosity have been correlated with fish species composition and diversity (Sullivan *et al.* 2006, Dauwalter *et al.* 2008). In a comparison of a channelized vs. a meandering section of an agricultural stream, Frothingham and colleagues (2001) found that the meandering reach had greater spatial variability in channel morphology, and by extension physical habitat, than the channelized reach. Sampling of the fish communities within the two contrasting reaches determined that species richness was similar between the two reaches but the meandering reach had greater average biomass and 25% greater abundance than the channelized reach (Frothingham *et al*. 2001). Channelized reaches have also been associated with less variable bed elevations, further supporting the notion of reduced habitat complexity (Rhoads *et al.* 2003). Sinuosity has also been linked to increased large/course woody debris (LWD) (Nakamura and Swanson 1994, McIlroy *et al.* 2008). Nakamura and Swanson (1994) found that channel width and sinuosity were the main factors controlling woody debris production and storage, with lateral cutting and landslides facilitating introduction of woody debris in sinuous reaches of Lookout Creek Oregon.

Slope adjusts more slowly than other channel variables such as channel width and depth, velocity, degree of sinuosity and grain size of sediment load (Allan and Castillo 2007). Changes in slope result from changes in watershed conditions that disrupt sediment transport continuity, bed load starvation leading to degradation and excessive bed-load inputs leading to aggradation

(Knighton 1998). In general, an increase in channel gradient leads to an increase in velocity and can serve as a proxy for instream-velocity measurements when identifying large scale patterns in environmental characteristics which may influence habitat suitability. Fractal dimension, a measure of the irregularity or intricacy in trains of meanders and relating to changes in overall river course, is another planform variable that has been linked to large scale geomorphic character (Snow 1989, Nikora 1991, Montgomery 1996). Fractal dimension has been found to reflect changes in tectonic provinces of varying uplifting intensity and age (Shen *et al.* 2011). Beauvais et al (1994) proposed that patterns in channel planform fractal dimension, which they termed the textural fractal dimension, to be related to the influence of local environmental factors such as soil type, vegetation cover, runoff and sediment transport. Understanding how planform channel variables relate to instream physical habitat attributes has the potential to inform managers interested in identifying large scale habitat characteristics in large river systems.

1.3.4 River Ecosystem Models and the Geomorphic Response Unit Method

Several different riverine ecosystem models have been developed over the past century in an effort to describe structural and functional patterns within and among rivers. Identification of longitudinal biotic zones in streams based on dominant fish species: trout (*Salmo*), grayling (*Thymallus*), barbell (*Barbus*), and bream (*Abramis*), began in the early twentieth century but Hynes (1970) identified limits in application of such methods due to differences in regional geographic distributions of species and the impacts of activities on species distributions. Since 1980 several models have been developed that greatly improved our understanding of how dynamic river ecosystems function and continue to contribute to current river science research. Five such models are the River Continuum Concept (RCC) (Vannote *et al.* 1980), the Serial Discontinuity Concept (SDC) (Ward and Stanford 1983), the Flood Pulse Concept (FPC) (Junk *et al.* 1989), the Riverine Productivity Model (RPM) (Thorp and Delong 1994), and the River Wave Concept (Humphries *et al.* 2014).

The River Continuum Concept (RCC) proposed by Vannote and colleagues (1980) was one of the first ecosystem models to have widespread influence on river science. The RCC views rivers as longitudinal gradients with predictable transitions in physical and biological characteristics from headwaters (orders 1-3), through medium (4-6) to large rivers (>6) (Vannote *et al.* 1980). Headwaters rely heavily on allochthonous sources of carbon, mainly leaves from riparian vegetation and collector and gatherer species that can break down such course detritus dominate the macroinvertebrate assemblages (Vannote *et al.* 1980). Terrestrial vegetation intercepts most of the sunlight keeping P/R ratios <1 and helps maintain cool water temperatures, limiting which fish species can inhabit such reaches (Vannote *et al.* 1980). Cold-cool water species including trout (*Salmonidae*), sculpins (*Cottidae*) and mountain suckers (*Catostomus platyrhynchus*), are invertivores, feeding primarily on drifting aquatic and terrestrial insects (Tyus 2012). Medium-sized rivers are wider, deeper, and warmer with terrestrial inputs becoming less important as flow transfers organic matter from upstream and increased sunlight exposure allows autochthanous primary production to occur (Vannote *et al.* 1980). P/R ratios tend to be >1 and grazers and scrapers dominate the macroinvertebrate assemblages. Grazers take advantage of fine particulate organic matter (FPOM) resulting from the processing of coarse particulate organic matter (CPOM) by upstream shredders and scrapers ingest algae growing on surfaces (Vannote *et al.* 1980). Coolwater species gradually decline and warm water species begin to dominate the fish assemblage (Vannote *et al.* 1980). Biodiversity increases as both invertivores and piscivorous species such as Walleye (*Sander vitreus*), perch (P*erca*), and Northern Pike (*Esox Lucius*) thrive (Tyus 2012). Large rivers are much warmer, wider, and deeper and effects of riparian vegetation become much less significant (Vannote *et al.* 1980). Velocities decrease and turbidity and depth attenuate sunlight so P/R <1 and FPOM collectors again dominate the macroinvertebrate assemblage with some predaceous species (Vannote *et al.* 1980). Some large rivers exhibit semi-lentic characteristics due to decreased velocities and extreme depth and plankton growth increases providing another food source (Vannote *et al.* 1980). Warm water species dominate the fish assemblage with catfishes (*Ictaluridae*), suckers (*Catostomidae*), and sunfishes (*Centrarchidae*) adding to the diversity of fish species (Tyus 2012).

Though these generalities provide insight into ecological processes within rivers there are several shortcomings of the RCC. A prevalent issue is transferability to rivers in different ecozones. This concept was developed based on patterns occurring in pristine temperate zone rivers with forested headwaters. Rivers that originate in un-forested regions still support diverse fish assemblages therefore other carbon sources must account for such discrepancies. The RCC also fails to address that the majority of rivers in the world today are greatly altered by human use and are faced with extractions, damming, pollution, and adverse land use practices. The RCC is limited in its ability to predict fish habitat as river ecosystems have become extremely fragmented which disrupts the continuum, altering nutrient and carbon cycling, sediment transport, and the chemical and physical characteristics of habitat both upstream and downstream of barriers. Although some of the overall patterns in fish species and biodiversity may still hold due to temperature limitations, habitat and associated species are much more likely to exhibit patch like distributions rather than transitioning smoothly along a gradient. Further to associations with certain temperature limits, different species may fall into different feeding guilds and often have different habitat requirements depending on season and life stage, thus habitat associations are much more complex than the longitudinal patterns described by the RCC.

The Serial Discontinuity Concept (SDC) improved upon the RCC by identifying some "exceptions to the rule" (Ward and Stanford 1983, Thorpe et al 2008). The SDC recognizes that impoundments can disrupt nutrient spiralling and the continuum of processes as described by Vannote *et al.* (1980) and proposed some useful generalizations about the influence of such barriers. For example, because they impede the transport of detritus, headwater dams are likely to have a greater impact on downstream CPOM: FPOM ratios than those in downstream reaches of large rivers (Ward and Stanford 1983). Reducing the influx of CPOM could greatly alter the macroinvertebrate assemblages in these downstream reaches and cause a decline in shredder species (Ward and Stanford 1983). Conversely, headwater impoundments are unlikely to have a substantial effect on downstream P/R ratios but impoundments in large rivers can greatly increase water clarity as flow velocities decrease and transport capacity decreases upon entering the reservoir, allowing sediments and FPOM to settle out of the water column which can lead to increased P/R ratios downstream (Knighton 1998, Ward and Stanford 1983). Changes to the amplitude of seasonal water temperatures, flow regime, nutrient spiraling, and effects of multiple impoundments are also addressed (Ward and Stanford 1983). Though these theoretical perspectives help us understand how impoundments may impact the ecological functioning of river reaches, several limitations and assumptions persist with the SDC and are recognized by the authors. Such assumptions include: inability to account for any disturbances other than impoundment, no pollution present, remaining lotic reaches are not disrupted by reservoir construction, and impoundments are assumed to be thermally stratified deep-release storage reservoirs that do not release either supersaturated nor oxygen deficient waters (Ward and Stanford 1983).

The Flood Pulse Concept (FPC) is in fundamental agreement with the RCC principle of a gradient in physical conditions from headwaters to river mouth but argues that it was developed for small temperate streams with permanent lotic habitats (Junk *et al.* 1989). They propose that in floodplain rivers flood pulses which connect the main channel to the floodplain are more important in determining the function of floodplain rivers than position along a river continuum (Junk et al, 1989). Floodplain areas provide access to nutrients and organic matter which increases productivity, and also allow access to habitats that are physically distinct from the main channel (Junk *et al.* 1989). They also suggest that river regulation has led to an underestimation of the importance of lateral migration of animals between the main channel and floodplain of large rivers because modified flow regimes have reduced connectivity between the main channel and floodplain. The FPC can offer insight into the distributions of fish species which rely on flood pulses as cues for different life history events such as migration or spawning, or require access to flooded riparian zones to complete such life history requirements. Though Junk and colleagues place emphasis on floodplain rivers with extreme flood pulses of long duration, such as tropical and subtropical floodplain rivers, reduced access to the floodplain can still negatively impact species in any river with historically predictable seasonal peak flow pulses.

The Riverine Productivity Model (RPM) continues to build upon previous models by addressing the importance of local instream primary production and allochthonous inputs in large rivers (Thorp and Delong 1994). They suggest that previous models underestimate the substantial amounts of organic carbon inputs that can be attributed to local autochthanous production by benthic algae, aquatic vascular plants, mosses and phytoplankton, as well as direct riparian inputs (Thorp and Delong 1994). Such forms of carbon are relatively more labile than benthic organic matter or inputs transported from upstream, suggesting that autochthonous and local terrestrial inputs are more readily assimilated by heterotrophs (Thorp and Delong 1994). Contrary to RCC prediction, macroinvertebrate density data from the large rivers in this study suggested that grazers account for a large portion of the total benthic macroinvertebrate assemblage of near shore habitats. These near shore areas, in addition to side channels and shallow bars, have reduced flow velocities relative to the main channel allowing greater retention and processing of local organic matter (Thorp and Delong 1994). It is of note that the RPM was developed based on the analysis of very large deep rivers of southern and Midwestern USA, such as the Mississippi, Ohio and Tennessee Rivers, therefore results may be biased to these specific river types with restricted channels and firm substrates (Thorp and Delong 1994).

Though all of these river ecosystem models provide valuable insight into patterns of ecological functioning within rivers they are all theoretical frameworks rather than widely applicable tools for identifying which reaches of a river or river network are similar or dissimilar. GRUs build on this extensive theoretical foundation by providing a means for delineating large-scale self-emergent patterns and patches within river systems. These patches generally coincide with river reach or river segment scales, the scales at which fish species are actually interacting with the river ecosystem. These patches can also repeat throughout the river and do not follow a gradient like the RCC or result simply due to discontinuities in a gradient as implied by the SDC. The GRU method is much more flexible in its application than the RCC as it does not require a pristine, forested headwater stream in order to identify patterns in geomorphic structure within a river.

1.4 Copyright and Author Permissions

Chapters 2 through 4 of this thesis consist of manuscripts that are in press or are currently in review. I provide the manuscript citations below in order to maintain consistency with copyright and author rights for each publisher. For all manuscripts, the student is the first author as per the College of Graduate Studies and research guidelines for manuscript style theses.

Chapter 2: Carr, M.K., Lacho, C., Pollock, M., Watkinson, D. and K.-E. Lindenschmidt. 2014. Development of geomorphic typologies for identifying Lake Sturgeon (*Acipenser fulvescens*) habitat in the Saskatchewan River System. *River Systems*. Open Access: http://www.ingentaconnect.com/content/schweiz/rs/pre-prints/content-86_Carr_ingenta
[E. Schweizerbart'sche Verlagsbuchhandlung]

Chapter 3: Carr, M.K., Watkinson, D.A., Svendsen, J.C., Enders, E.C., Long, J., and K.-E. Lindenschmidt. 2015. Geospatial modelling of the Birch River: Spawning distribution of Carmine Shiner (*Notropis percobromus*) in Geomorphic Response Units (GRU). *International Review of Hydrobiology*. 100: 1-12. DOI 10.1002/iroh.201501789 [Wiley-VCH]

Chapter 4: Carr, M.K., Watkinson, D.A., and K.-E. Lindenschmidt. 2015. Identifying Links between Fluvial Geomorphic Response Units (FGRU) and Fish Species in the Assiniboine River, Manitoba. *Ecohydrology*. Online. DOI: 10.1002/eco.1714 [John Wiley & Sons, Ltd.]

PREFACE TO CHAPTER 2: DEVELOPMENT OF GEOMORPHIC TYPES FOR IDENTIFYING LAKE STURGEON (*Acipenser fulvescens*) OVERWINTERING HABITAT IN THE SASKATCHEWAN RIVER SYSTEM

I assisted The Water Security Agency in field data collection in the lower South Saskatchewan and Saskatchewan Rivers, executed GIS and statistical analyses, and am the primary author of this manuscript. Christine Lacho provided Lake Sturgeon overwintering location data from the Upper South Saskatchewan River. Michael Pollock designed the Water Security Agency's Saskatchewan River Sturgeon Project sampling campaign, provided Lake Sturgeon overwintering location data, and proof read the manuscript. Douglas Watkinson collaborated with Christine Lacho on the design and implementation of Upper South Saskatchewan data collection and proof read the manuscript. Karl-Erich Lindenschmidt, supervisor of this research, was one of the developers of the theoretical GRU framework used in this study and made necessary revisions to the manuscript. I, Meghan Carr (80%) carried out the bulk of the contributions to the preparation of the manuscript with co-authors Michael Pollock (5%), Douglas Watkinson (5%), and Karl-Erich Lindenschmidt (5%) contributing comments during the review process.

Chapter 2 is published in River Systems. See: Carr, M.K., Lacho, C., Pollock, M., Watkinson, D., and K.-E. Lindenschmidt. 2014. Development of geomorphic typologies for identifying Lake Sturgeon (*Acipenser fulvescens*) habitat in the Saskatchewan River System. River Systems. Online: http://www.ingentaconnect.com/content/schweiz/rs/pre-prints/content-86_Carr_ingenta

CHAPTER 2: DEVELOPMENT OF GEOMORPHIC TYPES FOR IDENTIFYING LAKE STURGEON (*Acipenser fulvescens*) OVERWINTERING HABITAT IN THE SASKATCHEWAN RIVER SYSTEM

2.1 Abstract

Lake Sturgeon (*Acipenser fulvescens*) are a large migratory fish species native to the Saskatchewan River system. This species is currently challenged by habitat fragmentation and degradation due to river impoundment. Lake sturgeon are listed as endangered by the Committee on the Status of Endangered Wildlife in Canada and are being considered for listing under the SARA (Species at Risk Act). Lack of habitat data for the Saskatchewan River system hinders effective management practices for this species and the rivers in which they live. A novel habitat identification method has recently been developed combining techniques from various disciplines. GIS (Geographic Information System) and multivariate derived geomorphic response units (GRU) define reaches along river systems that exhibit similar geomorphic structure and provide a link between the hydrological regime and species habitat preference. Fish movement data collected by lake sturgeon studies in the Saskatchewan River system were analysed to identify known over-wintering sites and relationships between such sites and geomorphic types identified using GRU methodology were investigated. Overall habitat selection ratios for Upper South Saskatchewan Lake Sturgeon were 1.844 for Type 0 and 0.774 for Type 4 indicating that Type 0 is significantly selected for over all other possible geomorphic types identified in this study. Identification of these links has the potential to greatly increase efficiency of managing this endangered species by allowing *a priori* selection of sampling sites and prediction of how the effects of anthropogenic changes in river morphology may impact sturgeon habitat.

2.2 Introduction

2.2.1 Lake Sturgeon in the Saskatchewan River system

Water resource development affects rivers around the world. Such alterations often result in modified flow regimes due to river regulation. The Saskatchewan River and its major tributaries, the North and South Saskatchewan rivers, are regulated by hydroelectric dams and contribute large proportions of flow to agricultural, industrial and municipal uses (Saskatchewan Watershed Authority (SWA) 2007, SWA 2008, Pentney and Ohrn 2008). The Saskatchewan River systems fish fauna includes the lake sturgeon (*Acipenser fulvescens*), a species listed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Severe overfishing and slow population growth led to a rapid decline of sturgeon populations in the early 1900s but more recently many authors point to habitat loss and degradation as the most relevant threats to lake sturgeon populations (Auer 1996, Chiotti 2008, Cleator *et al.* 2010). Dams cause habitat fragmentation and, along with diversions and other anthropogenic influences, alter flow regimes and degrade riverine habitat. Though current studies suggest populations are beginning to stabilize (SWA 2012, Manitoba Conservation and Stewardship 2012) water resource development proposals continue to be put forward, posing a persisting threat to lake sturgeon populations.

Methods for determining habitat use of migratory fish in extensive river systems are labour and time intensive (SWA 2011). Despite a general understanding of lake sturgeon habitat preferences, identifying where these habitats are located remains a challenge, often requiring years of data collection and analysis that could be significantly decreased by the development of a reductive habitat classification method. Specifically, a geomorphological desktop study approach using data derived from GIS parameters would allow relatively rapid identification of macro-scale habitat areas and increase management efficiency. Lack of habitat data for the Saskatchewan River system hinders effective management for lake sturgeon and the rivers in which they live. Given this lack of knowledge it is crucial that these data gaps be filled to improve management efforts and ensure the recovery of the species. One such method has recently been developed combining techniques from various disciplines. GIS (Geographic Information System) and multivariate derived geomorphic response units (GRU) define reaches along river systems that exhibit similar geomorphic structure and provide a link between the hydrological regime and species habitat preference. Movement data collected in ongoing lake sturgeon studies in the Saskatchewan River system provide fish location and migration data allowing for the characterization of known over-wintering sites. By combining GRUs and fish movement data sets we can characterize areas of known use to locate previously unknown areas.

2.2.2 Linking geomorphology to ecology using Geomorphic Response Units (GRU)

Rivers are inherently dynamic environments with fluctuations in water quality, hydrology, connectivity and geomorphology. These variables exist in a dynamic equilibrium resulting in uniquely adapted flora and fauna (Lindenschmidt and Long 2012). The study of fluvial geomorphology examines riverine channels including the hydrological and geological processes that create specific structures (Lindenschmidt and Long 2012). Rodríguez-Iturbe and Valdés (1979) were the first to propose that geomorphological processes influence the hydrological response of a river. In turn, the flow timing and volume shape the biota and ecological functioning of river systems and influence habitat forming variables such as sediment, connectivity (Poff *et al.* 1997) and biogeochemical cycling (McDowell *et al.* 2002, Nestler *et al.* 2012). These geomorphological processes can be interpreted as periodic disturbance regimes working in concert with hydraulic activity, or simply as processes associated with long-term dynamic activity (Lindenschmidt and Long 2012).

The seminal works of Rodriquez-Iturbe and Valdes (1979) have resulted in geomorphology being recognized as an important factor in defining biological (Walters *et al.* 2003, D'Ambrosio *et al.* 2009) and ecological characteristics of rivers (Thorp *et al.* 2006, Bizzi and Lerner 2012) and aquatic habitat (Duncan *et al.* 2011, Bizzi and Lerner 2012). Studies have found links between fish assemblages and geomorphology in streams and rivers using varying numbers of geomorphological variables. Dauwalter *et al.* (2007) investigated influences of biogeography, ecoregions and geomorphology on fish assemblages in Oklahoma streams and found geomorphology explained the variation seen in fish species composition and determined which species were found locally within stream reaches. Similar studies testing as many as 95 (Walters *et al.* 2003) or as few as seven (D’Ambrosio *et al.* 2009) geomorphic variables found stream slope (gradient), a geomorphic variable that is easily derived from digital elevation model (DEM) data, to be a dominant factor determining fish assemblage and abundance. These fish assemblage studies required intensive field sampling of geomorphic and biological variables at the reach scale (Walters *et al.* 2003, Sullivan *et al.* 2006, D'Ambrosio *et al.* 2009). Though their findings support the view that geomorphology is linked to fish habitat, their methods are not transferable to a large prairie river system as the field and data processing requirements would be immense.

The Saskatchewan River system is a large prairie river system lacking extensive geomorphological or habitat datasets; therefore a reductive method using GIS derived data to delineate areas of similar geomorphic characteristics is desirable. Response units have been used extensively to organize large scale hydrological and geomorphological processes into computationally manageable units (Flugel 1997, Becker and Braun 1999, Cammeraat 2002, Sidorchuk *et al.* 2003, Güntner and Bronstert 2004). Cammeraat (2002) defines response units as:

> “built of several land units that have a characteristic response with respect to hydrological and geomorphological processes. Each response unit should be identifiable in a proper and preferably easy way… by selecting key indicators that reflect dominant processes within a response unit”.

Response units are commonly used in delineating areas of similar hydrological response within a watershed based on geomorphological (e.g. soil type, geology), topological (e.g. concavity, convexity, slope and aspect) and biological (e.g. vegetation) landscape characteristics paired with precipitation and temperature data to determine response in an output such as runoff (Flugel 1997, Becker and Braun 1999, Devito *et al.* 2005). Most response unit characteristics can be derived from readily available GIS data layers with moderate effort. In terms of delineating units of similar response within riverine ecosystems, Thorp et al (2006 & 2008) have developed Functional Process Zones (FPZ). They view rivers as longitudinal arrangements of functionally and structurally similar hydrogeomorphic patches formed by flow and geomorphology characteristics. Currently the FPZ theoretical framework requires the inclusion of several redundant morphological and flow variables (Thorp *et al.* 2008).

In contrast, the GRU method developed by Lindenschmidt and Long (2012) is an efficient first tier approach (simple desktop first-step analysis based on data derived exclusively from GIS variables) for determining areas of similar geomorphological and hydrological processes. Patterns and trends of geomorphological processes can be assessed at inter-annual to decadal temporal scales, and therefore cannot be linked to short term biological indicators. Rather, the geomorphological state of the river system itself is measured and associated with long term biological outputs (Lindenschmidt and Long 2012). Essentially, a GRU represents the structure of a river segment and links the hydrological regime and a specific habitat type to which species respond (Lindenschmidt and Long 2012). Fluvial geomorphological parameters such as sinuosity, fractal dimension, slope and stream width can be extracted from stream network and DEM GIS layers. Parameter values can be extracted every 50m along the river and statistically grouped (principal component analyses) to determine different geomorphic Types that can be associated back to a corresponding river reach. These Types can be left as is or combined to form different GRUs. Understanding the relationship between these GRUs and lake sturgeon location and migration is a promising first step in defining habitat areas in the Saskatchewan River system.

2.3 Methods

2.3.1 Study site

The Saskatchewan River System spans over 3,200km (Figure 2-2), originating from the East slopes of the Rocky Mountains in Alberta and flowing West across Saskatchewan and into Lake Winnipeg in Manitoba. This study focuses on the entire South Saskatchewan River, from the confluence of the Bow and Oldman rivers in Alberta to the confluence of the South Saskatchewan and North Saskatchewan Rivers, and the Saskatchewan River downstream to Codette Reservoir, formed by Francois-Finlay Dam. Gardiner Dam is located approximately 600 river Kilometers downstream of the Oldman and Bow river confluence and forms the Lake Diefenbaker reservoir (Figure 2-2). This structure serves multiple functions for the province of Saskatchewan providing irrigation, domestic and industrial water supplies, flood and drought protection, recreation and 1,000 GWh of hydropower annually (SWA 2011, SWA 2012). The river channel is primarily embedded in fine grained glaciolacustrine (fL) deposits of silt and clay and coarse grained glaciolacustrine (cL) deposits of sand silt and gravel, with patches of Eolian (E) deposits characterized by undulating plains of sand and minor silt, and a section of alluvial (A) deposits characterized by stratified silt, clay and gravel occurring 58km downstream of Gardiner Dam.

Lake sturgeon are a large migratory species that have unique characteristics and life history traits including life spans exceeding 100 years, late age-at-maturity (~15-25 years) and protracted spawning periodicity (~3-5 years) (Scott and Crossman 1973, Becker 1983). Proposals for the addition of dams along the Saskatchewan River prompted the Saskatchewan Water Security Agency (formerly the Saskatchewan Watershed Authority) to initiate an ongoing lake sturgeon study in 2009. At this time very little was known about the habitat use and migrations of lake sturgeon in the Saskatchewan River system within the province of Saskatchewan. After four years of intensive study, important overwintering areas for this species have been identified and can be factored into management plans.

2.3.2 Data Collection

2.3.2.1 Geomorphological variables

Geomorphological variables indicative of large scale river structure and functional processes were extracted from 1:50,000 digital elevation model (DEM) data (Department of Natural Resources Canada) using GIS (ESRI 2013). The river network was delineated by adding a centerline along the entire course of the river then inserting points every 50m along this centerline. Transects intersecting each of these centerline points and both riverbanks were then added (Figure 2-1). This delineation allowed four geomorphological variables to be extracted at each of the centerline points: sinuosity, slope, fractal dimension and stream width (Lindenschmidt and Long 2012). Sinuosity is a ratio of the actual flow path between two points along the stream centerline and the shortest path length between the same two points. A straight channel has a sinuosity value (S) = 1 and for meandering channels S >1. Sinuosity can be interpreted as a measure of meander ‘wiggliness’ (Ferguson 1977) whereas fractal dimension can be considered a measure of the intricacy or irregularity in trains of meanders (Snow 1989, Nikora 1991, Montgomery 1996). Fractal dimension occurs at a higher geometric level or larger scale than sinuosity (Nikora 1991) and relates more to changes in overall river course rather than channel pattern (Snow 1989). Both fractal dimension and sinuosity were calculated using the commercial software package Mathcad® v.15 (MathSoft Inc., Cambridge, MA, 2012). Sinuosity was determined at a slightly larger scale than width and slope using 110 adjacent points (5.5 km) along the river course. Fractal dimension was calculated based on the number of centerline points that fell within a 20 X 20 km square moved along the course of the river. These scales were chosen because they were the values at which peak variation was observed.

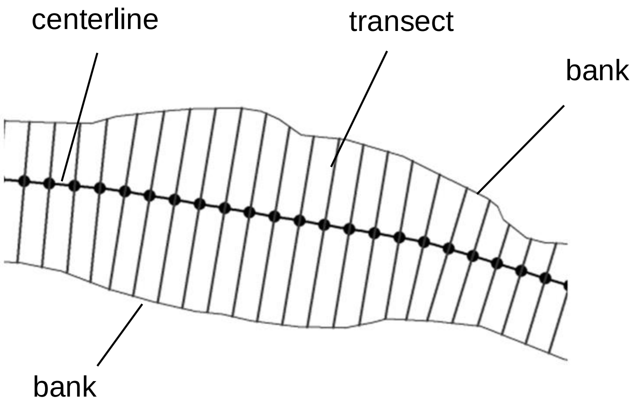

Figure 2-1. River delineation in GIS. Sinuosity, slope and fractal dimension are determined at each of the centerline points spaced every 50m along the river. Transects pass through each centerline point, their lengths representing river width at each centerline point.

Variables were then grouped via multivariate principal component analysis (PCA) using the statistical package R 2.15.2 (R Core Team 2012) to determine geomorphic Types. PCA is an ordination technique based on linear algebra that allows dimensionality reduction and uncovers latent patterns in data by highlighting similarities and differences (Legendre and Legendre 1998). The dataset was log10 +1 transformed to improve normality while accounting for the high incidence of zeros and very small positive values of slope. First the data were transformed into orthogonal eigenvectors or principal components with the first component accounting for the most variation in the dataset and each succeeding component accounting for the remaining variability. The explained variance of principal components one through four was 57%, 19%, 14% and 9% respectively. The original dataset was then scaled by the loadings to give us the scores that express the data in terms of the principal components. For each observation these scores were converted to a binary value (0 for negative scores, 1 for positive scores) and each unique combination of values yielded a different geomorphic Type. All four geomorphic variables were included in analysis resulting in 16 unique geomorphic Types. Each Type was assigned a unique colour and plotted to its corresponding 50m river segment (Figure 2-2).

2.3.2.2 Lake Sturgeon Telemetry

The Saskatchewan Water Security Agency (WSA) had undertaken a three year study investigating flow impact on Lake Sturgeon habitat, distribution and population health within the lower South Saskatchewan River, downstream of Gardiner Dam, and the North Saskatchewan and Saskatchewan rivers. Between September 2009 and October 2012, a total of 48 fish were successfully surgically implanted with Advanced Telemetry Systems radio tags allowing active tracking of the fish by snowmobile, aircraft and boat; and passive tracking using remote receiver towers (SWA 2011, 2012, WSA 2013). Fish were actively tracked as they moved back to overwintering areas in the fall and receiver towers set upstream and downstream of the overwintering sites allowed the identification of spring migration initiation when the majority of fish moved away from these sites (Figure 2-3c). These populations were confined to reaches below the Meewasin Riverworks Weir in Saskatoon, a structure which was originally built to regulate water flow and create a reservoir for the city prior to the development of Gardiner Dam in 1967. A study at the University of Lethbridge, in association with Fisheries and Oceans Canada and Alberta Environment and Sustainable Resource Development, tagged 123 Lake Sturgeon in the upper reaches of the South Saskatchewan River (101), and the lower reaches of the Bow (7) and Oldman Rivers (15). These fish were surgically implanted with Vemco coded hydroacoustic tags transmitting at 69 kHz approximately every 90 seconds. The fish were then tracked passively using stationary Vemco VR2W hydroacoustic receivers between August 2010 and October 2012 (Figure 2-3a, b). These datasets allowed the identification of overwintering areas used by these tagged individuals. For the purposes of this study any sturgeon observations documented during November, December, January and February were considered overwintering observations. These sturgeon observations were then linked to the nearest centerline point and its corresponding type using GIS (Figure 2-2).

It should be noted that there are some minor differences in methods between these studies. In the lower South Saskatchewan and Saskatchewan Rivers fish were tracked both actively, weekly during summer and fall and bi-weekly during winter months, and passively year round using two to three stationary receiver towers. This gives more specific location information but results in a much smaller dataset. Receiver tower locations were chosen based on initial observations of sturgeon aggregations, high bank areas that allowed the best reception over the largest area and accessibility (SWA 2011). The upper South Saskatchewan study only used passive receivers that were submerged in the river and had a range of up to 1.9 km in the river and 3km in Lake Diefenbaker. There were 24 receivers submerged at 26 different locations within the study area during overwintering (Fig. 3a). To reduce some of the bias based on tracking method only one observation per day, per receiver for each individual was included in analyses. Despite these differences the datasets are comparable.

2.3.3 Data Analysis

2.3.3.1 ANOVA on Ranks

Kruskal-Wallis analysis of variance on ranks was performed to determine whether values of geomorphological variables were significantly different between Types using the FSA package for statistical software R 3.1.2 (R Core Team 2014). Post-hoc comparisons were made using two-sided Dunn's Test with Bonferroni p-value correction for multiple paired tests.

2.3.3.2 Logistic Regression Models

To gain a better understanding of the ability of Types to predict lake sturgeon presence a logistic regression was performed comparing sturgeon observations to an equal number of randomly generated observations created in GIS using the statistical package R (R Core Team, 2015). This created a binary response variable where actual sturgeon observations were treated as observed sturgeon 'presence'=0 and randomly generated observations were treated as observed sturgeon 'absence'=1. Two additional binary vectors were created to test whether Type 0 and Type 4 individually predict significantly higher sturgeon presence than all other Types combined.

2.3.3.3 Habitat Selection Ratios

Habitat selection ratios were determined to infer whether lake sturgeon are selecting for specific Types. As the lower South Saskatchewan receiver locations were selected based on pre-existing habitat selection information only Lake Sturgeon observations detected using passive receivers in the Upper South Saskatchewan River were included in this analysis. Manly habitat selection ratios (*wi* =used/available habitat) were calculated and tested using the adehabitatHS package in R (R Core Team, 2015). Available habitat was calculated as the number of receivers located in a given Type over the two winters of data collection and each individual was treated as having equal access to these receivers as connectivity was maintained in the upper South Saskatchewan River study area. Used habitat was determined based on the number of times each

Lake Sturgeon was observed at a given receiver (Table2-1). Habitat selection was tested for each animal using Chi-square and an overall population selection determined using Bonferroni-adjusted 90% confidence intervals. Selection ratios greater than 1 indicate selection for a given habitat while avoidance is indicated by ratios less than 1.

2.4 Results

Of the 48 fish tagged in the lower South Saskatchewan and Saskatchewan Rivers, 33 returned to overwinter in the study area at least once during the study period. It is possible that individuals that did not return to the forks site overwintered in the North Saskatchewan River, which was not considered in the present study, or downstream in Codette Reservoir. Of the 123 fish tagged in the Upper South Saskatchewan, Oldman, and Bow rivers, 66 fish were logged by receivers in the South Saskatchewan River at least once during the overwintering months. It is likely that some individuals overwintered in the Oldman, Bow, or Red Deer Rivers, which were not considered in the present study, or other areas in the South Saskatchewan River that were beyond the range of the receivers. Based on a total of 5,269 Lake Sturgeon observations, 4205 (%79) of observations fell within Type 0 (royal blue), 1020 (%19) within Type 4 (red) and 44 (%1) within Type 6 (purple) (Figure 2-4a). All of the Type 6 and none of the Type 0 observations were in the Saskatchewan River (Figure 2-2). See Table 2-1 for a complete list of tagged lake sturgeon individuals and the number of observations associated with different Types. Tracking effort was not equal among all possible types, with eight of the possible fifteen types sampled (Figure 2-3, Figure 2-4b). Types 0 and 4 had higher sampling effort due to a priori knowledge of known overwintering sites which were monitored in both studies, 3 receiver locations in Type 0 and 4 receiver locations in type 4. The receiver in Type 6 was the only other receiver to detect Lake Sturgeon and when standardized by the number of days a receiver was present in a given type, proportions of sturgeon observations remain comparable (Type 0 = %89, Type 4= %11, Type 6 = %0.001). Though there is some variation in the proportion of Types within the study area the three Types of interest are not consistently more prevalent than the other Types (Figure 2-4c). Figure 2-3 further emphasizes an apparent preference for specific sites as receivers located in other Types had no associated sturgeon observations.

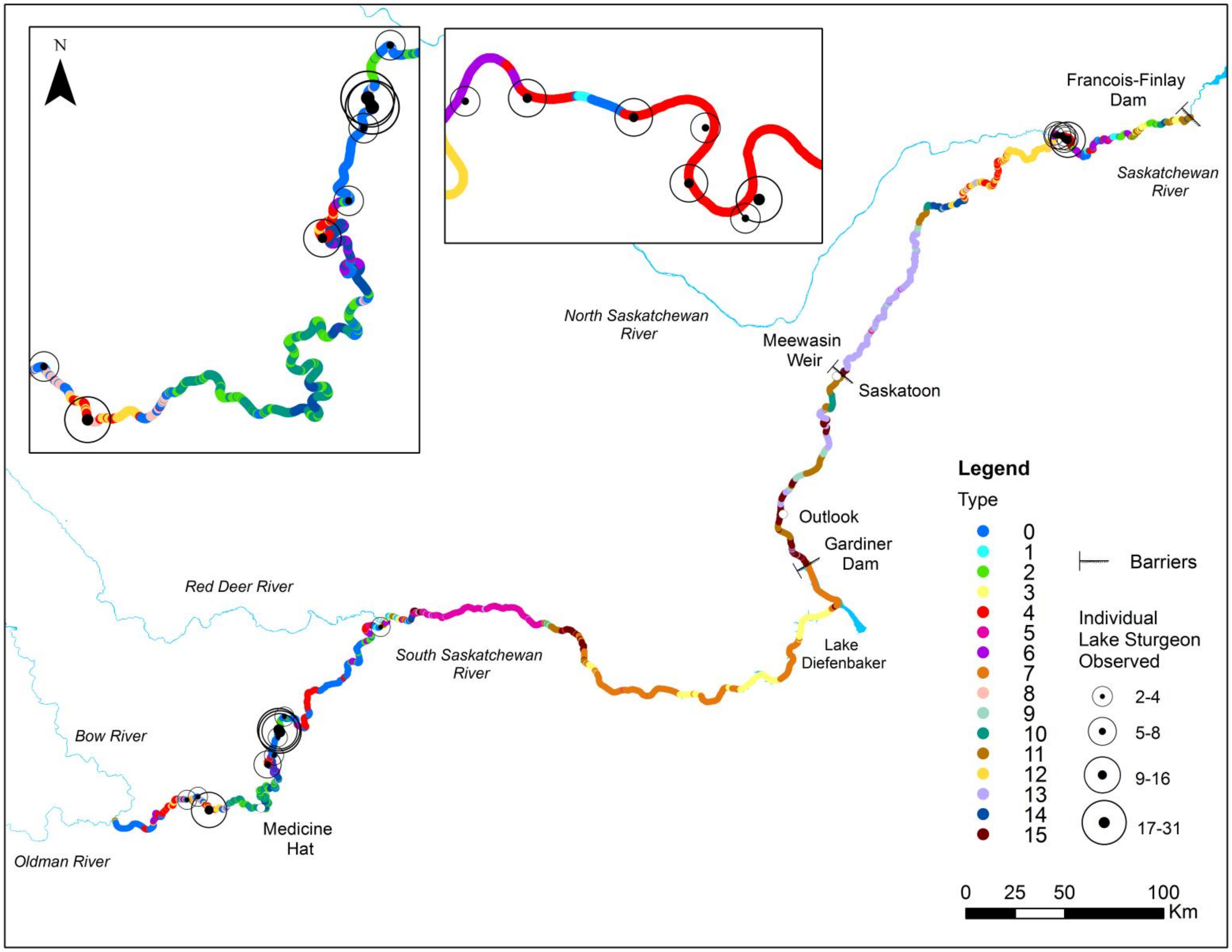

Figure 2-2. 50m river segments colour coded by Type with sturgeon overwintering locations. Size of circle around each center point is weighted by the number of individual Lake Sturgeon observed at that site over the study period.

Table 2-1. Tagged Lake Sturgeon individuals and the number of times they were observed within Types associated with the hydroacoustic and radio telemetry receivers. Individuals coded as ##f## are implanted with radio transmitters and individuals coded with numbers only are implanted with hydroacoustic transmitters.

Fish ID	**0**	**2**	**4**	**6**	**7**	**10**	**11**	**14**	**Fish ID**	**0**	**2**	**4**	**6**	**7**	**10**	**11**	**14**
00f65	0	0	13	0	0	0	0	0	339	0	0	17	0	0	0	0	0
02f65	0	0	10	3	0	0	0	0	341	0	0	44	0	0	0	0	0
03f65	0	0	9	0	0	0	0	0	342	79	0	0	0	0	0	0	0
04f65	0	0	27	0	0	0	0	0	344	39	0	0	0	0	0	0	0
05f65	0	0	24	0	0	0	0	0	345	0	0	75	0	0	0	0	0
08f65	0	0	15	0	0	0	0	0	346	165	0	0	0	0	0	0	0
09f65	0	0	21	0	0	0	0	0	347	34	0	0	0	0	0	0	0
11f65	0	0	12	1	0	0	0	0	348	128	0	0	0	0	0	0	0
12f65	0	0	11	0	0	0	0	0	48562	206	0	0	0	0	0	0	0
13f65	0	0	17	0	0	0	0	0	48563	184	0	0	0	0	0	0	0
14f65	0	0	14	0	0	0	0	0	48565	157	0	0	0	0	0	0	0
15f24	0	0	2	0	0	0	0	0	48566	155	0	0	0	0	0	0	0
15f65	0	0	10	0	0	0	0	0	48567	178	0	0	0	0	0	0	0
15f85	0	0	14	0	0	0	0	0	48568	117	0	0	0	0	0	0	0
16f65	0	0	10	0	0	0	0	0	48569	209	0	0	0	0	0	0	0
17f24	0	0	9	0	0	0	0	0	48570	106	0	0	0	0	0	0	0
17f65	0	0	16	0	0	0	0	0	48571	1	0	0	0	0	0	0	0
19f24	0	0	12	0	0	0	0	0	48572	281	0	0	0	0	0	0	0
19f65	0	0	20	0	0	0	0	0	48573	162	0	59	0	0	0	0	0
19f85	0	0	11	0	0	0	0	0	48574	199	0	0	0	0	0	0	0
20f24	0	0	0	40	0	0	0	0	48575	0	0	33	0	0	0	0	0
20f65	0	0	11	0	0	0	0	0	48576	184	0	0	0	0	0	0	0
21f24	0	0	8	0	0	0	0	0	48577	1	0	0	0	0	0	0	0
21f65	0	0	9	0	0	0	0	0	48579	12	0	0	0	0	0	0	0
22f24	0	0	10	0	0	0	0	0	48580	0	0	8	0	0	0	0	0
22f65	0	0	12	0	0	0	0	0	48581	45	0	0	0	0	0	0	0
23f24	0	0	24	0	0	0	0	0	48583	0	0	13	0	0	0	0	0
23f65	0	0	11	0	0	0	0	0	48585	42	0	0	0	0	0	0	0
24f24	0	0	4	0	0	0	0	0	48588	0	0	10	0	0	0	0	0
24f65	0	0	7	0	0	0	0	0	48590	0	0	37	0	0	0	0	0
26f65	0	0	11	0	0	0	0	0	48591	0	0	12	0	0	0	0	0
75f65	0	0	13	0	0	0	0	0	48592	300	0	0	0	0	0	0	0
287	34	0	0	0	0	0	0	0	48594	16	0	0	0	0	0	0	0
289	0	0	16	0	0	0	0	0	48597	0	0	14	0	0	0	0	0
294	0	0	23	0	0	0	0	0	48598	0	0	11	0	0	0	0	0
295	0	0	4	0	0	0	0	0	48605	0	0	26	0	0	0	0	0
302	0	0	19	0	0	0	0	0	48607	2	0	0	0	0	0	0	0
303	13	0	6	0	0	0	0	0	48608	0	0	12	0	0	0	0	0
305	0	0	16	0	0	0	0	0	48609	0	0	16	0	0	0	0	0
306	8	0	0	0	0	0	0	0	48610	0	0	35	0	0	0	0	0
311	0	0	16	0	0	0	0	0	48613	112	0	0	0	0	0	0	0
313	0	0	1	0	0	0	0	0	48614	170	0	0	0	0	0	0	0
316	115	0	0	0	0	0	0	0	48615	112	0	0	0	0	0	0	0
324	161	0	0	0	0	0	0	0	48616	46	0	0	0	0	0	0	0
326	42	0	0	0	0	0	0	0	48617	97	0	0	0	0	0	0	0
328	2	0	9	0	0	0	0	0	48618	17	0	0	0	0	0	0	0
329	25	0	0	0	0	0	0	0	48619	137	0	0	0	0	0	0	0
332	0	0	14	0	0	0	0	0	63334	0	0	65	0	0	0	0	0
337	0	0	12	0	0	0	0	0	63336	112	0	0	0	0	0	0	0
									Total	4205	0	1020	44	0	0	0	0

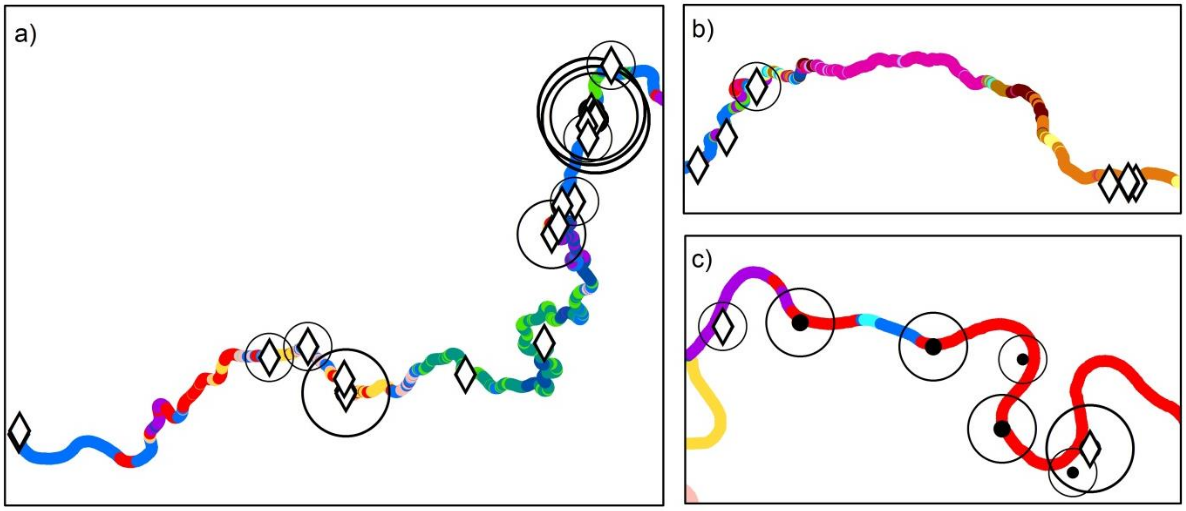

Figure 2-3. Receiver locations (diamonds) in relation to sturgeon overwintering observations in a) the South Saskatchewan River (a and b) and the Saskatchewan River (c).

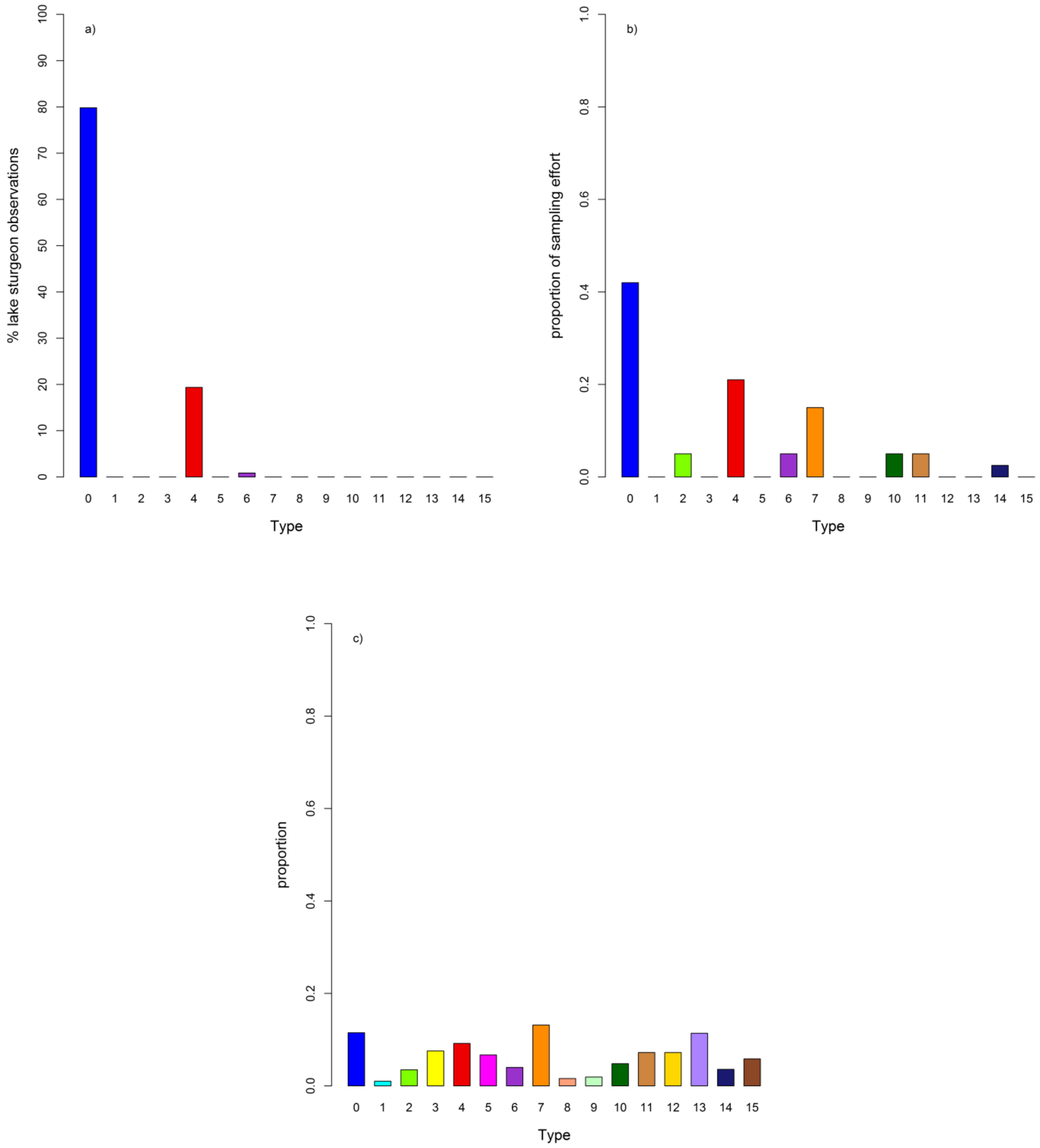

Figure 2-4. a) A bar plot showing the percentage of sturgeon overwintering observations within each Type. b) A bar plot showing the proportion of days that receivers were in a given Type to visualize sampling effort c) A bar plot showing the proportion of each geomorphic Type within the study area.

Results of logistic regression models suggest that Lake Sturgeon are not randomly distributed and that both Type 0 and Type 4 individually predict significantly higher sturgeon presence than all other Types combined (P = < 2e-16 for both). Overall habitat selection ratios for Upper South Saskatchewan Lake Sturgeon were 1.844 for Type 0 and 0.774 for Type 4 (Figure 2-5), indicating that Type 0 is significantly selected for over all other possible habitat types (Figure 2-5). Though Type 4 is selected for before the other remaining Types the ratio is below 1 suggesting it is not significantly selected for in the Upper South Saskatchewan River (Figure 2-5).

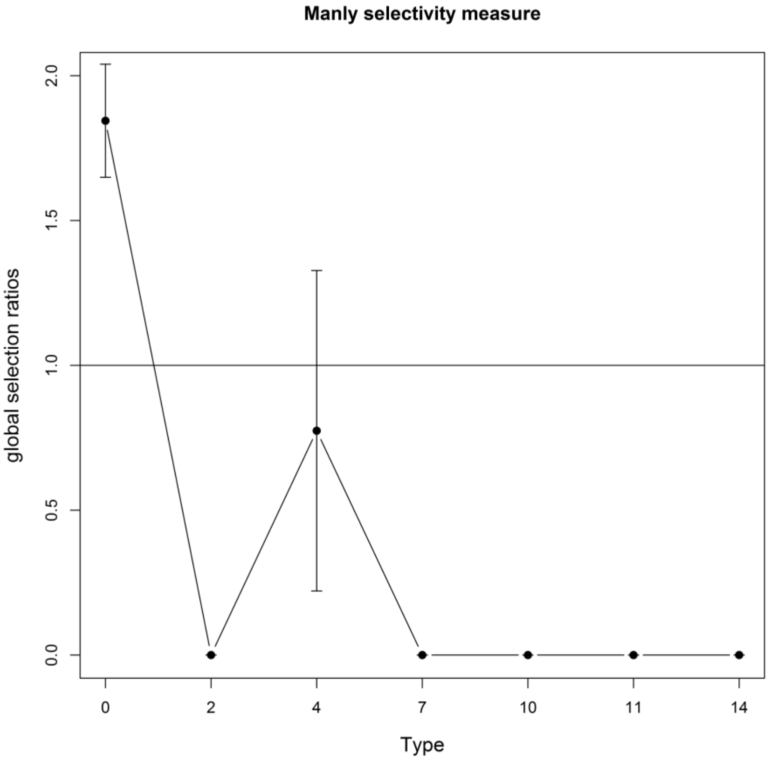

Figure 2-5. Plot of global selection ratios with Bonferroni-adjusted 90% confidence intervals for each possible Type associated with receivers in the Upper South Saskatchewan River.

Interpretation of general relationships between the four geomorphological variables stream slope, fractal dimension, sinuosity, and width, as well as their relationships within Types of interest were investigated using biplots. Figure 2-6 shows the PCA scores (colour coded by

Type) and variable vectors plotted in terms of principal component one on the x axis, and component two on the y axis. This two-dimensional representation of four dimensional data shows that in general slope and width are highly negatively correlated (see vectors are pointing in opposite direction) while fractal dimension and sinuosity appear to be positively correlated (vectors pointing in the same direction) (Figure 2-6).

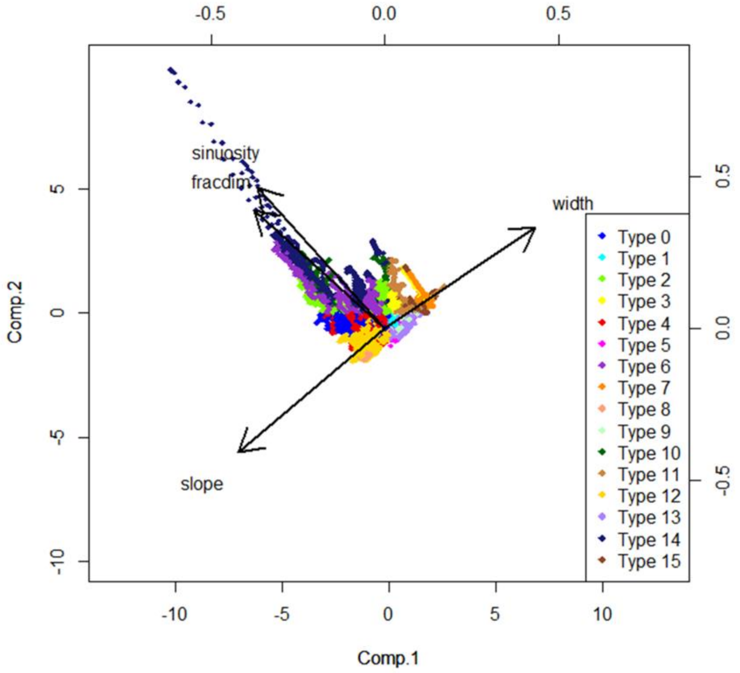

Figure 2-6. Biplot of PCA scores (colour coded by Type) and the four variable vectors: sinuosity, slope, fractal dimension, and stream width, plotted in relation to principal component 1 (x axis, 57% variance) and 2 (y axis, 19%).

Figure 2-7 specifically investigates the relationship between variables within the Types of interest, Type 0, Type 4 and Type 6. Figure 2-7 a) expresses the data in terms of principal components one and two that account for 76% of the variance in the dataset.

Type 0 (blue) and 4 (red) are closely related and therefore share similar characteristics of the four variables. Both tend to be negatively related to width (and therefore are relatively narrower sections of river), and positively related to slope (and therefore relatively steeper stream gradient) (Figure 2-7a). Variation between sinuosity and fractal dimension can be teased apart to better understand differences between Type 0 and 4 by rotating the PC axes and looking at components two and three that account for 34% of the variance in the dataset (Figure 2-7b). Due to the reduction in explained variance only general interpretations of differences between the two Types can be made. Based on Figure 2-7b we can infer that Type 0 tends to have higher fractal dimension values and Type 4 tends to have lower fractal dimension values, while Type 6 is positively correlated with sinuosity.

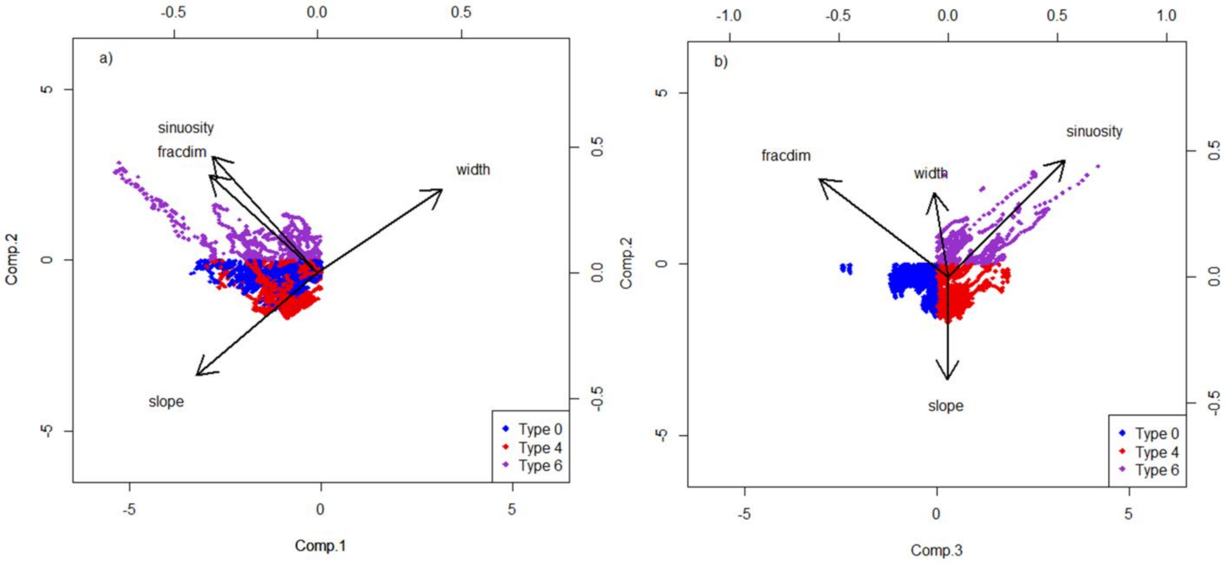

Figure 2-7. a) Type 0, Type 4, and Type 6 plotted in terms of principal components one (x axis) and two (y axis) accounting for 76% of variation within the dataset. b) Type 0, Type 4, and Type 6 plotted in terms of principal components 3 (x axis) and 2 (y axis) accounting for 34% of variation within the dataset.

Histograms of the normalized values of sinuosity, slope, fractal dimension, and channel width were used to further examine how these variables qualitatively contribute to each Type based on absolute means (Figure 2-8). Figure 2-8 provides an example of histograms for Type 0 and Type 4 and, similarly to the biplots, suggests that both are strongly negatively influenced by width and positively related to slope. Type 0 is positively related to Fractal dimension while Type 4 tends to be negatively correlated with Fractal dimension and sinuosity has negligible influence on both Types. Table 2-2 summarizes the findings for each Type. Results of the Krusal-Wallis analysis of variance on ranks show that every Type interaction has at least one geomorphological variable being significantly different, with the majority of interactions (69%) having significant differences between all four geomorphological variables (Table A-1).

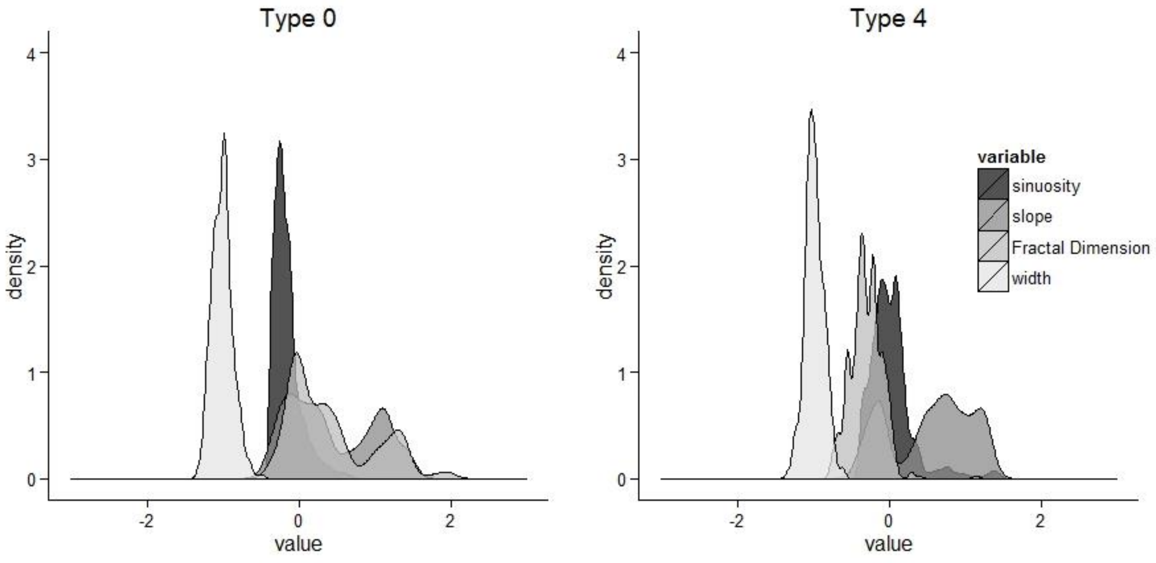

Figure 2-8. Histograms of the normalized values of channel sinuosity, slope, fractal dimension and width for Type 0 and Type 4.

Table 2-2. Qualitative contribution of variables to each Type derived from the principal component analysis. - = negative relationship, - - = highly negative relationship, + = positive relationship, and + + = highly positive relationship, 0= no discernable relationship.

Type	sinuosity	slope	fractal dimension	width
0	0	+	+	- -
1	-	-	-	-
2	+	+	++	-
3	0	- -	+	+
4	0	+	-	- -
5	0	0	-	-
6	+ +	-	+	- -
7	-	- -	- -	+
8	0	+ +	+	- -
9	-	0	-	+
10	+	+	+ +	-
11	-	-	+	+
12	0	+ +	-	- -
13	-	+	-	+
14	+ +	+	+	-
15	+	+	+	+

2.5 Discussion

By linking geomorphic Types to general lake sturgeon habitat characteristics identified in Saskatchewan River System studies we can improve our understanding of how fluvial geomorphological processes influence the formation of physical riverine habitats. Lake sturgeon overwintering areas in the Saskatchewan River System were related to specific geomorphic Types resulting from this study (Figure 2-2). When these types occur in relatively regular patterns we can combine them into GRUs allowing the identification of river sections that exhibit similar geomorphology and provide similar habitat. For example Type 0, 4 and 6 occur together fairly consistently and could therefore be combined into a sturgeon overwintering GRU. However, a different combination of types occurs at overwintering sites in the reach upstream of Medicine Hat (Figure 2-2). The overwintering sites are still in Type 0 and 4 but they are occurring in very short stretches alongside types 8 and 12 (Figure 2-2). This difference in pattern may be due to the influences of substrate or depth as they fall into a different surficial sediment deposit than the other overwintering locations. There are other obvious Type patterns occurring within the system including the Diefenbaker Reservoir where Types 3 and 7 occur together in a regular pattern, as well as upstream of the reservoir where Type 5 occurs consistently, or downstream of Saskatoon with Type 13 (Figure 2-2). These clear patterns do not occur throughout the entire system and areas with complex Type associations are difficult to assess visually and GRU definition can become arbitrary. Dimensionality reduction via the removal of principal components in the PCA step of analysis may aid the identification of GRUs by eliminating redundant Types.

Characterizing geomorphic Types allows the identification of patterns within the Saskatchewan River system and basic geomorphological concepts allow us to infer how these large scale patterns relate to in-stream patterns. Knighton (1998) identifies channel pattern as representative of the horizontal plane of channel form adjustment that is additional to but linked with both lengthwise and transverse modes of channel form adjustment. A natural stream moving toward a state of dynamic equilibrium will choose the path that minimizes the energy expenditure rate, or achieves minimum stream power (Yang and Song 1979). This is achieved by a reduction in stream slope or alternately, changes in meandering that reduces channel gradient relative to the straight path between two fixed points (Knighton 1998). Additionally, cross-sectional shape of a stream itself is an important factor governing the shape of river meanders with shallow and wide channels being associated with flat meanders (low tortuosity) and deep narrow channels with sharp meanders (high tortuosity) (Chitale 1973). This is influenced by differences in the location of active bank erosion within channel reaches that occurs at the apex of bends in deep narrow channels and a considerable distance downstream in shallow wide channels (Chitale 1973). Sediment load can also influence channel pattern with more sinuous, deep, and narrow channels having a low bed load: suspended load ratio and relatively straight, shallow, and wide channels having a high bed load: suspended load ratio (Schumm 1977).

In the Saskatchewan River System lake sturgeon have been found to congregate in small numbers of deep “holes” along river bends (R.L. & L. Environmental Services 1991, Watters 1993, SWA 2011, 2012, WSA 2013). Our results support these findings as sturgeon overwintering observations consistently occurred on river bends coinciding with Type 0 that tends to occur in meandering reaches with relatively high fractal dimension (Figures 2-2, 2-4). Despite unequal sampling effort among types, the receiver in type 6 was the only other receiver to detect Lake Sturgeon, suggesting that type 0 and type 4 are more likely to be associated with overwintering habitat than other sampled types. These areas are suitable for the formation of deep holes as they are relatively narrow with higher slope suggesting low bed load levels, and active erosion at the apex of the channel bend to counter the slope.

Although channel pattern characteristics are fairly consistent throughout both Type 0 and Type 4 lake sturgeon do not appear to be overwintering consistently throughout the entire length of these Types (Figures 2-2, 2-3). Studies have suggested that overwintering site selection is based on foraging (Chiasson 1997, SWA 2011, 2012). Therefore the presence of prey species within specific parts of a GRU may influence actual overwintering locations within a given GRU. Adult lake sturgeon diets are generally comprised of benthic macroinvertebrates and recent findings by the Saskatchewan Water Security Agency propose that crayfish comprise approximately 85% of lake sturgeon diet in the Saskatchewan River (SWA 2011, 2012, WSA 2013). This has also been found in Lake of the Woods and the Rainy River, Ontario where crayfish accounted for up to 70% of lake sturgeon diet (Mosindy and Rusak, 1991). The Northern Crayfish (*Orconectes virilis*) has been observed to move into deeper water to avoid freezing and they do not actively burrow, suggesting they may overwinter in similar areas and be available for forage (Aiken 1968). It is also possible that holes are only formed and maintained long term in these specific locations. A study of anomalous scour holes in the Mackenzie Delta System by Beltaos (2011) found that scour holes occur most often on river bends at confluences and restrictions in the river channel and they considered ice processes as a possible mechanism for the formation of deep scour holes via hanging dam formation or ice jamming. Ice processes often lead to localized events that may explain the apparently sporadic location of overwintering sites within certain Types though there is currently no historical ice dataset for the Saskatchewan River to investigate this possibility. These processes would most likely occur during spring break up (Beltaos 1984) when most sturgeon begin migrating away from the overwintering areas (SWA 2011, 2012, WSA 2013). A study of flow velocity modelling in a Mackenzie Delta scour hole found that the regions upstream of scour holes experience a greater magnitude of shear stress than areas directly in the hole and downstream (Gharabaghi 2007). Two vortices form over the hole, a larger one near the inner bank and the other near the outer bank, creating flow reversal and greatly reducing bed shear stress (Gharabaghi 2007). These areas likely provide an energetically advantageous refuge for large fish such as sturgeon. Gharabaghi (2007) did not investigate flow velocities under ice cover which would increase flow resistance at the surface and may increase flow depths (Teal *et al.* 1994). This is unlikely to affect bottom dwelling sturgeon as deep sections likely have a smaller average velocity relative to the rest of the river regardless of these conditions. Variation in erodability of bed materials is also an important consideration in the formation of deep scour holes (Gharabaghi 2007, Belatos 2011). Water discharge, bank material, depth and sediment characteristics such as mode of transport, concentration and size, are also important in dictating channel pattern as they influence erosion and deposition (Chitale 1973). It is possible that these variables are interacting in different ways within a given GRU to create subtle gradients of different in-stream habitats that exhibit similar large scale patterns.

2.6 Conclusion

Lake sturgeon overwintering areas in the Saskatchewan River System were associated with specific Geomorphic Types resulting from this study and habitat selection ratios suggest that fish in the Upper South Saskatchewan River are significantly selecting for Type 0 (Figure 2-2, 2-5). It is clear that in certain stretches these Types occur in very specific patterns and they can be agglomerated to form different GRUs (see Diefenbaker Reservoir, upstream of Diefenbaker Reservoir, or downstream of Saskatoon in Figure 2-2). This study was a first tier approach (desktop study), future work will investigate a second tier approach in which field data traditionally used in defining lake sturgeon habitat, such as depth and substrate (Chiasson 1997, Barth 2009, Gerig 2011, SWA 2011, 2012) will be integrated into the analysis and the model further refined. Understanding how these variables are linked to GRUs and how their inclusion in deriving Types influence overall GRU delineation will further verify the effectiveness of using GRUs to identify lake sturgeon habitat areas. The findings of this study have the potential to greatly increase the efficiency of managing lake sturgeon in large prairie rivers. Knowing which geomorphic Types are preferred for overwintering sites allows the prediction of where wintering holes may be in other rivers such as the North Saskatchewan. These areas can then be surveyed to see if there are significantly more sturgeon present than would be expected by chance and serve as further validation for the GRU model. This model can contribute to the management decision process as it allows the identification of river reaches that should be investigated as possible key overwintering habitat areas for Lake Sturgeon. This can help determine which reaches should be protected from development and conserved to ensure sturgeon populations are maintained. It can also be a valuable tool for study design as reaches can be selected *a priori* and sampling programs developed as needed saving valuable time and funding.

PREFACE TO CHAPTER 3: GEOSPATIAL MODELLING OF THE BIRCH RIVER: DISTRIBUTION OF CARMINE SHINER (*Notropis percobromus*) IN GEOMORPHIC RESPONSE UNITS (GRU)

Through his work on the Birch River, Jeff Long, along with Karl-Erich Lindenschmidt, recognized that the GRU model could potentially identify critical habitat of the Carmine Shiner and pinpoint predictive restoration habitat of the species at risk in the upper reaches of the Birch River. Both Karl and Jeff presented this concept at the Canada-Manitoba Fisheries Advisory Committee in Winnipeg in 2011. I executed GIS and statistical analyses, and am the primary author of this manuscript. Eva Enders and Jon Svendsen conducted fish surveys and laboratory analyses and proof read manuscript drafts. Douglas Watkinson prepared fish survey methods for inclusion in the manuscript and provided feedback on manuscript drafts. Karl-Erich Lindenschmidt (supervisor of this research) in collaboration with Jeff Long, developed the theoretical GRU framework used in this study and made necessary revisions to the manuscript. I, Meghan Carr (80%) carried out the bulk of the contributions to the preparation of the manuscript with remaining authors: Douglas Watkinson (5%), Jon Svendsen (5%), Eva Enders (5%), and Karl-Erich Lindenschmidt (5%) contributing comments during the review process. Funding for this project was provided by the Manitoba Fisheries Enhancement Fund.

Chapter 3 is published in International Review of Hydrobiology. See:

Carr, M.K., Watkinson, D.A., Svendsen, J.C., Enders, E.C., Long, J., and K.-E. Lindenschmidt. 2015. Geospatial modelling of the Birch River: Spawning distribution of Carmine Shiner (*Notropis percobromus*) in Geomorphic Response Units (GRU). International Review of Hydrobiology. 100: 1-12. DOI 10.1002/iroh.201501789

CHAPTER 3: GEOSPATIAL MODELLING OF THE BIRCH RIVER: DISTRIBUTION OF CARMINE SHINER (*Notropis percobromus*) IN GEOMORPHIC RESPONSE UNITS (GRU)

3.1 Abstract

The Carmine Shiner (*Notropis percobromus*) is a threatened cyprinid with a limited distribution in Canada occurring only in a few tributaries in the Winnipeg River watershed in southern Manitoba. Very little is known about the critical habitat requirements of Carmine Shiner. The Geomorphic Response Unit (GRU) method was used to identify potential critical spawning habitat of Carmine Shiner. The GRU method is a promising geospatial modelling technique that allows the identification of river reaches that exhibit similar geomorphic structure and provides a link between the hydrological regime and species habitat preference. Carmine Shiner catch data from spring 2011, GIS (Geographic Information System), and multivariate derived GRUs were used to characterize possible Carmine Shiner spawning sites in the Birch River. Differences in the median mature Carmine Shiner CPUEs among the GRUs are not statistically different (Kruskal-Wallis test H =1.723; df = 3, p value = 0.632), though interesting qualitative relationships were identified which may inform further studies. Results indicate that immature Carmine Shiner (58%) prefer geomorphically variable reaches while mature Carmine Shiner (50%) prefer low sinuosity reaches punctuated by increases in slope for spawning habitat. Identifying spatial patterns in the distribution of Carmine Shiner during spawning has the potential to increase understanding of habitat requirements and can aid in management efforts for this threatened species.

3.2 Introduction

Rivers are inherently dynamic systems with fluctuations in water quality, connectivity, hydrology, and geomorphology (Lindenschmidt and Long 2012). Flora and fauna are uniquely adapted to the dynamic equilibrium formed by the interaction of these variables (Lindenschmidt and Long 2012). The study of fluvial geomorphology examines riverine channels including the hydrological and geological processes that create specific structures (Lindenschmidt and Long 2012). Rodríguez-Iturbe and Valdés (1979) were the first to propose that geomorphological processes influence the hydrological response of a river. Flow timing and volume in turn shape the biota and ecological functioning of river systems and influence habitat forming variables such as sediment, connectivity (Poff *et al.* 1997), and biogeochemical cycling (McDowell *et al.* 2002, Nestler *et al.* 2012). Geomorphology has since been recognized as an important factor in defining biological (Walters *et al.* 2003, D'Ambrosio *et al.* 2009) and ecological characteristics of rivers (Thorp *et al.* 2006, Bizzi and Lerner 2012), and more specifically, aquatic habitats (Duncan *et al.* 2011, Bizzi and Lerner 2012).

Studies have found links between fish assemblages and geomorphology in streams and rivers using geomorphological variables (Walters *et al.* 2003, Sullivan *et al.* 2006, Dauwalter *et al.* 2007, D'Ambrosio *et al.* 2009). These studies required intensive field sampling of biological and geomorphological variables at the reach scale (Walters *et al.* 2003, Sullivan *et al.* 2006, D'Ambrosio *et al.* 2009). Though findings support the view that geomorphology is linked to fish habitat, a reductive method that identifies large scale patterns may be a more efficient approach to understanding such relationships. Response units have been used extensively to organize large scale hydrological and geomorphological processes into computationally manageable units that exhibit similar characteristics, most of which can be derived from readily available GIS data layers with moderate effort (Flugel 1997, Becker and Braun 1999, Cammeraat 2002, Sidorchuk *et al.* 2003, Güntner and Bronstert 2004). Thorp *et al.* (2006, 2008) developed Functional Process Zones (FPZ) to delineate units of similar response within riverine ecosystems. They view rivers as longitudinal arrangements of functionally and structurally similar hydrogeomorphic patches formed by flow and geomorphological characteristics. Currently, the idealized FPZ theoretical framework is extensive, including several morphological and flow covariates (Thorp *et al.* 2008). In contrast, the Geomorphic Response Unit (GRU) method developed by Lindenschmidt and Long (2012) is a purely geomorphological approach using data derived exclusively from GIS to identify river reaches exhibiting similar hydrological and geomorphological processes and provides a link between the hydrological regime and habitats of fish species. Geomorphological processes are in dynamic equilibrium, thus, trends and patterns are considered at inter-annual and decadal temporal scales and can only be linked to long term biological outputs (Lindenschmidt and Long 2012).

Although links have been identified between GRUs and Lake Sturgeon (*Acipenser fulvescens*) overwintering locations (Carr *et al.* 2014) and within-site relative species abundance (Lindenschmidt and Long 2012), GRU's have yet to be examined for their ability to establish links between the spatial distribution of an individual species during the spawning period. Identifying spatial patterns in the distribution of Carmine Shiner during spawn has the potential to increase understanding of habitat requirements and can aid in management efforts for this threatened species (SARA 2003, COSEWIC 2006). An intensive field sampling of Carmine Shiner (*Notropis percobromus*) was conducted in the Birch River in 2011. By combining GRUs and fish location data, we can characterize areas of known use in the Birch River and potentially predict the presence of Carmine Shiner habitat in other Winnipeg River tributaries as well as potentially refine critical habitat requirements identified for the species in the SARA Recovery Strategy (Fisheries and Oceans 2013).

The objective of this study was to examine if Carmine Shiner distribution and abundance in the Birch River during the spawning period is related to specific GRUs. Understanding the relationship between GRUs and Carmine Shiner locations is a promising first step in identifying potential spawning habitat in the Birch River and predicting occurrence of critical habitat elsewhere within their distribution.

3.3 Methods

3.3.1 Study Site

The Birch River has a drainage area of 864 km² (Water Survey of Canada 2014) and is located in the Whitemouth River watershed in south eastern Manitoba (Figure 3-1). It originates at Birch Lake and flows north approximately 17 river kilometers (rkm) to a major confluence with the Boggy River and then continues approximately 52 rkm west and north before its confluence with the Whitemouth River. The watershed cover is dominated by wetlands, trees/shrubs, grasslands/pasture, and annual crops, and the upper portions have low levels of anthropogenic disturbance (Clarke 1998). The Birch River predominantly flows through alluvial sediments characterized by sand, gravel, silt, clay and organic detritus. The river originates in organic deposits with the upper reaches then flowing through sand and gravel dominated marginal glaciolacustrine sediments formed by waves at the margin of glacial Lake Agassiz. Alluvial deposits become more common throughout the mid and lower reaches of the river. Deposits of calcareous silt diamicton till, predominantly derived from dolomite and limestone, occur throughout the mid reaches. Offshore glaciolacustrine sediments characterized by clay, silt, and minor sand dominate in the lower reaches of the river (Matile and Keller 2004). Low relief bedrock outcrops are also relatively common throughout the river as it lies along the fringe of the Canadian Shield which is exposed in the Eastern portion of the watershed (Clarke 1998). The Birch River supports a unique fish fauna in Manitoba that includes Carmine Shiner, Hornyhead Chub (*Nocomis biguttatus*), and Northern Brook Lamprey (*Ichthyomyzon fossor*).

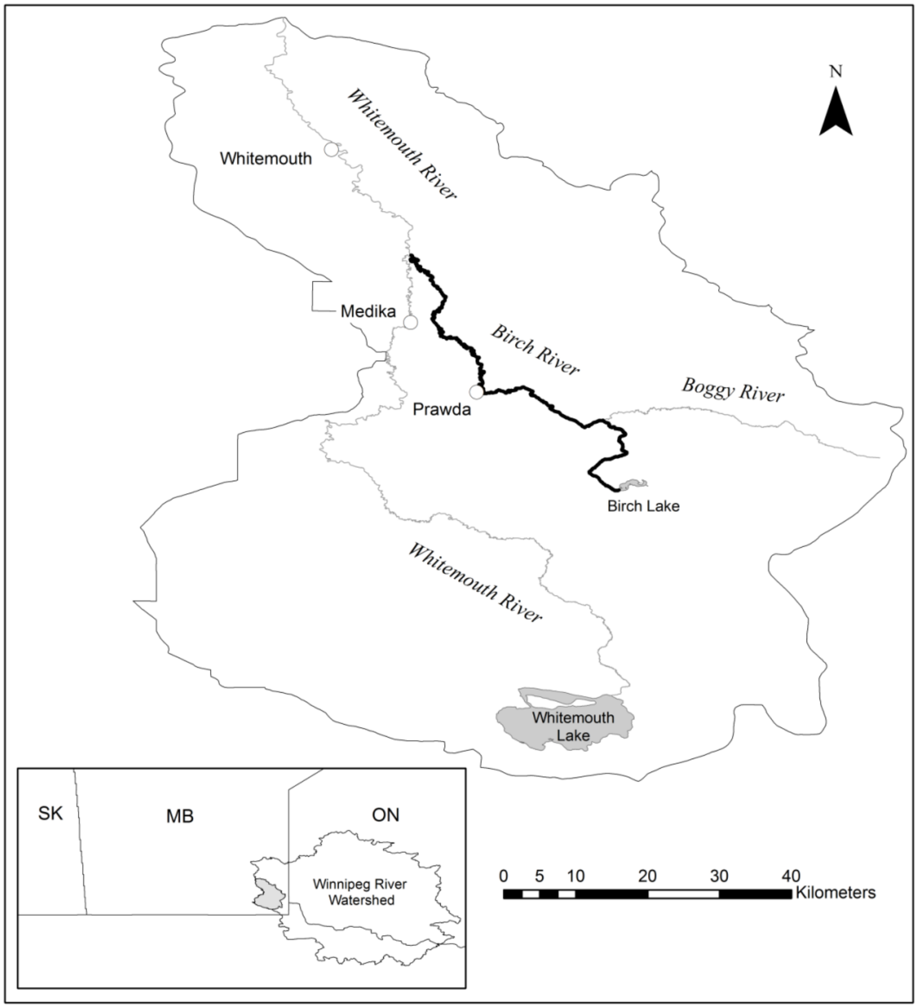

Figure 3-1. The Whitemouth River Watershed, Manitoba, Canada

3.3.2 Data Collection

3.3.2.1 Geomorphological Variables

GIS (ESRI 2013) was used to extract geomorphological variables characteristic of large scale river structure and functional processes from 1:50,000 digital elevation model (DEM) files (Department of Natural Resources Canada). The river was delineated by adding a centerline along its length, inserting points every 50 m along this centerline, then intersecting each of these centerline points and both riverbanks with transects (Figure 3-2) (Lindenschmidt and Long 2012). This delineation allowed four geomorphological variables to be calculated at each of the centerline points: sinuosity, slope, fractal dimension, and stream width (Lindenschmidt and Long 2012).

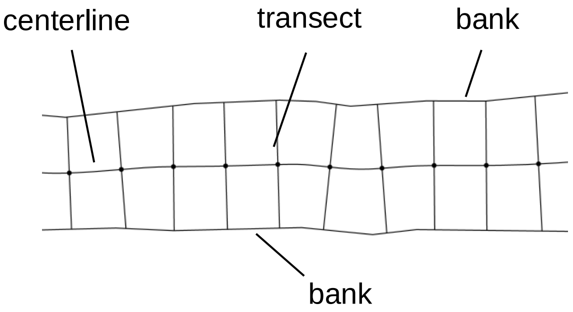

Figure 3-2. River delineation in GIS. Sinuosity, slope, and fractal dimension are determined at each of the centerline points spaced every 50 m along the river. Transects pass through each centerline point, their lengths representing stream width at each centerline point.

Sinuosity is the ratio of the actual flow path between two points along the stream centerline and the shortest path length between the same two points. A sinuosity value (S) = 1 is a straight channel and meandering channels have S > 1. Sinuosity can be translated as a measure of meander ‘wiggliness’ (Ferguson 1977) whereas fractal dimension can be interpreted as a measure of the intricacy or irregularity in trains of meanders (Snow 1989, Nikora 1991, Montgomery 1996). Fractal dimension occurs at a larger scale or higher geometric level than sinuosity (Nikora 1991) and is more indicative of overall changes in river course rather than channel pattern (Snow 1989). Both sinuosity and fractal dimension were calculated using the commercial software package Mathcad® v.15 (MathSoft Inc., Cambridge, MA, 2012).

Geomorphic Types were determined via multivariate principal component Analysis (PCA) using the statistical package R 2.15.2 (R Core Team 2012) as described in Lindenschmidt and Long (2012). The explained variance of principal components one through four was 35%, 25%, 22% and 17%, respectively. Following Jolliffe's (1972, 2002) modified Kaiser's rule, the eigenvalue for component 4 was less than 0.7 (0.678), therefore only the first three principal components (accounting for 82% cumulative variance) were used to derive Types. This resulted in eight unique geomorphic Types as opposed to 16, greatly improving ease of large scale pattern identification which is the goal of the GRU method. Each Type was assigned a unique colour and plotted to its corresponding 50 m river segment (Figure 3-3). Density plots of the normalized values of sinuosity, slope, fractal dimension, and channel width were used to further examine how these variables qualitatively contribute to each geomorphic Type based on absolute means. The Type patterns were then visually assessed to identify spatial groupings of Types and five unique Geomorphic Response Units were identified (Fig. 3). Once initial boundaries were identified the proportions of Types within each GRU were placed in a table and compared to GRU classification rules: 1) GRUs must be at least one km (20 adjacent points) in length; 2) Type proportions must be within 25% of one another for each reach of a given GRU with the exceptions that a) when shifting GRU boundaries only serves to negatively impact proportions in adjacent GRUs, delineation is considered acceptable when the total proportion of 2-4 main Types is >70%, and b) one GRU may be considered highly variable if each reach is composed of >4 Types and does not fit the delineation rules. These rules were developed by comparing results of ongoing GRU studies and appear to be robust across multiple prairie rivers.

3.3.2.2 Fish Surveys

Fish catch data were obtained from Fisheries and Oceans Canada (DFO) surveys performed in June and July, 2011. The Birch River has limited public access, so the river was accessed at one of six road crossings located approximately at rkm 9, 16, 30, 37, 43, and 52 upstream from the confluence of the Birch and Whitemouth rivers. A boat was used to move on the river and sample sites at different rkm. Access point selection and rkm selection were both randomized, without replacement and the left or right bank was randomly chosen. The river was fished approximately twice a week following this strategy from June 6th to July 20th, 2011. Fish were collected at each sample site with three pass seining similar to Reid and Hogg (2014). The seine was 9.14 m long x 1.82 m high with a 1.82 x 1.82 m bag and 4.76 mm ace meshing throughout. One end of the seine was held stationary on shore and the other end was stretched out along shore in the upstream direction and then pulled fully deployed the half arc of a circle to complete the haul (Bonar *et al.* 2009). If the water was deeper than 1 m, the boat was used to pull the seine. Fish were removed from the seine after each haul and placed in a holding tub. Larger fish (> 30 mm) were identified to species, fork length (F_L) measured to the nearest 1 mm, and released back at the site at the completion of sampling. Much of the catch was composed of fish less than 30 mm; these fish were preserved in 95% ethanol on site and transported back to the lab for species identification and to measure fork length. Substrate (including vegetation and woody debris) was estimated to the closest 5% composition using a modified Wentworth scale (Cummins 1962); clay (<0.0039 mm); silt (0.0039-0.0625); sand (0.0625-2 mm); gravel (2-64 mm); cobble (64-256 mm); boulder (>256 mm); and bedrock. Time and location was recorded with a handheld GPS. Sampling was conducted between 08:30 and 17:00 h.

Individual spatially referenced Carmine Shiner locations (GPS coordinate) from each sampling were then overlain in GIS and linked to the nearest 50 m centerline point and its corresponding GRU (Figure 3-3). As the GRUs were identified after the fish surveys were completed, the sampling effort was not equally distributed across the GRUs. To correct for the unbalanced sampling, the catch-per-unit-effort (CPUE) was calculated for each GRU by dividing the CPUE in a given GRU by the number of times the GRU was sampled during the study (Table 3-1).

In addition to the fish surveys, a total of 240 Carmine Shiner (F_L range: 13.9 - 60.4 mm) were collected between July-October 2011 to determine sex and maturity status. Fish were preserved in ethanol and in the laboratory sex and maturity status were examined under a dissecting microscope. Sex was determined to be male, female or unknown. Maturity status was defined as immature, pre-spawning or mature similar to Kaeding and Koel (2011). The ovaries of immature Carmine Shiner were thin and had sand-grain size, primordial ova evident therein when a bright background (e.g., knife blade) was placed behind the ovary. Immature testes were thin, smooth, showed no such granules and were mainly anterior in the abdominal cavity. Mature female Carmine Shiners that had spawned were identified when residual ova were present in ovaries. If residual ova were absent mature females had developing, loosely-packed ova in ovaries that themselves appeared shrunken, extended along much of the length of the abdominal cavity, and may have shown purplish blotches suggestive of prior hemorrhages. The testes of mature Carmine Shiner were no longer string-like, as were the gonads of immature Carmine Shiner of both sexes, but were enlarged, and in prespawners were white (but shrunken and purplish or gray in post-spawners). An observed minimum F_L for mature fish was determined. This length of ≥ 46 mm was used to define if a caught and released fish during the June and July fishing surveys was immature or mature.

3.3.3 Data Analysis

3.3.3.1 PCA Validation

PCA stability was investigated to validate the PCA model. A non-parametric bootstrap PCA was performed using 1000 iterations to calculate eigenvalue confidence intervals in R. Following Jackson (1993) and Jollife (2002), if small gaps between eigenvalues are avoided and confidence intervals for consecutive PCs do not overlap then the likelihood of instability in the retained PCs is greatly reduced.

3.3.3.2 Autocorrelation

Ecological data are commonly influenced by spatial structures due to spatial autocorrelation, whereby observations from geographically near sample locations are more likely to have similar magnitude than by chance alone (Fortin *et al.* 2002). A Mantel test was used to infer whether total CPUE expresses a non-random linear relationship, or spatial autocorrelation, by examining correlation between two distance matrices using the ade4 package in R. One distance matrix contained the spatial distances between sample sites and the other contained distances (differences) between catch per unit effort values at each sample site. An exact randomization technique based on 1000 replicates was applied to determine whether samples located closer together have significantly higher correlation between CPUE values.

3.3.3.3 ANOVA on Ranks

Kruskal-Wallis analysis of variance on ranks was performed to determine whether Carmine Shiner CPUE's were statistically different between GRUs using the statistical software SigmaPlot version 11.0 (Systat Software Inc., San Jose, CA). Graphical analyses were performed using the statistical package R 2.15.2 (R Core Team 2012).

3.4 Results

3.4.1 PCA validation and auto correlation

PCA results were effectively stable as eigenvalues differed and there was no overlap in eigenvalue 95% confidence intervals: PC1= (1.338, 1.460), PC2= (0.969, 1.053), PC3= (0.882, 0.937), PC4= (0.646, 0.710). Mantel test results (r= 0.0294, p value= 0.244) show no significant correlation between matrices suggesting that the CPUE data is not spatially autocorrelated.

3.4.2 Geomorphic Types associated with different GRUs

Figure 3-4 provides an example of density plots showing relationships between the distribution of normalized values for the different geomorphological variables for the Types present in GRU I and GRU II (Fig. 3-4). Table 1 provides an interpretation of density plots and describes how each variable contributes to geomorphic Types (Table 3-1).

GRU I is the most variable of all of the Birch River GRUs, with four different Types: 4, 5, 6 and 7 repeating throughout these reaches (Fig. 3-3). Types 4, 6, and 7 are all positively related to sinuosity, while Types 4, 5, and 7 are all positively related to fractal dimension, and Types 5, 6, and 7 are negatively related to slope (Fig. 3-4, Table 3-1). Type 7 is also positively related to width and is the only Type to have any relationship with this variable (Table 3-1). Type 4 is the only Type in GRU I that is positively related to slope (Table 3-1). Overall, this GRU is the most sinuous unit, with high fractal dimension, and variable widths and slope (Fig. 3-3). GRU II is composed mainly of Type 3 with some Type 1 and GRU III is primarily Type 1 (Fig. 3-3). Type 1 and 3 are both negatively related with sinuosity, while Type 1 is highly positively related to fractal dimension and Type 3 is highly negatively related to slope (Fig. 3-4, Table 3-1). Type 1 has highly variable slope but tends to be more positively related (Table 3-1). Thus, both GRU II and III are straight reaches with GRU II having very low slopes and GRU III having variable but higher slopes and high fractal dimension (Fig. 3-3). GRU IV is mainly Type 2 with some Type 0 and 3, and GRU V is characterized by Type 0 (Fig. 3-3). Types 2 and 0 are both strongly positively related to slope and negatively related to sinuosity while type 2 has low fractal dimension and 0 has high fractal dimension values (Fig. 3-3, Table 3-1). Both GRU IV and V have relatively straight, high slope channels, with GRU IV having lower fractal dimension than GRU V.

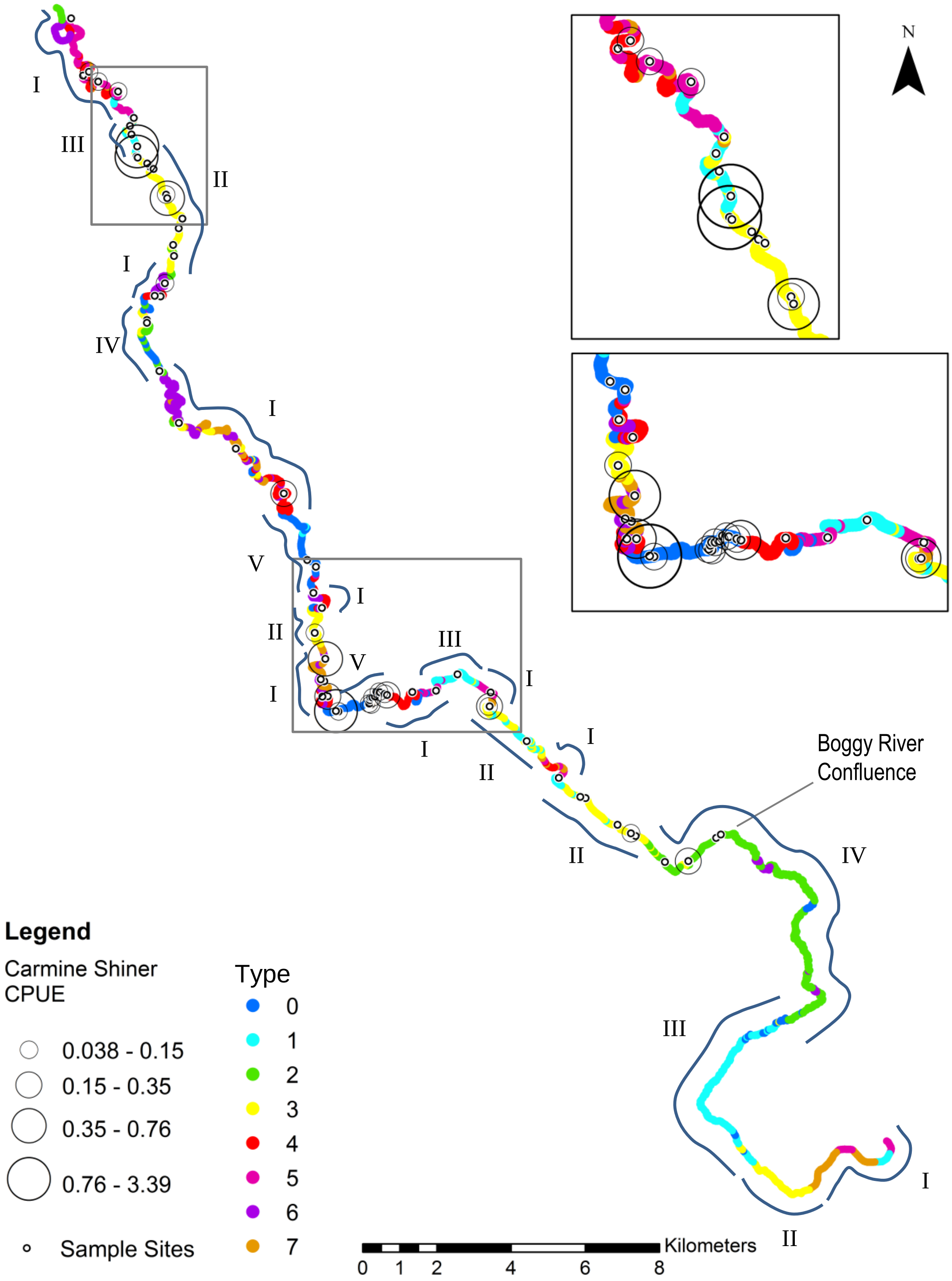

Figure 3-3. Geomorphic Response Units (GRU: I-V) derived from 50m river segment Types and associated Carmine Shiner locations. The size of the circle is weighted by the Carmine Shiner CPUE at a given site.

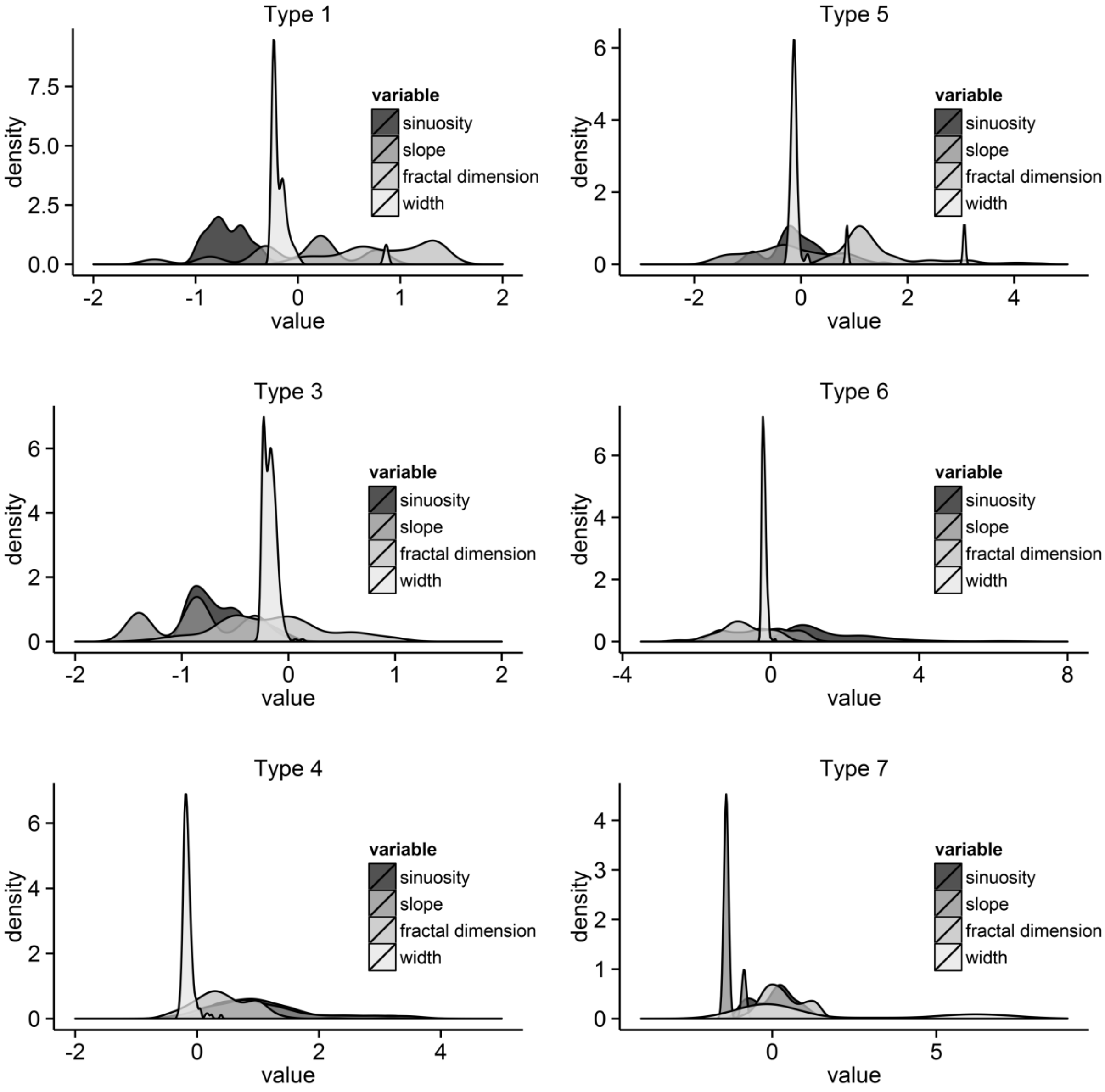

Figure 3-4. Histograms of the normalized values of channel sinuosity, slope, fractal dimension, and width for Types 1, 3, 4, 5, 6, and 7.

Table 3-1. Qualitative contribution of variables to each Type derived from the principal component analysis. - = negative relationship, - - = highly negative relationship, + = positive relationship, + + = highly positive relationship, 0= no discernable relationship.

Type	Sinuosity	slope	fractal dimension	width
0	- -	++	+	0
1	- -	+	+ +	0
2	-	+ +	- -	0
3	- -	- -	0	0
4	+	+	+	0
5	0	-	+ +	0
6	+ +	-	- -	0
7	+	-	+	+

Relative abundance of substrate types within different GRUs suggests that substrate compositions among GRUs are similar though GRU IV has the highest abundance of silt and roughly 50% more sand than all other GRUs and GRU III has no vegetation or woody debris and has the highest proportion of hard substrates (Figure 3-5).

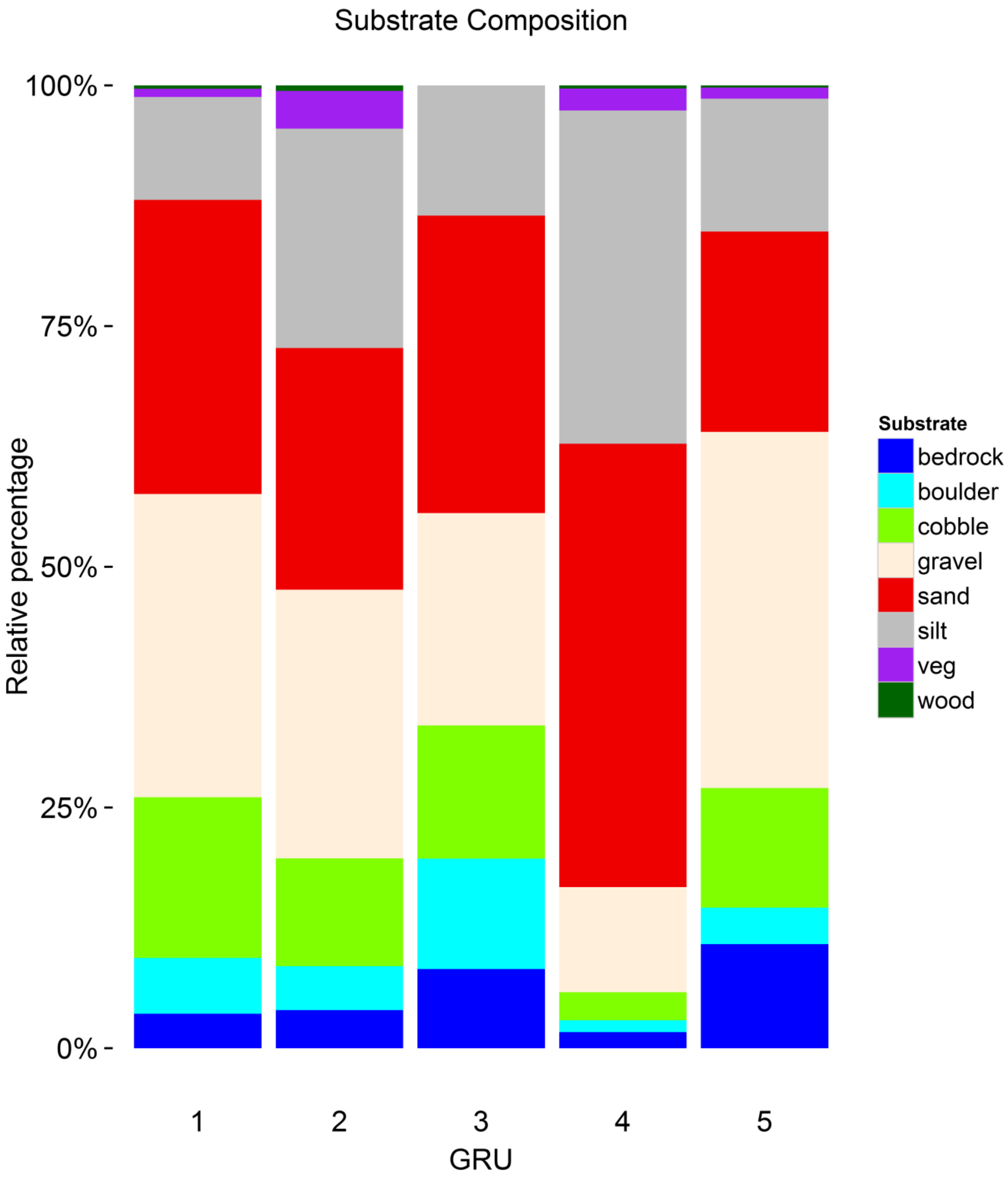

Figure 3-5. Relative abundance of substrate types in Birch River GRUs. Substrate, including vegetation and woody debris, was estimated to the closest 5% composition using a modified Wentworth scale (Cummins 1962); clay (<0.0039 mm); silt (0.0039-0.0625); sand (0.0625-2 mm); gravel (2-64 mm); cobble (64-256 mm); boulder (>256 mm); and bedrock.

3.4.3 Carmine Shiner distribution with respect to GRUs

Based on a total catch of 164 Carmine Shiner in June and July, GRU I and GRU II had the most observations, with a total of 89 and 45, respectively, while GRU IV and GRU III had the fewest observations with only 2 and 8, respectively (Table 3-2). However GRU II has the highest CPUE of 4.24, followed by 2.00 in GRU III, 1.73 in GRU I and 1.18 in GRU V (Table 3-2). Percent samples with Carmine Shiner observations ranged from only 13% in GRU IV to 41% in GRU V (Table 3-2).

GRU I and GRU II were with 34% and 28%, respectively, the most commonly sampled GRUs present in the study area, with GRU IV (11%) and GRU VI (22%) being the second most common. Although GRU III is the least often sampled unit within the Birch River, it was associated with the second highest Carmine Shiner CPUE (Table 3-2). However, the differences in the median Carmine Shiner CPUEs among the GRUs are not statistically different (Kruskal-Wallis, test H =1.891; df = 4, p value = 0.756).

Table 3-2. Numbers and CPUE of Carmine Shiner in each of the GRUs

GRU	I	II	III	IV	V
# samples	26	21	4	8	17
Total Carmine Shiner observed	45	89	8	2	20
% samples with Carmine Shiner	35	29	25	13	41
% samples with mature Carmine Shiner	19	19	25	0	35
% samples with immature Carmine Shiner	19	14	0	13	6
CPUE	1.73	4.24	2.00	0.25	1.18
SD	0.14	0.74	1	0.09	0.18

3.4.4 Maturity status of Carmine Shiner

The minimum fork length (F_L) of mature Carmine Shiner specimens was ≥ 46 mm allowing assignment of maturity to 153 of the 164 total fish caught and released during the fishing surveys (Table 3-3). Of all recorded samples, eleven fish did not have recorded fork length measurements and were excluded from analysis. Twenty-two fish were identified as immature with a F_L range of 26.5-45 mm and mean F_L of 36.9 mm (SD = 5.1 mm). A total of 131 fish were identified as mature with a F_L range of 46-64 mm and a mean F_L of 53.5 mm (SD = 3.6 mm) (Table 3-3). Percent samples with mature Carmine Shiner observations ranged from 0 in GRU IV to 35% in GRU V, while percent samples with immature Carmine Shiner ranged from 0 in GRU III to 19% in GRU I (Table 2).

Table 3-3. Assigned maturity status of the caught and released Carmine Shiner during the June-July fishing surveys in the Birch River.

Maturity	Immature	mature
n	22	131
range (mm)	26.5 - 45	46 - 64
Mean F_L (mm) ± 1 SD	36.9 ± 5.1	53.5 ± 3.6

A graphical comparison of immature and mature Carmine Shiner CPUEs within each GRU suggests that immature fish are most often associated with GRU I (58%) while mature fish are most often seen in GRU II (50%) and GRU III (25%) (Figure 3-6). Although GRU III is often associated with mature individuals, immature individuals were not collected in this GRU (Figure 3-6). Though small sample size prevents a statistical comparison of CPUE between GRUs for immature individuals, differences in the median mature Carmine Shiner CPUEs among the GRUs are not statistically different (Kruskal-Wallis test H =1.723; df = 3, p value = 0.632).

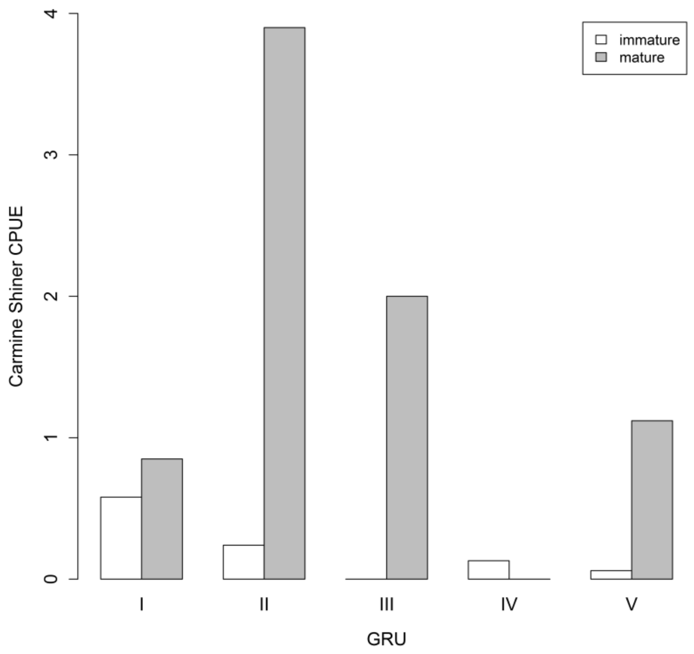

Figure 3-6. Carmine Shiner catch-per-unit-effort (CPUE) within each GRU grouped by maturity. Individuals with fork length (L_F) of ≥ 46 mm were considered mature. No immature fish were caught in GRU III and no mature fish were caught in GRU IV.

3.5 Discussion

General patterns in the distribution of Carmine Shiner were observed and can inform further studies in the Winnipeg River watershed. By linking GRU characteristics to general Carmine Shiner habitat characteristics identified in existing studies, we can improve our understanding of how geomorphological processes influence the formation of physical riverine habitats. Mature Carmine Shiner are most often associated with GRU II (50%) and GRU III (25%), suggesting these GRUs may be associated with favorable Carmine Shiner spawning habitat. Though little information exists on the spawning habits of Carmine Shiner in Manitoba, they are likely similar to those of Rosyface Shiner (*Notropis rubellus*) (Watkinson and Sawatzky 2013). Rosyface Shiner typically spawn in riffles over depressions in clean gravel (Pfeiffer 1955), sandy gravel, and bedrock (Trautman 1981), which are often nests constructed by other cyprinids including the Hornyhead Chub (*Nocomis biguttatus*) and Common Shiner (*Luxilus cornutus*) (Baldwin 1983). Eggs adhere to the substrate in the nests and larvae remain in bottom gravel until the yolk is absorbed (Pfeiffer 1955). Rosyface Shiner in Ontario and southern populations of Carmine Shiner typically begin spawning when water temperatures range between 20-30 °C (Pfeiffer 1955, Baldwin 1983, Becker 1983), which typically occurs between mid-June and into July in Manitoba (Watkinson and Sawatzky 2013). Field observations made during the 2011 data collection found some Carmine Shiner in spawning condition between June 10th to July 20th. Although all GRUs were sampled in June, Carmine Shiner locations were only associated with GRU I, II, and V during this month. Immature Carmine Shiners were most often associated with GRU I and to a lesser degree GRU II, which consistently occurs in sequence with GRU I (Fig. 3-5). Currently, habitat requirements for immature Carmine Shiner are largely unknown though immature Rosyface Shiners are often found in pool habitat with partially forested shores (Baldwin 1983).

The diverse surficial geology of the Birch River watershed contributes to the formation of diverse habitat features throughout the river. GRU I was the most sinuous unit, and had the most variable geomorphological characteristics according to the derived geomorphic Types (Figure 3). This GRU occurs in reaches dominated by alluvial deposits which have a more diverse mix of substrates and lower proportions of cohesive silt and clay than other deposits in the watershed. In GRU I, Type 7 consistently occurs near riffle areas, bedrock outcroppings, road crossings, and low level rock dams. Such local variations in the cross sectional form of a river can influence downstream hydraulic geometry relationships and are, thus, related to channel pattern and bed topography (Wolman 1955, Thompson 1986). In riffle-pool sequences, which are characteristic of both straight and meandering channels with heterogeneous bed material, width fluctuations likely result from flow characteristics produced by changes in bed topography (Richards 1976, Knighton 1998). As bed height increases over a riffle, flow is deflected toward one or both banks, which can induce undercutting, causing riffle widths to regularly surpass pool widths (Knighton 1998). Habitat for immature individuals is likely to occur in the lower gradient sinuous sections of GRU I where low bed load levels are expected and active erosion occurring at the apex of channel bends facilitates the formation of pool habitats. GRU I, II, and III also regularly occur in sequence, thus, proximity to GRU I could increase the accessibility to and therefore importance of these GRUs to different life stages. The variability associated with GRU I indicates that pool-riffle sequences are a common feature and may support the formation of suitable Carmine Shiner rearing and spawning habitat. It is also of note that immature fish, but no mature fish, were associated with GRU IV which may be due to the much higher proportion of sand within this unit (Fig. 3-5) as immature fish caught in the Whitemouth River have been associated with sand dominated substrates (Carmine Shiner Recovery Team 2007).

GRU II and III are also associated with several riffle areas and bedrock outcroppings, though they do not exhibit the same riffle-pool type of sequence characterised by width fluctuations and high sinuosity like GRU I. This suggests that these relatively straight reaches punctuated by higher gradient Type 1 are more constrained by bank materials preventing widening and meandering (Carling 1991). When the river subsequently begins to flow through less resistant alluvium, it will choose the path that minimizes the energy expenditure rate or achieves minimum stream power (Yang and Song 1979). This is achieved by a reduction in stream slope or alternately, changes in meandering that reduces channel gradient relative to the straight path between two fixed points (Knighton 1998), which is the transition into the highly sinuous GRU I (Fig. 3-3, Table 3-3). This transition is generally characterised by the initial presence of high slope Type 4, which then transitions into increased occurrence of lower gradient types 5, 6 and 7 or other constrained reaches of variable gradient (Fig. 3-3, Table 3-3). GRU II characteristics are also likely to coincide with favourable foraging habitats as adult Carmine Shiner are known to frequent shallow riffles with warm, clear water, and rocky substrates dominated by gravel and sand for feeding (Watkinson and Sawatzky 2013), which would likely be present in a high slope channel with resistant bed materials. Carmine Shiner are also often found taking cover behind boulders and fallen trees, features that were found in all GRUs with the exception of no woody debris present in GRU III sample sites (Fig. 3-5) (Carmine Shiner Recovery Team 2007).

Bedrock outcroppings occur throughout the river and can constrain channel morphology and influence channel width, lateral shifting, and gradient (Schumm 2005). When alluvial meanders encounter bedrock the upstream limb of the meander continues to migrate, while the downstream limb of the meander remains fixed in position. This can deform the meander in various ways such as creating a flattened top, multiple bends or sharp meanders. This variable morphology is further influenced by the variability of bank sediments and can differ greatly from one reach to the next. Such features are common within the Birch River, with sharp meanders and bends occurring in areas where alluvial sediments are more common, such as GRU I, and flattened or truncated bends being more common in GRU II and III (Fig. 3-3). GRU II and III are associated with glaciolacustrine and till deposits, with offshore deposits being dominated by cohesive sediments and marginal till deposits having higher proportions of less readily erodible gravel, cobble, and boulder elements. These features restrain erosion leading to deformed meanders. Bedrock deposits lying close to the surface can also force groundwater to the surface, increasing water supply to riparian vegetation (Schumm 2005). The interactions between riparian vegetation and fluvial geomorphology are complex (Tal *et al.* 2004) and vegetation can have both stabilizing and destabilizing effects on banks due to hydrologic and mechanical processes (Simon *et al.* 2004). The majority of the Birch River is surrounded by a forested riparian buffer so the influence of riparian vegetation on channel planform is difficult to infer. Though varying densities and species characteristics, such as roughness, root structure, and tensile strength can influence channel morphology through alteration of flow velocity/patterns, and deposition/erosion processes (Van De Wiel and Darby 2004), this is beyond the scope of the current study.

It is important to consider that fish often exhibit complex temporal movement patterns, even considerable diel movements, which were not examined in this study (Nunn *et al.* 2009). Habitat use was inferred based on the CPUE of Carmine Shiner within different GRUs. This study did not consider particular interactions of individuals with physical features, nor inter or intra-specific interactions and how these influence distribution of individuals within the study area. It is also of note that the majority of mature Carmine Shiner were caught at a specific GRU II location within 15 km of the confluence with the Whitemouth River. It is possible that the fish are responding to a particular habitat feature present at this location rather than the general characteristics of GRU II. Proximity to the confluence with the larger Whitemouth River may also influence the distribution of mature Carmine Shiner if a seasonal migration occurs from the Whitemouth River into the Birch River. However, sampling conducted later in the year confirmed young of the year Carmine Shiner were found in upstream reaches of the Birch River despite connectivity to these reaches being lost by the end of July. This suggests that spawning habitat was not limited to the lower reaches of the Birch River as it is unlikely that YOY individuals would have migrated that far upstream in such a short period of time. Determining the amount of time spent within specific GRUs would expand upon this initial investigation and increase our understanding of how GRUs relate to Carmine Shiner habitat. Existing literature suggests lateral and longitudinal connectivity is an important factor dictating current distribution patterns of this species. The presence of riparian vegetation that facilitates the addition of terrestrial insects is likely important due to the large proportion of terrestrial insects in their diet (Watkinson and Sawatzky 2013). As aforementioned, where riparian vegetation acts to stabilize shorelines erosion may be reduced (Beeson and Doyle 1995, Abernethy and Rutherford 1998) benefitting turbidity sensitive species like Carmine Shiner. Though exact effects are not known turbidity possibly interferes with visual feeding mechanisms (Zamor *et al.* 2007) and increased siltation could have negative effects on eggs and immature Carmine Shiner (Watkinson and Sawatzky 2013).

3.6 Conclusion

This study has identified qualitative relationships between geomorphology and Carmine Shiner CPUE data that may inform further studies. Immature Carmine Shiner were most often (58%) associated with geomorphically variable reaches while mature Carmine Shiner (50%) were most often associated with low sinuosity reaches punctuated by increases in slope. This information can contribute to habitat conservation and restoration efforts by informing habitat monitoring decisions.

The findings of this study suggest that GRUs have potential as a broadly applicable fisheries management tool. The efficiency of management efforts for Carmine Shiner and other riverine fish species can be greatly improved by identifying links between large scale patterns in geomorphic structure and species habitat preferences. Understanding which Geomorphic Response Units (GRU) are most commonly associated with Carmine Shiner locations in the Birch River allows the prediction of where suitable Carmine Shiner habitat may be in other Winnipeg River tributaries. This model can be a valuable tool for developing sampling programs, allowing efficient *a priori* site selection that ensures sampling of all unit types and thus greater representation of the range of physical habitats present in a system. GRUs can also help predict how anthropogenic changes in hydrology may influence connectivity and diversity of habitats within a system, though modelling specific changes to the geomorphic variables, and how long it will take such changes to occur is beyond the scope of the current model. GRUs could also allow the identification of river reaches that should be conserved and those that should be restored to ensure Manitoba Carmine Shiner populations are maintained.

PREFACE TO CHAPTER 4: IDENTIFYING LINKS BETWEEN GEOMORPHIC RESPONSE UNITS (GRU) AND FISH SPECIES IN THE ASSINIBOINE RIVER, MANITOBA

I executed GIS and statistical analyses, and am the primary author of this manuscript. The fish data collection was directed by Dr. Bill Franzin, and Dr. Patrick Nelson. Jeff Anderson, Stephanie Backhouse, Jeff Eastman, Dr. Bill Franzin, Dr. Patrick Nelson, North South Consultants, Richard Penner, Tommy Sheldon and Ernie Watson assisted with the fish collections. Douglas Watkinson prepared fish survey methods for inclusion in the manuscript and provided feedback on preliminary drafts. Karl-Erich Lindenschmidt, supervisor of this research, was one of the developers of the theoretical GRU framework used in this study and made necessary revisions to the manuscript. I, Meghan Carr (90%) carried out the bulk of the contributions to the preparation of the manuscripts with Douglas Watkinson (5%) and Karl-Erich Lindenschmidt (5%) contributing comments during the review process.

Chapter 4 has been accepted for publication by the journal Ecohydrology and the early view version is currently published online. See:

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CHAPTER 4: IDENTIFYING LINKS BETWEEN GEOMORPHIC RESPONSE UNITS (GRU) AND FISH SPECIES IN THE ASSINIBOINE RIVER, MANITOBA

4.1 Abstract

The Assiniboine River, located in east central Saskatchewan and southwestern Manitoba, provides recreational opportunities, irrigation, and industrial and municipal water resources to Manitoba residents while supporting a diverse fish fauna. Improving our understanding of patterns in the spatial distribution of different fish species in relation to physical habitat features can aid management of this important water resource. Geomorphic Response Unit (GRU) method is a geospatial modelling technique that allows the classification of large scale river reaches that exhibit similar geomorphic structure and provide a link between the hydrological regime and physical riverine habitats. Historical electrofishing data provides catch per unit effort data for various fish species and allows an investigation of fish distribution among different GRUs. This study has identified significant differences (Kruskal-Wallis test, $p<0.05$) in catch per unit effort (CPUE) between three GRUs for ten fish species in the Assiniboine River. These findings have the potential to increase our understanding of habitat complexity, availability and connectivity in Prairie rivers, a valuable tool for resource managers. This model can contribute to the development of sampling programs by allowing efficient *a priori* site selection, ensuring sampling of diverse unit types and thus a greater representation of the range of physical habitats present within a river system.

4.2 Introduction

Classification of dynamic river ecosystems has been a growing field of research since the introduction of the Riverine Continuum Concept (RCC) (Vannote *et al.* 1980). The RCC identified a longitudinal gradient in physical and biological characteristics of rivers as they move from headwaters (orders 1-3), through medium (4-6) to large rivers (>6) (Vannote *et al.* 1980). Carbon sources, primary production, respiration ratios, and general species assemblages tend to shift predictably along these gradients (Vannote *et al.* 1980). Though this model has been invaluable in helping understand the ecological functioning of rivers there are several shortcomings, including an inability to address impacts of water pollution, extraction, and damming on the longitudinal gradient. Additionally, this model was developed for application in relatively pristine forested catchments making it difficult to transfer to other ecozones. Other river ecosystem models such as the Serial Discontinuity concept (Ward and Stanford 1983), the Flood Pulse Concept (Junk *et al.* 1989), and the Riverine Productivity Model (Thorp and Delong 1994) have expanded upon the RCC by addressing the influence of damming, flood pulses, and local instream primary production and allochthonous inputs on the functional processes and patterns within river ecosystems. These studies suggest that river type and section are important factors influencing which ecological processes dominate, and thus, which models are most applicable in a given river reach (Humphries 2014). The recently proposed River Wave Concept (Humphries *et al.* 2014), provides an interesting theoretical framework for synthesising these riverine ecosystem models using wave theory to describe river flow. Their framework links different models to flow conditions based on the temporal or spatial position on the river wave: ascending or descending limbs (rising or falling hydrograph), trough (baseflow), and crest (peak flow) (Humphries *et al.* 2014). These models provide valuable insight into patterns of functional processes within rivers but they lack a framework for large scale application and classification of river reaches and associated physical habitats.

Thorpe and colleagues (2006, 2008) developed the heuristic Riverine Ecosystem Synthesis Model (RES) that integrates aspects of hierarchical patch dynamics from terrestrial landscape models in an effort to explain discontinuous patterns along river networks rather than the chiefly clinal perspectives of earlier models (Vannote *et al.* 1980, Ward and Stanford 1983, Junk *et al.* 1989). This conceptual framework identifies Functional Process Zones (FPZ) that delineate units exhibiting similar physical hydrological and geomorphic function (Thorpe *et al.* 2006, 2008). They view rivers as longitudinal arrangements of hydrogeomorphic patches, or FPZs, that can occur repeatedly along the length of the river network (Thorpe *et al.* 2006, 2008).Currently, the idealized FPZ theoretical framework is extensive, including several interdependent morphological and flow variables (Thorp *et al.* 2008). In contrast, the Geomorphic Response Unit (GRU) model developed by Lindenschmidt and Long (2012) provides a framework for identifying large scale patches that exhibit similar geomorphological and hydrological characteristics using data derived entirely from GIS (Geographic Information System). A GRU is representative of river segment structure and provides a link between the hydrological regime and physical habitat types to which species respond (Lindenschmidt and Long 2012).

Riverine fish exhibit complex life cycles and habitat use patterns associated with variations in body size as they grow from embryo to adult (Schlosser 1991). Geomorphological processes are directly and indirectly linked to the formation and maintenance of different habitat areas used during these stages of development. Physical habitat conditions can directly impact distribution of species as well as act indirectly by determining type and abundance of food resources (Rabeni and Minshall 1977) and influence the roles of competition or predation. Previous studies have determined that reach scale physical habitat features are influenced by geomorphic character (Bizzi *et al.* 2012, Dugdale *et al.* 2015) and that measures of channel geomorphology can be important predictors of species composition (Walters *et al.* 2003, Sullivan *et al.* 2006, Dauwalter *et al.* 2007). The GRU method has been used to classify geomorphic structure of the Similkameen River in British Columbia (Liu *et al.* submitted 2015) as well as the South Saskatchewan, Saskatchewan, Qu'Appelle, and Little Saskatchewan Rivers in the Canadian Prairie Provinces (Lindenschmidt and Long 2012, Carr *et al.* 2014, Meissner *et al.* submitted 2015). These initial studies identified relationships between geomorphic structure and Lake Sturgeon overwintering locations (Carr *et al.* 2014) and qualitative within-site relative species abundance (Lindenschmidt and Long 2012), but GRU's have yet to be investigated for their ability to identify statistical relationships between geomorphology and spatial distribution patterns of multiple fish species in prairie rivers. Previous studies have also focused on deriving geomorphic Types within individual rivers whereas this study uses a larger, network scale approach to GRU delineation by including the Qu'Appelle River tributary and the downstream Red River in the delineation in an effort to capture large scale differences in geomorphic character within the river network. The Assiniboine River, Manitoba, supports a diverse fish fauna including several game species such as Walleye (*Sander vitreus*), Sauger (*S. canadensis*), Channel Catfish (*Ictalurus punctatus*), Burbot (*Lota lota*), and Rock Bass (*Ambloplites rupestris*). Extensive electrofishing surveys conducted in the Assiniboine River between 1995-1996 and 2002 provide an opportunity to identify spatial patterns in the distribution and catch per unit effort (CPUE) of various fish species and how they relate to hydrogeomorphic character of the river system. The objective of this research is to identify relationships between GRUs and the CPUE of fish species that can contribute to our understanding of habitat complexity and connectivity within Prairie rivers, a valuable tool for identifying, managing, and maintaining riverine fish habitats.

4.3 Methods

4.3.1 Study Site

The Assiniboine River has a drainage area of 41,500 km² and is located in the Red River drainage basin in southwestern Manitoba (Figure 4-1). It originates in east central Saskatchewan flowing through the Boreal Plains Ecozone and into the Prairies Ecozone through the mid and lower Assiniboine (AAFC 2004). Agriculture is the primary land cover in the watershed with grassland, tree cover, and wetlands accounting for the majority of the remaining cover (Agriculture and Agri-Food Canada 2004). The Assiniboine flows through a region of diverse bedrock and surficial geology (Figure 4-1). The river channel is primarily embedded in alluvial (A) deposits characterized by stratified silt, clay and gravel, glaciofluvial plain, fine grained glaciolacustrine, course grained glaciolacustrine, and eolian deposits.

The study area runs from the Qu'Appelle confluence to the confluence of the Assiniboine at the Red River in the city of Winnipeg, Manitoba (Figure 4-1). Major tributaries within the study area are the Birdtail Creek and the Arrow, Oak, Little Saskatchewan, and Souris rivers (Figure 4-1). The Portage Diversion, located near Portage La Prairie, is a water control structure that diverts flow from the Assiniboine River north to Lake Manitoba through the Portage Diversion Channel in an effort to mitigate flooding in the Red River Valley (Figure 4-1). The Assiniboine River is home to over 50 species of fish (Stewart and Watkinson 2004) and provides several ecosystem services including municipal water supplies, irrigation, and recreational opportunities such as canoeing, fishing, boating activities, and swimming.

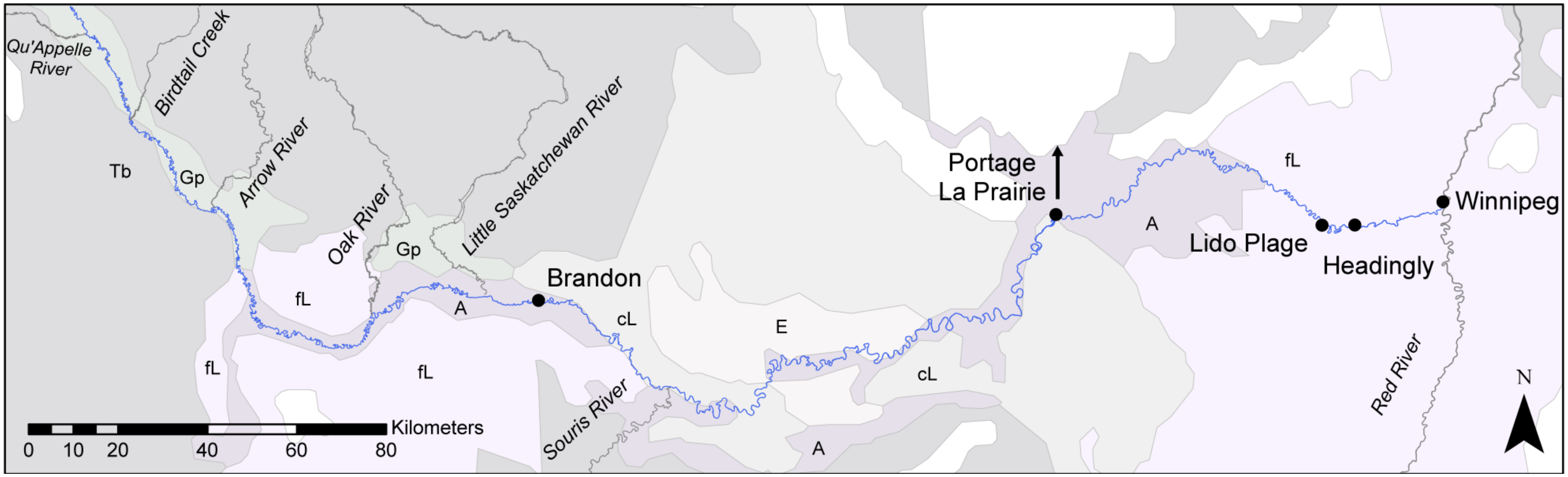

Figure 4-1. The Assiniboine River Study area and surficial geology. Tb- Till Blanket (thick continuous till), fL-Fine Grained Glaciolacustrine (silt and clay, containing stones; deposited as quiet water sediments), Gp- Glaciofluvial Plain (sand and gravel; deposited as outwash sheets, valley trains, and terrace deposits), cL- Coarse Grained Glaciolacustrine (sand, silt, and gravel; deposited as deltas, sheet sands, and lag deposits), A- Alluvial Deposits (stratified silt, sand, clay, and gravel; floodplain delta and fan deposits; in some areas overlies and includes glaciofluvial deposits), E-Eolian Deposits (sand and minor silt; dunes blowouts and undulating plains; mostly overlies deltaic sediments, coarse lacustrine sediments or glaciofluvial deposits). Arrow indicates direction of Portage Diversion Channel.

4.3.2 Data Collection

4.3.2.1 Geomorphological Variables

Geomorphological variables characteristic of large scale river structure and functional processes were extracted from 1:50,000 digital elevation model (DEM) data (Department of Natural Resources Canada) using Geographic Information System (GIS) software (ESRI 2013). The river was delineated by adding a centerline along its length, inserting points every 50m along this centerline, then adding transects that intersect each centerline point and both river banks (Figure 4-2) (Lindenschmidt and Long 2012). This delineation allowed four geomorphological variables to be calculated and extracted at each of the centerline points: fractal dimension, sinuosity, slope, and stream width (Lindenschmidt and Long 2012).

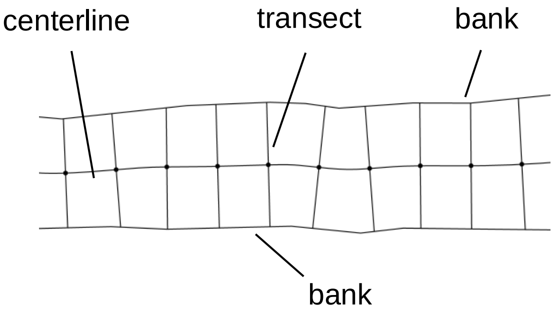

Figure 4-2. River delineation in GIS. Sinuosity, slope, and fractal dimension are determined at each of the centerline points spaced every 50 m along the river. Transects pass through each centerline point, their lengths representing stream width at each centerline point.

Sinuosity is the ratio of the actual flow path between two points along the stream centerline and the shortest path between the same two points, with sinuosity values (S) = 1 representing a straight channel and S > 1 a meandering channel. Sinuosity can be interpreted as a measure of meander 'wiggliness' (Ferguson 1977) whereas fractal dimension is a measure of the intricacy or irregularity in trains of meanders (Snow 1989, Nikora 1991, Montgomery 1996). Fractal Dimension occurs at a higher geometric level or scale than sinuosity (Nikora 1991) and is more indicative of overall changes in river course rather than channel pattern (Snow 1989). Sinuosity was calculated at a slightly larger scale than slope and width using 50 adjacent points (2.5 km) along the river course. Fractal dimension is calculated at a larger scale than sinuosity based on the number of points that fell within a 40 X 40 km square moved along the course of the river. These scales were chosen because they were the values at which peak variation was calculated. Both sinuosity and fractal dimension were calculated using the commercial software package Mathcad® v.15 (MathSoft Inc., Cambridge, MA, 2012).

Geomorphic Types were identified via multivariate principal component analysis (PCA) using the statistical package R 3.1.2 (R Core Team 2014) as described in Lindenschmidt and Long (2012). The explained variance of principal components one through four was 38%, 25%, 21%, and 16% respectively. Only the first three principal components (accounting for 84% cumulative variance) were used to derive Types as PC4 (0.631) did not pass the 0.7 eigenvalue threshold for significant components (Jolliffe 1972, 2002). This resulted in eight unique geomorphic Types. General relationships between the four geomorphological variables of sinuosity, slope, fractal dimension, and channel width, as well as their relationships within different types were inferred using a biplot. 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 type based on absolute means. Each Type was assigned a unique colour and plotted to its corresponding centerline point (Figure 4-3). The Type patterns were then visually assessed to identify spatial groupings and four unique Geomorphic Response Units were identified along the Assiniboine River study area (Figure 4-3). Because the objective of this study is to identify geomorphologically similar reaches along the river GRUs were assigned to reaches that exhibited repetitive patterns in Type associations, separating such units in transition zones where large scale patterns gradually or abruptly change (Figure 4-3). Patterns are assessed at the reach to segment scale examining approximately 100 km of river moving upstream to downstream. This resolution allows identification of patterns occurring at the segment scale, typically one to tens of kilometers in length, the scale at which major channel and floodplain features can be observed (Frissell *et al.* 1986).

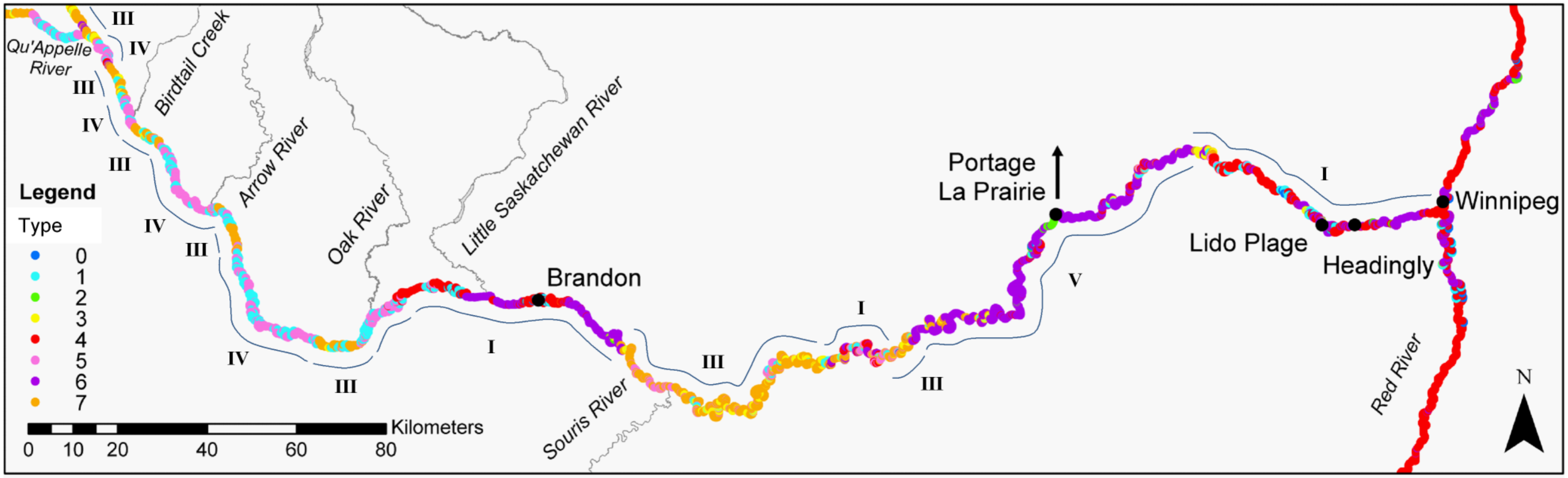

Figure 4-3. Geomorphic Response Units (GRU) derived from 50m river segment Types.

Once initial boundaries were identified the proportions of types within each GRU were placed in a table and compared to GRU classification rules: 1) GRUs must be at least 1km (20 adjacent points) in length; 2) type proportions must be within 25% of one another for each reach of a given GRU with the exceptions that a) when shifting GRU boundaries only serves to negatively impact proportions in adjacent GRUs, delineation is considered acceptable when the total proportion of 2-4 main types is >70%, and b) one GRU may be considered highly variable if each reach is composed of >4 types and does not fit the delineation rules. These rules were developed by comparing results of ongoing GRU studies and appear to be robust across multiple prairie rivers.

4.3.2.2 Electrofishing Surveys

Fish sampling was conducted over several different years. The first surveys were completed every month, August and September, 1995, and May to September 1996 in the Assiniboine River from Portage La Prairie (rkm 160) downstream to the confluence with the Red River (rkm 0) (Figure 4-4). The sample reach was stratified into sixteen 10 kilometre blocks and within each 10 kilometre block, three one kilometre sample sites were selected randomly for each of the seven sampling months (Nelson and Franzin 2000). Each one kilometre site was divided into three equal and sequential transects: the first along the right bank, the second in the center of the channel, and the third along the left bank, looking downstream, and fished for 150 seconds in an upstream to downstream direction with boat speed maintained slightly faster than the surface water velocity. Effort was recorded in seconds. Fishing was conducted using a single boom electrofishing boat equipped with a Smith-Root Mark VI electrofisher (450 volts pulsed DC; 2.5-3.5 amperes) (Nelson and Franzin 2000). This sampling design was repeated once for rkm 170-455, July 9-25, 2002 using a single boomed electrofishing boat equipped with a Smith-Root Type VI-A 5kW electrofishing unit set at 354 volts pulsed DC, 4 amperes. Fish were captured, placed in a holding tank, identified to species, measured for fork length and returned to the water after sampling. All sampling was conducted during daylight hours. Catch per unit effort (CPUE) was calculated as catch per minute (Guy *et al.* 2009). Velocity and depth measurements were recorded at each site and substrate was assessed at the beginning, middle, and end of the fishing transect using a 5-metre aluminum pole. Particle size was assigned based on a modified Wentworth scale (Cummins 1962); clay (<0.0039 mm); silt (0.0039-0.0625 mm); sand (0.0625-2 mm); gravel (2-64 mm); cobble (64-256 mm); boulder (>256 mm); and bedrock. If more than one substrate was present at an assessment site they were ranked as dominant, secondary or tertiary. Substrate at each sample site was then classified as fine (all particle sizes at the site ≤ sand), coarse (all particle sizes at the site > sand), mixed (any combination of fine and coarse particle sizes present).

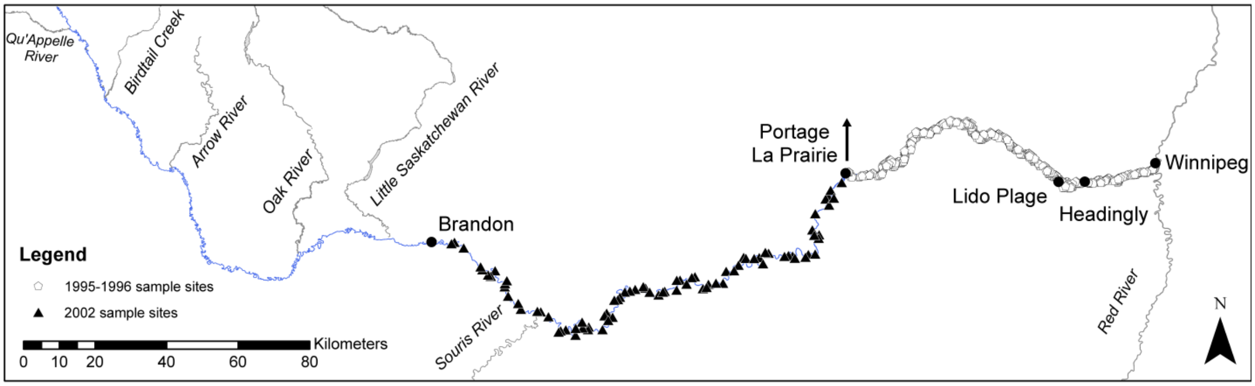

Figure 4-4. Electrofishing sample sites for 1995-1996 and 2002 sampling surveys.

4.3.3 Data Analysis

4.3.3.1 PCA Validation

The PCA model was validated by estimating stability using eigenvalue confidence intervals. A non-parametric bootstrap PCA was performed using 1000 iterations to calculate eigenvalue confidence intervals in R. Following Jackson (1993) and Jollife (2002), if small gaps between eigenvalues are avoided and confidence intervals for consecutive PCs do not overlap then the likelihood of instability in the retained PCs is greatly reduced.

4.3.3.2 Autocorrelation

Ecological data are commonly influenced by spatial structures due to spatial autocorrelation, whereby observations from geographically near sample locations are more likely to have similar magnitude than by chance alone (Fortin *et al.* 2002). A Mantel test was used to infer whether total CPUE expresses a non-random linear relationship, or spatial autocorrelation, by examining correlation between two distance matrices using the ade4 package in R. One distance matrix contained the spatial distances between sample sites and the other contained distances (differences) between catch per unit effort values at each sample site. An exact randomization technique based on 1000 replicates was applied to determine whether samples located closer together have significantly higher correlation between CPUE values.

4.3.3.3 ANOVA on Ranks

Kruskal-Wallis analysis of variance on ranks was performed to determine whether values of geomorphological variables were significantly different between GRUs using the FSA package for statistical software R 3.1.2 (R Core Team 2014). Kruskal-Wallis ANOVA was also performed on individual species to determine whether CPUE was statistically different between GRUs. Only species with ≥ 20 sampled individuals present in >5% (62) of sites were included in this analysis. In the event of a significant result post-hoc pairwise multiple comparisons were performed using two-sided Dunn's Test with Bonferroni p-value correction for multiple paired tests using the package FSA. Graphical analyses were performed using the statistical program R 3.1.2 (R Core Team 2014).

4.4 Results

4.4.1 PCA validation and auto correlation

PCA results were effectively stable as eigenvalues differed and there was no overlap in eigenvalue 95% confidence intervals: PC1= (1.519, 1.543), PC2= (0.995, 1.003), PC3= (0.831, 0.849), PC4= (0.623, 0.692). Mantel test results (r= -0.0142, p value= 0.684) show no significant correlation between matrices suggesting that the CPUE data is not spatially autocorrelated.

4.4.2 Geomorphic Types

Figure 4-5 shows the PCA scores (colour coded by Type) and variable vectors plotted in terms of principal component one on the x axis, and component two on the y axis. Principal component one and two account for 63% of the total variation in the dataset. This two-dimensional representation of four dimensional data shows that in general, width tends to be more negatively related to Fractal dimension and sinuosity (vectors are pointing in opposite directions) and slope has a variable relationship to width, fractal dimension and sinuosity (vectors are more perpendicular) (Fig. 4-5). GRU I, the most commonly sampled unit, is mainly composed of Type 4 with Type 1, Type 6, and in some reaches Type 5 and 7 also making large contributions (Figure 4-3). GRU III is largely composed of Type 7 with Type 1 and Type 3 being secondarily important (Figure 4-3). The majority of GRU Vis comprised of Type 6 with sporadic occurrences of all other Types accounting for <7% of Type proportion in all reaches (Figure 4-3). Figure 4-6 provides an example of density plots for common Types in the three sampled GRUs (Figure 4-6). General relationships for all eight types are summarized in Table 1. Results of the Krusal-Wallis analysis of variance on ranks show that all GRU interactions had at least three geomorphological variables being significantly different, with only slope having an insignificant difference between GRU I and III (Table B-1).

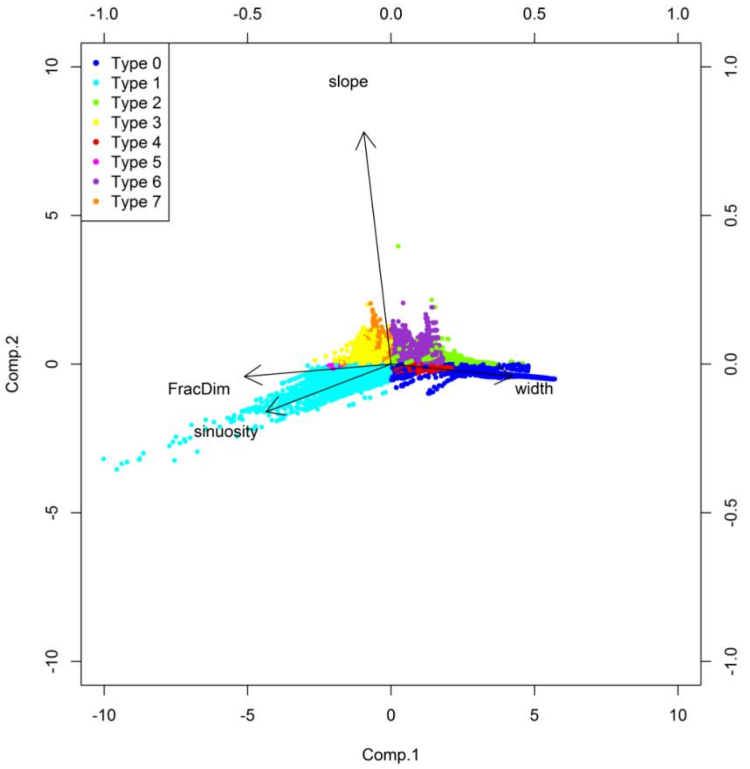

Figure 4-5. Biplot of PCA scores (colour coded by Type) and the four variable vectors: sinuosity, slope, fractal dimension, and stream width, plotted in relation to principal component 1 (x axis, 36% variance) and 2 (y axis, 25% variance).

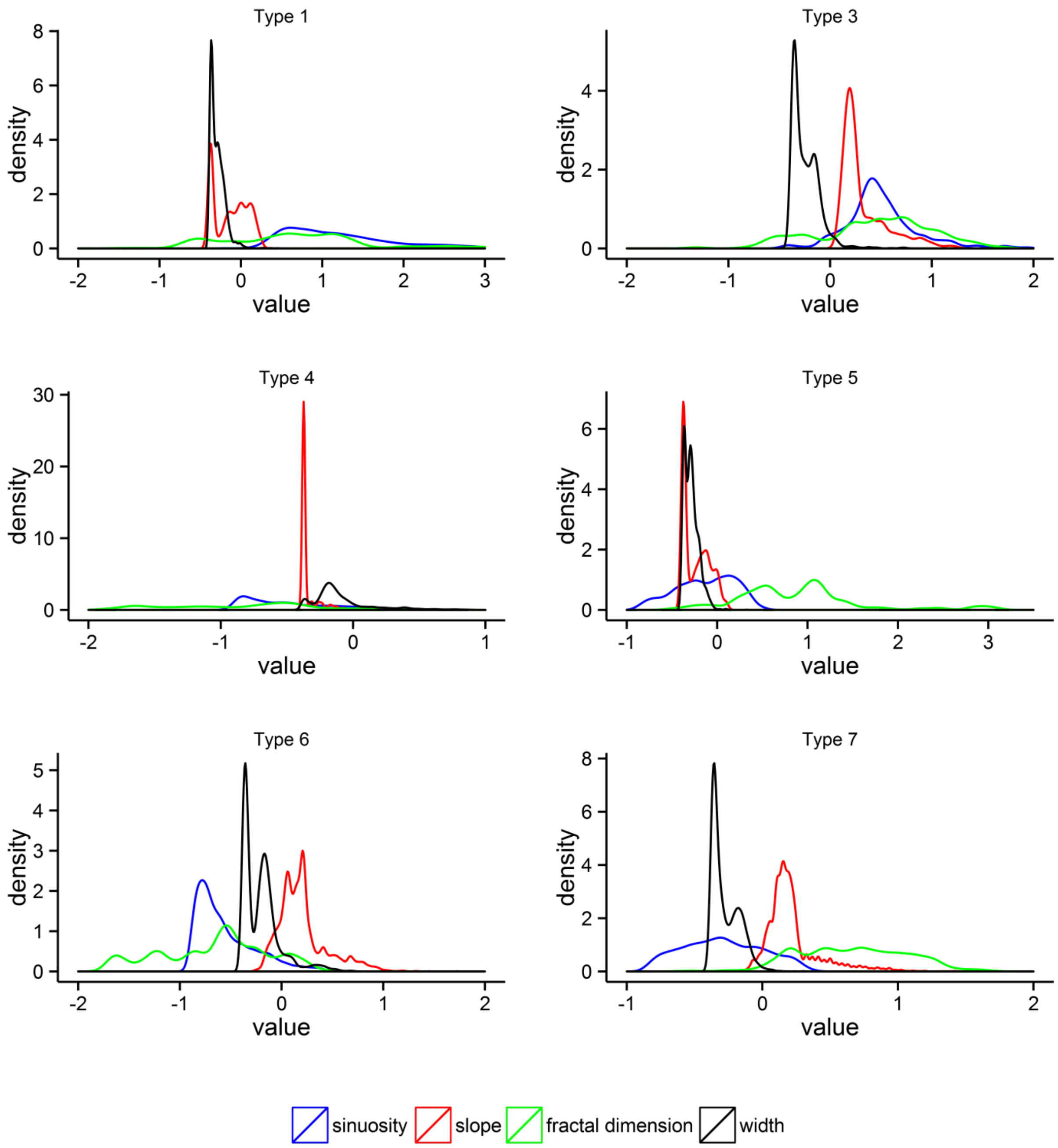

Figure 4-6. Histograms of the normalized values of channel sinuosity, slope, fractal dimension and width for Types 1, 3, 4, 5, 6, 7.

Table 4-1. Qualitative contribution of variables to each Type derived from the principal component analysis. - = negative relationship, - - = highly negative relationship, + = positive relationship, + + = highly positive relationship, 0= no discernable relationship.

Type	Sinuosity	slope	fractal dimension	width
0	-	0	- -	++
1	+ +	0	+	-
2	-	+	- -	+
3	+	+	+	-
4	-	-	- -	-
5	0	-	+ +	-
6	-	+	- -	-
7	-	+	+ +	-

Type 4 is negatively related to all of the variables, notably fractal dimension, while type 6 has similar relationships with the exception of a positive relationship with slope (Fig. 4-6, Table 4-1). Type 0 is highly positively related to width, negatively related to sinuosity and fractal dimension and has no clear relation to slope (Fig. 4-6, Table 4-1). Type 1 is highly positively related to sinuosity, positively related to fractal dimension, negatively related to width, and has no discernable relation with slope (Fig. 4-6, Table 4-1). Type 7 is positively related to slope and fractal dimension and negatively related with sinuosity and width while Type 3 is positively related to sinuosity (Table 4-1). Type 5, which occurs in GRU IV, has no relation with sinuosity, is negatively related to slope and width, and highly positively related to fractal dimension (Table 4-1). Results of the Krusal-Wallis analysis of variance on ranks show that all GRU interactions had at least three geomorphological variables being significantly different, with only slope having an insignificant difference between GRU I and III (Table B-1). Relative substrate class composition within each GRU shows that GRU I has the highest proportion of coarse substrates (27%) compared to GRU III (17%) and GRU V (5%) (Fig. 4-7), GRU III has the highest proportion of mixed substrates (44%) compared to GRU I (17%) and GRU V (13%), while GRU V has the highest proportion of fine substrates (82%) compared to GRU I (55%) and GRU III (39%) (Fig. 4-7).

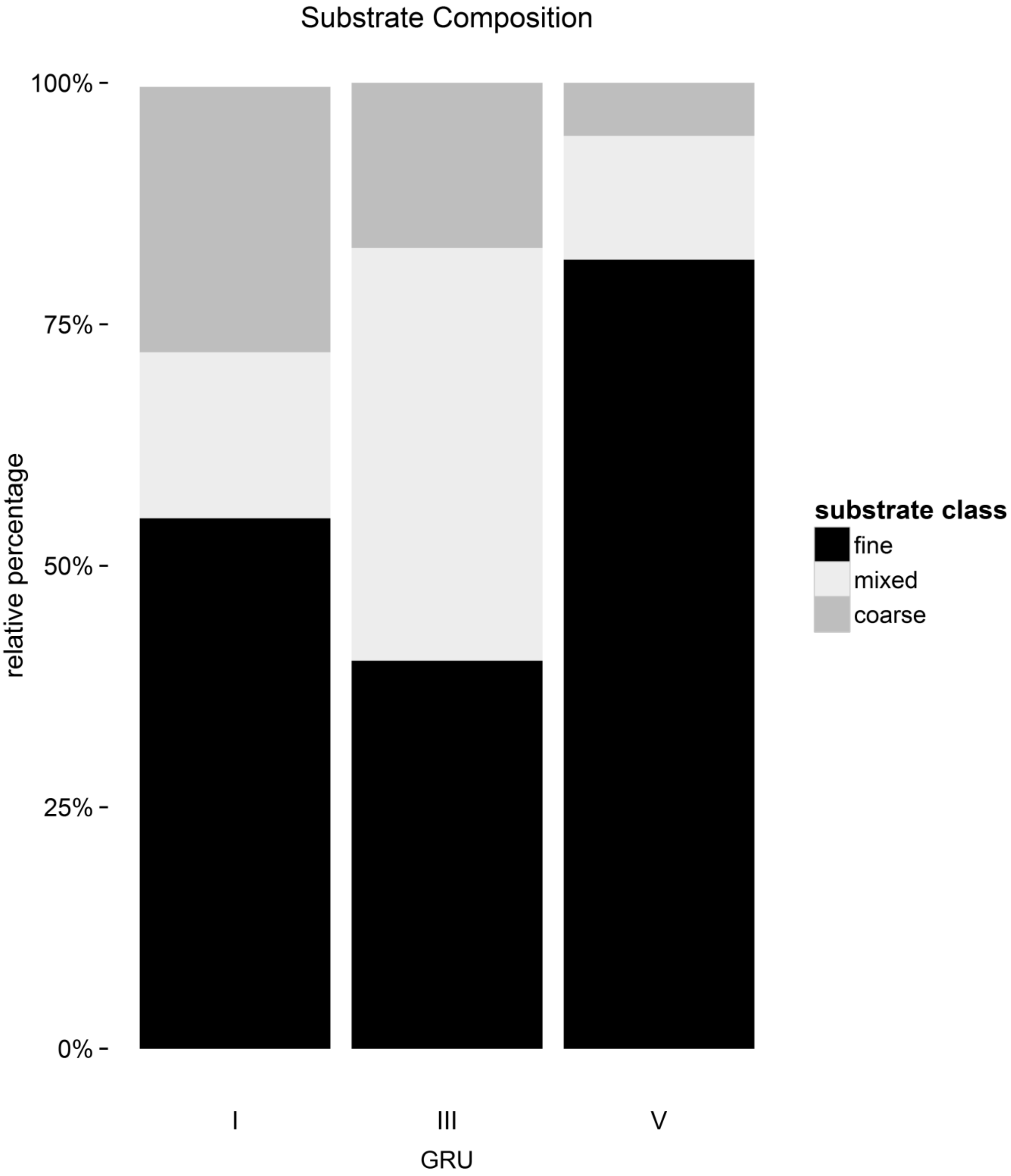

Figure 4-7. Relative percent composition of substrate classes within the three sampled GRUs.

4.4.3 Electrofishing Survey

The electrofishing surveys were conducted at 1257 sites throughout the study area (Figure 4-4). A total of 3,142.5 minutes (52.375 hrs) of fishing effort collected 6,983 fish, represented by 40 species. GRU I had the most observations with a total of 4,233 individuals, while GRU III had the fewest observations with a total of 424 (Table 4-2). GRU I has the highest CPUE while GRU III has the lowest CPUE (Table 4-2). Of the 40 fish species collected, six species were rare within the study site (occurring at <5% of sites) and were excluded, resulting in 14 species with ≥20 observations being included in statistical analysis (Table 4-3).

Table 4-2. Fish CPUE and Associated GRUs.

GRU	I	III	V
# fish observed	4233	424	2326
Effort (minutes)	1757.5	292.5	1092.5
CPUE (fish/minute)	2.41	1.45	2.13

Results of the Kruskal-Wallis test (Table 4-3) indicate that there are significant differences in CPUE among GRUs for 10 of the 14 tested species (Table 4-3). Post-hoc pairwise multiple comparisons using Dunn’s Method with Bonferroni p-value correction for multiple paired tests isolated the GRUs that were different from one another (Table 4-4).

Table 4-3. Results of Kruskal-Wallis Analysis of Variance on Ranks.

Common name	Scientific name	H value	df	P value
Common Carp	*Cyprinus carpio*	32.092	2	<0.001*
Channel Catfish	*Ictalurus punctatus*	2.756	2	0.252
Flathead Chub	*Platygobio gracilis*	65.456	2	<0.001*
Freshwater Drum	*Aplodinotus grunniens*	13.847	2	<0.001*
Golden Redhorse	*Moxostoma erythrurum*	44.310	2	<0.001*
Goldeye	*Hiodon alosoides*	37.225	2	<0.001*
Mooneye	*Hiodon tergisus*	19.858	2	<0.001*
Quillback	*Carpiodes cyprinus*	38.150	2	<0.001*
Sauger	*Sander canadensis*	35.686	2	<0.001*
Shorthead Redhorse	*Moxostoma macrolepidotum*	24.755	2	<0.001*
Silver Chub	*Macrhybopsis storeriana*	5.382	2	0.068
Silver Redhorse	*Moxostoma anisurum*	5.702	2	0.058
Walleye	*Sander vitreus*	0.153	2	0.926
White Sucker	*Catostomus commersonii*	31.994	2	<0.001*

* indicates a significant P-value

Table 4-4. Results of post-hoc pairwise multiple comparison using Dunn's Method.

	I vs III			**I vs V**			**III vs V**		
Species	Z value	P value	P value adjusted	Z value	P value	P value adjusted	Z value	P value	P value adjusted
Common Carp	-5.65139	0	0*	-0.94057	0.345	1	4.8705	<0.001	<0.001 *
Flathead Chub	5.55942	0	0*	7.01502	0	0*	-1.2274	0.22	0.659
Freshwater Drum	-3.41759	<0.001	0.002*	-2.23066	0.026	0.077	1.9728	0.049	0.146
Golden Redhorse	-4.09663	<0.001	<0.001 *	-6.05924	0	0*	0.3836	0.701	1
Goldeye	-5.96458	0	0*	-2.64335	0.008	0.025*	4.1744	<0.001	<0.001 *
Mooneye	-4.34304	<0.001	<0.001 *	-1.98586	0.047	0.141	3.0037	0.003	0.008*
Quillback	-0.57750	0.564	1	5.84392	0	0*	3.9739	<0.001	<0.001 *
Sauger	-5.65585	0	0*	-3.19234	0.001	0.004*	3.5570	<0.001	0.001*
Shorthead Redhorse	-4.68674	<0.001	<0.001 *	-2.71991	0.007	0.02*	2.9039	0.004	0.011*
White Sucker	-1.15270	0.249	0.747	-5.65368	0	0*	-2.2029	0.028	0.083

* indicates a significant P-value

Three species had significant differences between all three sampled GRUs (Figure 4-8, Table 4-4) and five species had significant differences between at least two GRUs (Figure 4-9, Table 4-4). GRU I and GRU III were significantly different for eight species, GRU I and GRU V were significantly different for seven species, and GRU III and GRU V were significantly different for six species (Table 4-4). CPUE is highest in GRU I for Goldeye (Hiodon alosoides), Sauger, and Shorthead Redhorse (*Moxostoma macrolepidotum*) with GRU V having the second highest CPUE for all three species (Figure 4-8).

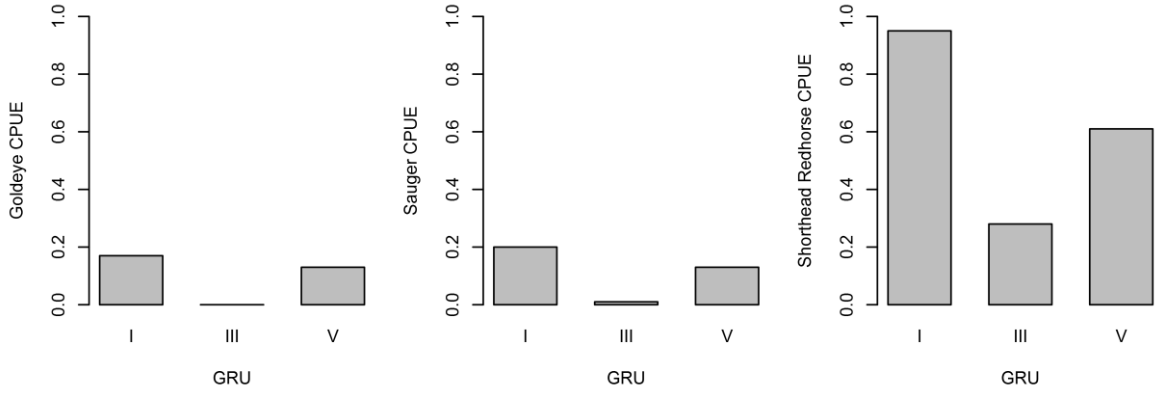

Figure 4-8. CPUE within each GRU for three species with significantly different CPUE between all three sampled GRUs: Goldeye, Sauger, and Shorthead Redhorse.

CPUE is highest in GRU I and V for Common Carp (*Cyprinus carpio*) and Mooneye (*Hiodon tergisus*) (Figure 4-9). CPUE is highest in GRU III for Flathead Chub (*Platygobio gracilis*) while CPUE is highest in GRU V for Quillback (*Carpiodes cyprinus*) and in GRU I for Golden Redhorse (*Moxostoma erythrurum)* (Figure 4-9).

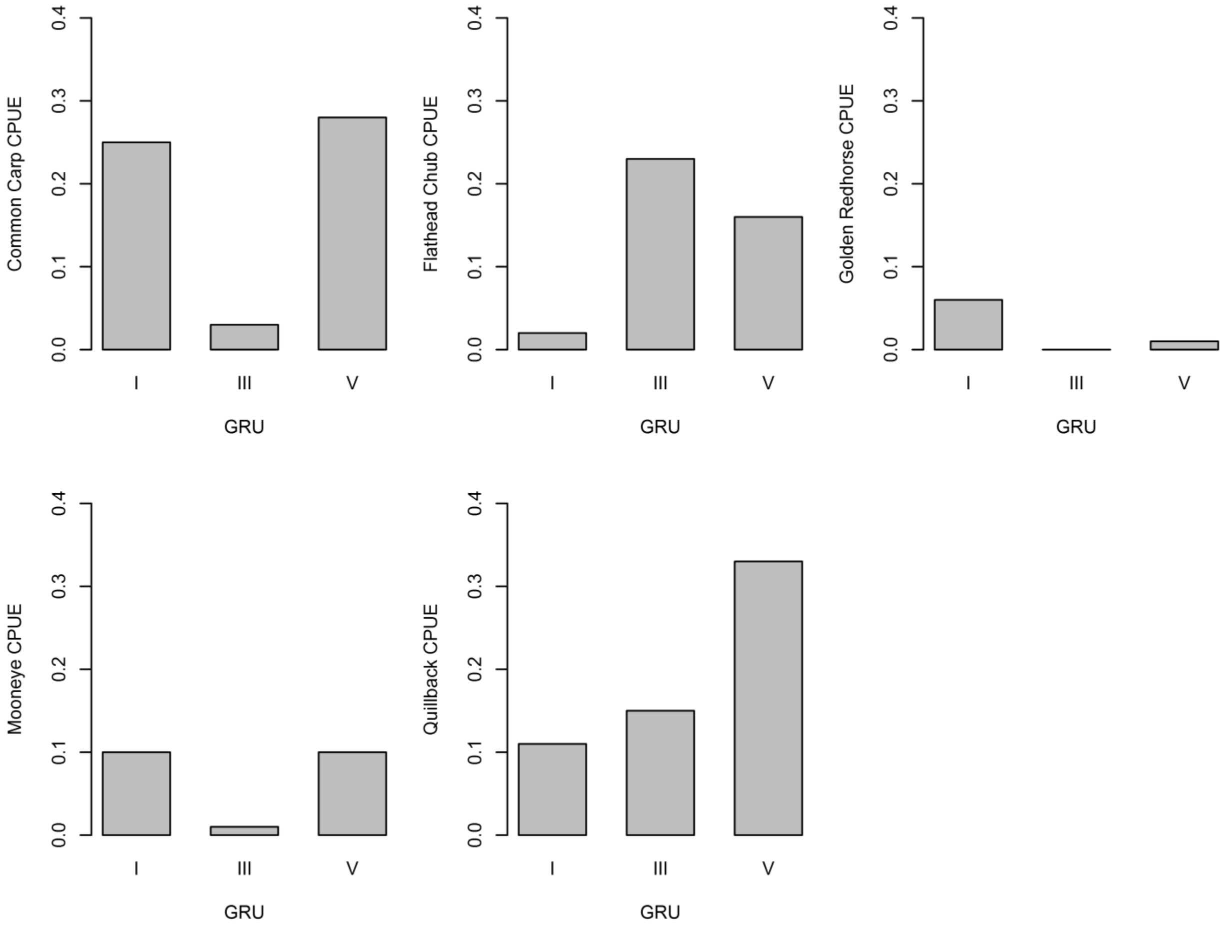

Figure 4-9. CPUE within each GRU for ten species with significantly different CPUE between two of the sampled GRUs: Common Carp, Flathead Chub, Golden Redhorse, Mooneye and Quillback.

4.5 Discussion

This study found significant differences in CPUE between different GRUs for 10 of the 14 tested species (Table 4-3). This suggests that species prefer certain GRUs over others due to differences in hydrogeomorphic character which result in different physical habitat characteristics. Though the random sampling design and unequal sampling of GRUs should be taken into consideration, environmental variables collected during fish sampling appear to support the notion that GRUs exhibit general differences in habitat features. Overall, relationships between variables appear to be fairly consistent across months and years. Although depths are relatively consistent between GRUs, velocity patterns appeared to differ and were significantly different for half of the tested interactions (Figure B-1, Table B-2). GRU III appears to have the highest velocities, GRU V the second highest and GRU I the lowest (Figure B-1).

GRU I is associated with large settlements and anthropogenic influence along the Assiniboine River (Figure 4-3). This unit was sampled most often and it is associated with high CPUE values for several species (Figure 4-8). This GRU is characterized by relatively narrow reaches with low sinuosity and fractal dimension and contrasting areas of low and high slope values (Figure 4-6, Table 4-1). Both GRU I reaches are constrained by natural and man-made features which can contribute to the formation of narrow, high slope channels with low fractal dimension and sinuosity. The upstream reach is constrained by the Manitoba Escarpment and coarse glaciofluvial plain and coarse grained glaciofluvial deposits to the north (Figure 4-1). In the downstream GRU I reach there are 134 km of dikes east of Portage la Prairie which protect communities, farms, farmland and residences from floodwaters. A large portion of this reach also flows through fine grained glaciolacustrine deposits characterised by cohesive clay and silt substrates suggesting that sediment load in this region is predominantly wash load. Schumm (1960) contended that streams with sediment loads dominated by wash load should have relatively narrower channels. This GRU is also likely to contain patches of coarse substrate due to areas of high slope and increased stream power which facilitate the removal of finer sediments and exposure of coarser, more resistant alluvium. GRU I characteristics also suggest that this unit provides riffle pool sequences alternating between narrow, high slope areas, narrow low slope areas, and intermittent increases in width and sinuosity (Figure 4-3, Table 4-1). Riffle pool sequences commonly develop in meandering channels with heterogeneous bed materials, with pools forming at the apex of bends in narrower, deeper sections, (Chitale 1973). Erosion at the apex of bends creates sharp, high tortuosity meanders (Chitale 1973) leading to higher sinuosity values, and lateral bars tend to form in association with pools creating riffle-pool sequences (Knighton 1998). Type 0 and Type 1 occur occasionally within GRU I, Type 0 being associated with a substantial increase in width and Type 1 being associated with a large increase in sinuosity and higher fractal dimension (Figure 4-6, Table 4-1). In areas where the river channel is not restricted by dikes or resistant alluvium the river can dissipate increased stream power by increasing channel width and sinuosity. In moving toward a state of dynamic equilibrium a stream will follow the path that minimizes the energy expenditure rate, or achieves minimum stream power (Yang and Song 1979). This can be achieved by a reduction in stream slope or alternately, increased meandering that reduces channel gradient relative to the straight path between two fixed points (Knighton 1998). As stream power decreases in these areas deposition is likely to increase. General habitat characteristics of GRU I include the highest proportion of coarse substrates, high levels of anthropogenic influence, relatively more confined channels, and higher occurrence of riffle pool sequences.

GRU I had the highest Goldeye, Sauger and Shorthead Redhorse CPUE (Figure 4-8) and also had relatively high CPUE for Golden Redhorse (Figure 4-9). These fish species are typically most abundant in large rivers and the connectivity of the Assiniboine to the Red River may be driving the observed CPUE differences. Goldeye prefer turbid water in large rivers and lakes and do not have an affinity for specific substrates or depths as they generally inhabit mid to surface waters for both feeding and spawning (Stewart and Watkinson 2004). Although Goldeye can inhabit a wide range of habitats GRU I is likely to have relatively higher wash load leading to increased turbidity, a habitat feature Goldeye are well adapted to. Sauger are found in lakes, rivers, and streams throughout Manitoba and are more common in rivers than Walleye (Stewart and Watkinson 2004). Sauger are most often associated with rocky substrates though they have been found on substrates ranging from clay and silt to rubble and boulders, and like Goldeye have an affinity for large turbid rivers. Golden Redhorse have more general habitat requirements tending to inhabit mid-channel regions of larger rivers (Stewart and Watkinson 2004). In general, these species all tend to be associated with more turbid waters with substrates ranging from silt and clay to coarser gravel and rubble substrates, a combination of features that are likely common in GRU I where substrate class composition has a high proportion of fine sediments yet has the highest proportion of sites with coarse sediments (Figure 4-7). These fish species are typically most abundant in large rivers and the connectivity of the Assiniboine to the Red River may an important factor influencing observed CPUE differences.

GRU III is mainly comprised of narrow reaches characterised by high slopes and fractal dimension (Table 4-1). There are also instances, particularly at transitions between different surficial deposits, where sinuosity increases and slope decreases (Figure 4-1). The only fish species that had its highest CPUE in GRU III was Flathead Chub (Figure 4-9). Flathead Chub are considered a habitat specialist and only occur in flowing sections of turbid medium to large rivers, typically with sand substrates (Quist *et al.* 2004). The substrate in this GRU had the highest proportion of mixed substrates though the largest component of the fine and mixed substrates was sand, the dominant substrate at 76% of GRU III sample sites. GRU III occurs in close proximity to the major tributary inflows along the Assiniboine, often forming downstream of such inflows (Figure 4-3). Tributary inflows are associated with an influx of sediment contributing to increased turbidity and higher proportions of fine sediments downstream of such confluences. General habitat characteristics of GRU III are sand dominated mixed substrates, higher velocities, tributary inflows and associated increases in sediment load and discharge, with sand bars and sparsely vegetated islands being more common.

GRU V is characterised by narrower channel widths, high slope, and low sinuosity and fractal dimension (Figure 4-6, Table 4-1). A patch of Type 2, rare along the Assiniboine, coincides with the Portage Diversion (Figure 4-3). The Portage Diversion Dam creates a small reservoir, substantially increasing width and decreasing sinuosity and fractal dimension for approximately 4 river kilometers (rkm) upstream of the diversion (Figure 4-3, Table 4-1). This GRU passes through a large alluvial deposit with high proportions of silt, sand, and clay (Figure 4-1). Channels with high silt and clay content tend to be cohesive resulting in relatively low sinuosity, narrower channels, and higher slope (Rosgen 1994). Overall, general habitat features in GRU V include the highest proportion of fine substrates, higher rates of point bar formation, and the presence of the Portage Diversion Reservoir. GRU V had the highest Common Carp and Quillback CPUE (Figure 4-9). Common Carp prefer low velocity waters in large streams, rivers and lakes, and are found over a variety of substrates (Stewart and Watkinson 2004). Common Carp have the most diverse diet of all Manitoba cyprinids though they are typically benthic feeders, preferring shallow water and soft substrates for feeding (Stewart and Watkinson 2004). The reservoir upstream of the Portage Dam likely provides appropriate habitat for this species as it creates a semi-lentic zone with lower flow velocities which facilitates deposition, providing soft substrates for feeding. Similar to Common Carp, Quillback prefer turbid, low velocity waters over sand and silt substrates in large rivers and lakes though spawning requirements differ, occurring during peak flows in riffles over coarse to fine gravel (Parker 1987). Substrate classification composition shows that GRU V has an extremely high proportion of fine substrates compared to other GRUs (Figure 4-7), an appealing habitat feature for both Quillback and Common Carp.

The Portage Diversion Dam appears to have a significant effect on the distribution of certain species within the study area. No Goldeye, Golden Redhorse, or Freshwater Drum were collected upstream of the dam. These fish species were collected at more than 5% of all the collection sites and GRU I and V were present both above and below the dam. A lack of these species suggests that lost connectivity in the Assiniboine River has a significant influence on species distributions. CPUE of Mooneye, Common Carp, Quillback, Sauger, and Freshwater Drum also appear to be significantly affected by the Portage Diversion Dam. The CPUE values downstream of the dam were higher, despite higher discharge during the sampling period that can reduce catchability of species due to great river depth (Bayley and Austen 2002, Hughes *et al.* 2002, Flotemersch and Blocksom 2005) and velocities (Hughes *et al.* 2002). The dam was completed and operated in 1970 so the influence on species abundance has occurred quite recently. These differences in CPUE may be a result of fish migrations being blocked and subsequent increased densities below the dam. Habitat above the dam is likely limiting some aspect of the life history of the species, resulting in lower abundance or complete loss of species diversity. The connectivity of the Assiniboine River to the larger Red River below the dam is likely a significant factor in the diversity and abundance of species in the Assiniboine River. The GRU method facilitates the identification of spatial patterns that are representative of processes operating at decadal temporal scales. This allows comparison of GRUs with historical fish sampling data though other confounding variables such as seasonal influence on distribution cannot be accounted for in the present study.

4.6 Conclusion

This study has established relationships between GRUs and anthropogenic alterations, tributary inflow, and surficial geology of the Assiniboine River; identified significant differences in catch per unit effort (CPUE) between different GRUs for many fish species; and described qualitative relationships between geomorphology and physical habitat preferences, as described in the literature, for several species. These findings have the potential to inform other studies and increase the efficiency of resource management practices. Classifying river reaches with the same hydrogeomorphic attributes can increase our understanding of habitat availability, complexity, and connectivity within river systems. Understanding links between GRUs and fish species in the Assiniboine River can allow prediction of important habitats in other prairie rivers. This model can contribute to the development of sampling programs by allowing efficient *a priori* site selection, ensuring sampling of diverse unit types and thus a greater representation of the range of physical habitats present within a river system. Overall findings suggest that the GRU model has potential as a valuable tool for resource managers. Future work should aim to delineate GRUs first and implement a blocked sampling design whereby fish are sampled randomly with equal effort in all GRUS. Field measurements of habitat features and geomorphic variables should also be incorporated into sampling design to validate relationships between GRUs and habitat features.

CHAPTER 5: CONCLUSIONS-UNDERSTANDING LINKS BETWEEN GEOMORPHIC RESPONSE UNITS AND PRAIRIE FISH SPECIES

5.1 Synopsis

The previous chapters present three varied applications of the GRU method in an effort to understand relationships between GRUs and the presence of particular fish species. The spatial extent of GRU delineation ranged from the single 58 km Birch River, to a large 1,173km stretch spanning the South Saskatchewan and Saskatchewan Rivers, up to an inter-watershed analysis including three major prairie rivers spanning over 1,000 km. Each chapter investigated a different type of fish data set: two years of winter telemetry data for a single long lived, highly mobile migratory species (Chapter 2), two months of seine hauls focusing on catch of two age classes of a small threatened cyprinid (Chapter 3), and electrofishing surveys spanning three years and a range of species (Chapter 4). These varied data sets allowed an investigation of links between GRUs and fish observations for a range of common gear types and sampling methodologies over a range of delineation scales. Relationships between abundance of individual species and GRUs were identified for these variable applications. Lake Sturgeon overwintering areas were associated with specific geomorphic types in the South Saskatchewan and Saskatchewan Rivers and one of seven possible sampled types was significantly selected for in the Upper South Saskatchewan River. Several fish species in the Assiniboine River had significant differences in CPUE between different GRUs and, although no statistical differences in either immature or mature Carmine Shiner CPUE was observed between different GRUs in the Birch River, interesting patterns in associations were observed and can inform further studies of this threatened species.

Expanding the spatial scale of river delineation increases the range of values associated with each variable which in turn influences the complexity of the resulting Type associations. Increasing the range of values allows for more readily defined changes in variables and therefore Types, resulting in large scale patterns that reflect ecologically significant differences between individual types and their associations with one another. The South Saskatchewan River study addressed the issue of redundant types being more likely unless dimensionality of the dataset is reduced. Though reduction of PCs is generally an inherent step of the PCA process, the South

Saskatchewan study sought to replicate the GRU method as applied in the preliminary study (Lindenschmidt and Long 2010). The inclusion of all four principal components when deriving geomorphic types leads to the differentiation of unique Types based on variance that may be ecologically negligible. There are both statistical and non-statistical methods for determining the appropriate number of components to include in subsequent analysis (Jackson 1993). Commonly, non-statistical approaches such as the scree test, Kaiser-Guttman rule, and percent of cumulative variance are used to select an appropriate number of components though *a priori* considerations can also be important when replicating methodology of previous studies. Jolliffe (1972, 2002) has suggested reducing the Kaiser threshold to 0.7 when dealing specifically with PCA. Applying the 1.0 threshold, which is more applicable to factor analysis, can result in loss of information about variables of interest because it will not retain PCs dominated by a single variable that has low correlation with all other variables (Jolliffe 2002). In order to reduce the complexity of GRU models only three principal components were retained in chapter 3 and chapter 4 analyses, accounting for 82% and 84% cumulative variance in the Birch River and the Assiniboine River respectively. Once Types were identified larger scale GRUs were delineated based on the emergent patterns formed by the associations of unique Geomorphic Types. Emergent properties arise due to smoothed, averaged or filtered properties of lower levels providing input into higher levels and cannot simply be deduced from the specific functioning of parts (Parsons and Thoms 2007).

The results of the previous chapters suggest that a network scale approach identifies differences in geomorphic structure at a scale appropriate to that which fish interact with the riverine environment during ice free months. It has been recognized since the 1980s that little would be gained from river classification schemes that focus on transient characteristics and processes of highly temporally and spatially variable stream systems (Frissel *et al.* 1986). The hierarchical framework of Frissel *et al.* (1986) emphasized a watershed context for stream habitat classification wherein classification variables define long term capacities of systems, rather than fleeting short-term states. Their approach merges biogeoclimatic land classification methods with stream classification in a hierarchical fashion. Frissell and colleagues (1986) identify five different system levels within streams: 1) Stream, 2) Segment, 3) Reach, 4) Pool/riffle, and 5) Microhabitat systems, each with different linear spatial scale, major evolutionary events, developmental processes, and time scales of continuous potential persistence. GRUs reflect a spatial scale most closely linked to the segment level though they are not necessarily bound by tributary junctions or major waterfalls as described by Frissel *et al.* (1986). The segment level can be described by variables such as channel flood slope (1:20,000 to 1:80,000 map scale), channel floor lithology, drainage network position, valley side slopes, potential climax vegetation, and soil associations. GRUs, much like Frissell's segment class, provide information about which types of reach habitats may be present at the lower hierarchical level. Reaches can be described by variables such as bedrock relief/slope, channel pattern, bank composition, riparian vegetation characteristics *etc.* Types operate at a hierarchical level similar to the pool/riffle and reach scales and can be associated with variables such as substrates immovable by <10 year floods, bank configuration and bed topography. As such, GRUs provide information giving insight into two different scales of geomorphic character.

Once hierarchical levels are defined boundaries between different systems have to be delineated then the similarities and dissimilarities between different systems have to be described (Frissel *et al.* 1986). Further studies have emphasized a need to conceptualize rivers as spatially continuous longitudinal and lateral mosaics as opposed to sampling points, lines, or gradients (Fausch *et al.* 2002). The GRU method provides a means of identifying boundaries between such systems, mosaics, or patches, and general substrate information collected in conjunction with fish sampling allowed relative comparisons of substrate composition, an important physical habitat feature for many fish species, in the Birch River and Assiniboine River GRUs.

Other studies have identified links between the presence of individual fish species and/or fish assemblages and habitat variables across varying scales. Gido *et al.* (2006) quantified how the addition of habitat measurements from increasingly finer scales increases the predictability of fish species occurrence in the Kansas River basin. Their approach first used catchment variables to explain the variability of individual species occurrence and assemblage structure and secondarily determined how much additional variation could be explained by the addition of habitat variables from finer spatial scales. They found that although predictive performance of models increased with the addition of site-scale habitat variables, the relative magnitude of increase was small (less than 3%) due to species associations with catchment area and soil factors. Reach level variables stream order, sinuosity, and geology, and the site variable width were most frequently included in predictive species occurrence models. They claim that reach and catchment-scale habitat variables accounted for the majority of variation in species occurrences that were explained by site scale field variables (Gido *et al.* 2006). They also found that catchment scale variables accounted for a slightly higher percent variation in fish-assemblage structure across sample sites than reach- or site-scale habitat variables and concluded that field habitat measurements were less informative than catchment data for predicting species occurrences within the Kansas River basin. There was also a large percentage of variation attributed to the interaction of the habitat variables across the three different scales so it is unclear if this is an accurate assumption. Regardless, it appears that GIS derived river variables from various scales are useful for identifying patterns in fish species distribution. Similar findings were obtained for the dryland Barwon-Darling River, where regional differences in relative abundance of species occurred at scales that most closely correspond to geomorphological zones (Boys and Thoms 2006). These findings corroborate earlier indications that systematic river segment to watershed scale censuses of coarse grained habitat features are likely to be more revealing of important factors influencing fish assemblages than detailed data at the wrong scale (Fausch 2002).

These studies support our selection of geomorphological variables that are descriptive of the river channel itself and readily derived from GIS. However, the GRU method moves beyond these studies by providing a consistent, transferrable, and quantitative way of delineating sections of river that have the same channel characteristics. Where these studies seek to identify relationships between a wide range of highly correlated variables and the presence of different fish species, the GRU method used the same four variables to describe differences and similarities between river reaches. We include a spatial range of variables, from fractal dimension (river segment-catchment), to slope and sinuosity (reach), and finally width (site). These variables have previously been linked to fish species presence and/or assemblage structure (Walters *et al.* 2003, Gido *et al.* 2006, D’Ambrosio *et al.* 2009). This method is simple to apply with a basic knowledge of GIS and allows for a relatively quick assessment of potential habitat areas to facilitate further sampling. Though some subjectivity remains in the present iteration of the model, specifically in the determination of boundary points between different GRUs as determined by a visual assessment of large scale patterns of geomorphic types, this was improved upon with the development of delineation rules (Chapter 3 and 4) and will continue to be developed in future iterations.

Though findings suggest that a network or watershed scale is appropriate for river delineation, it is important to recognize the value of the two different scales of geomorphic pattern that result from the identification of both Geomorphic Types and GRUs. As aforementioned, when considering assemblages or individual species which are highly mobile during ice free months, a larger scale GRU approach has been found to be appropriate for identifying patterns in abundance between different GRUs (Chapter 4). When we consider seasonal implications for habitat availability and fish behaviour in cold water regions, scale considerations are likely to shift to a smaller, Type level scale. As fall brings a decline in water temperatures, larger fish tend to stop using shallow higher velocity areas and move into deeper pools (Brown and Mackay 1995, Lyons and Kanehl 2002, WSA 2013). As water temperatures decrease, fish body temperatures decrease and metabolic processes slow down (Parsons and Smiley 2003). This change causes a decline in the abilities of fish to feed, swim, and avoid predators (Parsons and Smiley 2003). These changes in behaviour lead to an overall decrease in mobility and increase associations with a very specific habitat feature: deep holes which provide an energetically advantageous refuge.

5.2 Contributions and Significance

Future applications of the GRU method should aim to delineate all major rivers within a given watershed in order to identify ecologically significant difference in geomorphic character. The GRU methodology identifies patterns at two different scales, each which can be applied depending on the specific habitat goals of managers. Large scale, GRU level patterns are most appropriate for considering habitat diversity and connectivity relating to patterns in abundance for individual, mobile species during ice free months, and are most likely to be related to regional differences in species assemblages. Connectivity can be investigated in terms of both natural and anthropogenic barriers to fish movement and how these disrupt accessibility to different GRUs and related habitat features. This can also be applied in a predictive capacity to address questions of how future barriers may impede access to different habitats. Types can help us infer the physical complexity of individual GRUs and identify smaller scale differences in geomorphic character that may be more representative of unique features.

Studies have long indicated that the scale at which habitat is naturally created and used by fish may be much greater than the scale at which habitat management is typically attempted (Frissel and Nawa 1992). Fisheries ecologists must aim to make observations and test predictions at the scale at which managers effect change (Fausch *et al.* 2002). Fausch and colleagues (2002) stated that more intensive, large scale approaches are required in order to improve research regarding the management of habitat for threatened and endangered species, addressing invasions of non-native species, managing ecosystems to sustain fish populations for sport and commercial fishing, and addressing intermediate and long term impacts of climate change. They recommend shifting research focus to larger scales by adopting sampling strategies that include continuous spatial censuses that are followed by long-term sampling at strategic rather than randomized locations (Fausch *et al.* 2002). The GRU method provides a means of classifying river reaches that exhibit different geomorphological characteristics and thus represent the diversity, connectivity and complexity of physical habitats within a given river system. This can inform fisheries and river managers by allowing them to predict variation in large scale river characteristics providing *a priori* insight for sampling designs. GRUs are then treated as blocks within which sampling of randomized locations or specific features can occur, ensuring that a greater range of physical habitats are represented in fisheries surveys.

5.3 Uncertainty and Assumptions

5.3.1 Geomorphological variables

DEM data resolution varied depending on source. For example, the Assiniboine study used Canadian Digital Elevation data (CDED) which consists of an ordered array of ground or reflective surface elevations, recorded in metres with variable accuracy depending on data source. GRUs were delineated using CDED data from the Qu'Appelle, Assiniboine and Red Rivers which overall had a mean horizontal accuracy of 17.1 ± 15.7m and mean vertical accuracy of 4.4 ± 1.8m. This introduces error at the initial step of analysis. Secondarily, elevation values were smoothed along the longitudinal profile increasing error in slope calculations. Sinuosity and fractal dimension require decisions of what scale the variables should be calculated at. At least two sample points, representative of 100m of river, are required for these calculations but a 100m length of a large river is not an appropriate scale because it is not long enough to capture the meandering or changes in flow direction desired. Conversely, calculating these variables on a scale that is too large may also result in a loss of information by generalizing variable patterns into a single representative value. At the step of data extraction the goal is to represent the largest range of a given variable present in the river. For each study this was achieved by calculating sinuosity and fractal dimension iteratively, using increasing scales, until peak variation was achieved. This ensured that these variables were calculated in a manner that reflected the variation within each individual river.

Geomorphological variables included in this study were selected based on 1) being easily extracted from readily available DEM data, and 2) being commonly cited in the literature as predicting patterns in fish species composition and diversity (Sullivan *et al.* 2006, Dauwalter *et al.* 2008, Frothingham *et al.* 2001) and relationships with physical habitat features (Nakamura and Swanson 1994, Rhoads et al. 2003, McIlroy et al. 2008). Fractal dimension has yet to be investigated in terms of relationships to instream physical habitats at a large scale but was incorporated due to cited relationships with environmental factors such as soil type, runoff, and sediment transport which can have implications for substrate, discharge variability, and water chemistry (Allan and Castillo 2007). This suggests that fractal dimension is an appropriate candidate for identifying large scale patterns in channel characteristics that may relate to differences in physical habitat. PCA loadings for the three rivers show that contributions of the four variables differ between rivers but that each of the four variables loaded strongly on the first PC for at least one of the three study rivers. This means that each variable counted for a considerable proportion of variance in at least one river, therefore when testing consistent application of the GRU method or identifying patterns in channel planform, inclusion of all four variables is justifiable. Despite this, it is still possible that other planform channel variables may be better candidates for inclusion in the GRU model. Island formations and side channels were not accounted for in analyses and may be important habitat features and should be incorporated in future GRU applications. Depending on the system of interest variables such as valley width, which could be a proxy for floodplain accessibility, may be another important habitat feature for species that require access to flooded vegetation in order to meet specific life history requirements. A statistical variable selection process should be applied in future iterations of the GRU model to ensure that the most informative variables are used to delineate different units.

5.3.2 Principal Component Analysis and Statistical Analyses

Principal component analysis was used to group centerline points based on similar characteristics of channel pattern variables extracted from GIS. The PCA step of analysis further generalizes the geomorphological data set when PC values are converted to binary values. This groups sample points based on how they are related to each PC or, in other words, based on which variables contribute high vs. low values for that given sample. The sum of these generalized binary values then groups individual centerline points into a Geomorphic Type. This method can lead to wide ranges in variable values associated with some Types because some sites may have average values of a given variable but be grouped in with other sites that express much higher or lower values. This does not mean that this technique does not identify valuable patterns in relationships of channel pattern variables, but there is uncertainty as to whether these patterns are the most ecologically significant relationships. Though validation techniques were applied in Chapters 3 and 4 to determine the stability of overall PCA results, it is possible that stronger relationships between CPUE and GRUs could be derived by different multivariate methods.

Ecological data are commonly influenced by spatial autocorrelation, whereby observations from geographically near sample locations are more likely to have similar magnitude than by chance alone (Fortin *et al.* 2002). If these underlying environmental gradients are not considered in analyses then sample sites are not independent and similarity due to spatial proximity may confound relationships between species assemblages and our explanatory variables of interest (Rahel and Jackson 2007).Though one may argue that samples within dynamic and highly connected river systems are never truly independent, accounting for such spatial structures reduces some uncertainty when interpreting results. A Mantel test was used to infer whether total CPUE expresses a non-random linear relationship, or spatial autocorrelation, in Chapters 3 and 4 reducing uncertainty introduced by spatial autocorrelation.

5.3.3 Fish sampling

Sampling efficiencies and fish assemblage structure can simultaneously be influenced by the physical, chemical, and biological attributes of aquatic ecosystems (Kwak and Peterson 2007). For example, depth can be an important factor influencing both the efficiency of sampling methods as well as fish assemblage structure. Kwak and Peterson (2007) suggest using analyses based on qualitative measures such as rank abundance or species presence when sampling conditions are challenging such as in reservoirs and large rivers. Apparent lack of distinct differences in assemblage between GRUs, as determined qualitatively by relative percent abundance, in both the Birch River and Assiniboine data sets may in fact reflect a limitation of the sampling gear. Habitat characteristics, specific species characteristics and body size, and gear type can all introduce more bias into sampling efforts. Benthic and wide-ranging pelagic species are difficult to sample and species with cryptic colouring and reduced swim bladders are difficult to locate while electrofishing (Kwak and Peterson 2007, Hayes *et al.* 1996). Depth and stream width can change capture efficiency with wider and deeper sections exceeding the catch area (e.g., seine dimensions or electrical field size) allowing fish to avoid the field by either swimming around or sounding (Portt *et al.* 2006). When electrofishing, high velocities can displace stunned fish before they are captured, and refuges created by structures such as vegetation, boulders, and woody debris can limit sampling efficiencies (Bayley and Dowling 1990, Kwak and Peterson 2007). Such biases can result in samples that over represent species occupying more easily sampled habitats and underrepresent those in habitats with features that impair sampling (Kwak and Peterson 2007).

Different fish capture methods were used in each chapter which introduces more uncertainty in comparing results between rivers. As summarized by Plafkin and colleagues (1989), electrofishing and seining have unique advantages and disadvantages. Electrofishing CPUE is more easily standardized, is less selective than seining, adverse effects on fish are minimal, and it can be applied in a variety of habitats. Conversely, Turbidity and conductivity influence sampling efficiency and it is selective on larger body sizes and species. Seining is not restricted by water quality parameters and it has minimal effects on the fish population, though knowledge of fish habitats and behaviour and experience and skill of field crews become more important. Sample effort and variability of results tend to increase with seining and its use is generally restricted to smaller streams with slower velocities and little cover. CPUE calculations assume constant catchability, or that fishing efficiency remains constant throughout the sampling period (Hubert and Fabrizio 2007). Differences in the abilities of fishing crews and wear on fishing gear can change efficiency of sampling which introduces uncertainty. Are there actually more fish at a given site or were those crew members better at using the equipment? If different nets were used throughout the sampling period, one net may be more effective than another.

All of these capture methods also have an inherent assumption that fish are freely choosing to spend time in or move to different locations. Though life history requirements were considered to some degree in interpretation and discussion throughout the previous chapters, little attention was given to other behavioural influences on fish distribution. For example, the presence of predators or competitors can influence catchability if prey species seek refuge to hide from or leave the area to evade predators (Beauchamp *et al.* 2007). This will reduce their catchability in the sampling area and may reflect a behavioural response to other fish rather than habitat suitability. Evaluating habitat use aims to determine if fish spend more or less time in some habitats than would be expected based on the availability of those habitats. Selection is the process by which an animal chooses habitat and preference is the likelihood that a resource will be chosen if all habitats are offered up equally (Johnson 1980, Manly et al. 1993). Availability of habitat to each individual may vary and there is also inherent heterogeneity in use among individuals in a population. Pooling information across individuals may mask the selection of two different habitats by different individuals and suggest that no selection is occurring (White and Garrott 1990). This is why habitat selection ratios calculated in chapter 2 incorporated the variation in resource selection for each individual when calculating selection for the entire population.

Spatiotemporal relationships within river systems are complex and highly heterogeneous, with riverine habitats and organisms being connected in three potential spatial dimensions: along longitudinal, lateral and vertical pathways which act under the temporal hierarchy of the fourth dimension, time (Ward 1989). Spatial and temporal constraints influence the distribution of fish species and must be considered when making inferences about habitat use and distribution. As mentioned in previous chapters, dams significantly impact the distribution of fish by preventing migrations between reaches upstream and downstream of the barrier. As suggested in chapter 4, this can lead to clear patterns in the distribution of fishes where, once historically abundant throughout an entire river, a given species is notably absent upstream or downstream of a barrier. This is likely due to blocked migration to key habitats that meet life history requirements, resulting in extirpation due to mortality or emigration to other reaches that support the diversity of required habitats. Beyond physically preventing movement of fish themselves, dams can also disrupt the connectivity of flow and associated sediment and nutrient transport which can have variable impacts on habitat features causing a shift in the fish community. For example, as dams begin to store in flowing water the local base level is raised in proportion to the height of the dam (Knighton 1998). This usually results in an increase in depth and width of the river as a reservoir forms, and a decrease in flow velocities leads to sedimentation as transport ability is lost (Knighton 1998). Deposition of fine sediments may lead to a shift in species composition within the reservoir. Certain species of fish and macroinvertebrates, an important food source, tend to be associated with particular substrates during specific life stages and a shift to fine sediments may displace species with an affinity for coarser substrates (Allan and Castillo 2007). Below the barrier, changes in flow regime and sediment load can lead to massive reductions in flood peak magnitudes and sediment load (Knighton 1998). Sediment-starved flows lead to degradation downstream of the dam as erosion increases. This may expose coarser substrates, increasing channel roughness and possibly causing more turbulent flow which results in greater local variance and extremes in flow velocity. Species will respond differently to such changes though in general studies have shown that increased surface texture and roughness tends to promote greater abundance and diversity of organisms (Allan and Castillo 2007). Despite a likely increase in the exposure of coarse substrates, altered flow regimes may affect access to such areas if flows are greatly reduced and if peak flow timing and volume changes greatly. Fish eggs or larvae may desiccate if discharge decreases and substrates are exposed, while unnaturally extreme flow velocities may wash individuals downstream or cause them to be crushed by shifting substrates. Increased water clarity due to decreased sediment load directly downstream of impoundments may also impact fish communities by promoting growth of periphyton and mosses due to decreased light attenuation (Allan and Castillo 2007). This could facilitate a shift toward grazer species and promote colonization by a more diverse macroinvertebrate assemblage beneficial to invertivores and omnivores (Tyus 2012). Lateral connectivity is also an important consideration for the spatial distribution of fish species in rivers (Schlosser 1991, Diana 2012). Floodplains can support a great diversity of habitats such as backwater swamps, sloughs and marginal pools which certain fish species interact with to complete life history requirements such as spawning and can provide access to different, often higher quality, food resources (Junk et al 1989, Tyus 2012). In large floodplain rivers organisms are often adapted to floods and changes in flow regime that alter the timing and magnitude of flood peaks can reduce connectivity with important floodplain habitats. When lateral connectivity is lost, whether from altered flow regimes, dikes etc., the spatial distribution of certain species may change, either forcing them to emigrate to reaches that provide necessary habitat or increasing mortality through decreased fitness and reproductive output. Drought conditions present during the sampling season in the Birch River (Chapter 3) have implications for the distribution of fish throughout this system. A review by Rolls and colleagues (2012) identified several negative impacts of low flows and droughts on riverine ecosystems. Low flows control: the extent of habitat available; changes to water quality and habitat conditions; and restrict connectivity and diversity of habitat, influencing the distribution, recruitment, and diversity of biota. Although field observations suggest that connectivity was maintained until the end of July it is possible that reduced flows had some influence on the distribution of Carmine Shiner, necessitating the use of refugia that may or may not reflect typical habitat preferences. If GRUs are delineated well after the construction of barriers or other dramatic changes in connectivity we can expect the model to account for any changes to channel pattern and related habitat features that may result. In contrast, the model may not be able to detect very recent changes to connectivity, whether from damming or low flow drought conditions, which may impact fish distribution before influencing changes in channel pattern characteristics.

Temporal patterns are another important consideration when examining fish distribution within large rivers. Fish often exhibit complex temporal movement and migration patterns, including considerable diel and/or seasonal migrations which fish are evolutionarily adapted to for various reasons including spawning, feeding, predator evasion, and climatic conditions (Nunn *et al.* 2009, Tyus 2012). Lake Sturgeon telemetry data analyzed in chapter 2 only included observations made during winter months therefore any identified Type associations and distributions are unlikely to be transferable to patterns which occur during ice free months. Lake Sturgeon have highly spatially and temporally variable migration patterns and it has been suggested that they require a minimum 250-300km barrier free combined river and lake range to support a self-sustaining population, with distances 750-1000 km not being unusual (Auer 1996). Individuals tagged in the lower South Saskatchewan and Saskatchewan Rivers by the Water Security Agency reflect these suggested values with individuals migrating an average of 209.9 rkms ± 244.6 rkms (mean ± 1 SD) in 2011 (Water Security Agency 2013). These migrations are generally attributed to movements from deep overwintering “holes” (SWA 2011 and 2012, WSA 2013, R.L.&L. Environmental Services 1991) to spawning habitats characterised by shallow (0.6-5m) fast flowing areas below rapids (Wallace 1997), deeper slow velocity summering habitat, or more localized foraging areas (COSEWIC 2007). Conversely, single observations of individuals from seining and electrofishing surveys performed at randomized sites (Chapter 3 & 4) are associated with greater uncertainty in terms of spatiotemporal patterns in distribution. One cannot infer whether individuals caught at a given site are resident fish staying within a localized area, are temporarily using the area for a specific life history requirement, or are in the process of migrating and are not actively using the area they were captured in. Without mark-recapture, telemetry, or behavioural observation data one can only infer about how individuals may be interacting with a sample site.

Since existing data sets were used in analyses, fish data and GIS data were not always collected in the same year. Though it is likely that habitat features within a GRU will change and shift over time, GRUs are delineated based on patterns identified at spatial scales representative of processes occurring at temporal scales of 10^1 - 10^3 years. Thus, GRU scale processes operate at a lower frequency and effectively maintain a geomorphological ‘memory’ of such processes. As such, data sets occurring within 1-50 years should be compatible unless the system of interest has undergone a dramatic change in hydrological or geomorphological character, for example, due to diversion, damming, restoration, channelization, massive flood or drought events *etc.*

5.4 Validation of Ecological Models

There has long been debate over validation philosophy, terminology and concepts in relation to environmental and ecological modeling (Oreskes *et al.*1994, Rykiel 1996). Validation is generally considered a demonstration that a model possesses a satisfactory range of accuracy consistent with the intended use of the model within its domain of applicability (Rykiel 1996). As Rykiel (1996) discusses, validation is not essential for evaluating research models, but it can be important for building credibility with those who want to use the model for forecasting or management purposes. In terms of validating ecological models, we can consider testing both the ability of the model to perform its desired function as well as its theoretical content by applying operational, conceptual, and data validation methods (Sargent 1984, Rykiel 1996). Conceptual validity refers to acceptable justification of the scientific content of the model, or that the model representation of the system, including the logic, mathematical, and causal relationships are reasonable for the intended use (Sargent 1984, Rykiel 1996). Data validation ensures that the data meets a specified standard and that it is interpreted correctly (Rykiel 1996). A model may be conceptually valid but that does not guarantee that the model will make accurate predictions. Operational validation is concerned with how well the model mimics the system of interest and is often applied by comparing the model output with observed or field data (Power 1993, Rykiel 1996).

Efforts were made to ensure stability of PCA results and to determine whether spatial autocorrelation was confounding patterns in CPUE, both of which may be considered measures of data validation or statistical validation (Chapters 3 and 4). A more rigorous approach to data validation might also include validation of the selection of channel variables that are most likely to predict CPUE. This could be done using regression analysis to make inferences about the relationships between abundance and channel features. Initially, individual geomorphological variables can be compared to CPUE to determine which variables are correlated with CPUE. Results of previous chapters suggest that different fish species may have different relationships to channel planform variables, therefore regression analyses should be performed for individual species rather than pooled total CPUE. It is also important to consider synergistic and antagonistic effects of geomorphological variables which can be investigated with the application of generalized linear models and comparison of change in deviance, or log likelihood, when a given covariate is removed from the model (Lachin 1993, Crawley 2013). This information can help in selecting appropriate variables for the PCA step of analysis by determining which variables account for the most variation in the multiple regression model. If non-linear relationships are present generalized additive models can be used to apply non-parametric smoothers to describe relationships (Crawley 2013). Model selection can be validated further by split sample validation, whereby reductive models are compared to see if the same patterns of interactions are observed.

Methods of operational validation include both quantitative and qualitative measures of system performance and tests may be project specific (Rykiel 1996). The GRU method is not a simulation model therefore validation techniques are more limited than for traditional modelling situations. Applicable tests include subjective visualization techniques where visual displays (spatial maps, time series plots etc.) form the basis for comparison between the model and system; statistical validation which can be applied to validate model data and model operation;

and predictive validation whereby the model output is used to predict system behaviour and comparisons are made to determine if the model and system behave similarly. For example, Lake Sturgeon overwintering locations in the South Saskatchewan River appear to be associated with specific geomorphic Types. The predictive capacity of the GRU model could then be examined by identifying Geomorphic Types in a similar river such as the North Saskatchewan. Types could then be sampled to determine which physical habitat characteristics, such as deep holes, riffles and runs, rapids, large wood, pools, vegetation etc. are most predominant in each type. The Type with the same characteristics of Type 0 in Chapter 2 (narrow, average sinuosity, higher slope and fractal dimension) should then correspond to a higher occurrence of stable deep pools that Lake Sturgeon overwinter in. Fish movement and distribution could also be investigated using radio and/or hydroacoustic tags to track fall fish movements to overwintering areas and see if they are most often associated with the predicted Type. Though the theoretical basis for the model is sound and both visualization and statistical data validation techniques have been applied, further validation, particularly predictive or field validation, would strengthen the credibility of the method with potential users.

Another important consideration for model validation is the qualification of the model, or the domain over which a validated model may be properly used (Rykiel 1996). For example, the GRU model has been applied in a prairie river context. These rivers flow through areas with cold winters, warm summers, little precipitation, and are subject to anthropogenic impacts including damming, water abstraction, and dike systems. These features have implications for the domain in which the GRU model is expected to perform and yield results comparable to those investigated here. Though I expect the GRU method will perform well in other types of rivers, it is possible that different channel variables will better describe variability in channel pattern and related physical habitat features in those systems. If the model is applied in a drastically different setting such as a montaine stream then re-validation would be necessary to determine if selected channel planform variables are related to ecologically significant differences in channel pattern.

5.5 Future Research

A key aspect of this research was to determine whether existing GIS and fisheries datasets can contribute to our understanding of large scale patterns in geomorphic character of Prairie rivers, as represented by channel planform variables, and how this might relate to the formation and maintenance of physical habitats. Investigating such links was limited to comparing abundance of individual fish species in relation to Geomorphic Response units then describing physical features within each unit based on characteristics of input variables, surficial geology, satellite imagery and physical habitat variables included in fish survey datasets. Existing studies addressing spatial hierarchies and links between large scale geomorphological patterns and fish habitat have occurred in small stream systems that can be sampled much more efficiently than large Prairie rivers.

In order to understand whether GRUs are related to differences in fish assemblages, future studies must tailor fish sampling strategies in efforts to overcome sampling biases that may be prevalent in large prairie rivers. A stratified sampling design whereby a combination of electrofishing and trawl gear types are used at each sample site would provide a more representative sample of assemblage structure encompassing a larger range of body sizes and guilds. Other variables that can be readily derived from GIS and be related to the formation of physical riverine habitats should also be considered in further analysis in order to ensure that the most descriptive variables are being used. As mentioned previously, island formations, side channels, and valley characteristics may be important indicators of habitat features. Future GRU applications should incorporate a greater variety of channel pattern variables and a statistical selection process to identify which variables are most likely to describe the variability in channel pattern characteristics that is related to instream habitat and abundance of fish species. It is also of interest to investigate other multivariate methods for identifying Geomorphic Types. Though GRUs hold promise as a management tool, application and interpretation of PCA may be beyond the scope of some managers. In addition, more field validation of the transferability and predictive capacity of GRUs would be valuable. This could be done by delineating GRUs in other prairie rivers similar to those examined in this thesis and subsequently systematically sampling the units to determine if similar relationships between GRUs, fish CPUE, and habitat variables emerge. Such field validation would increase value of this model to managers.

5.6 Sustainability Considerations

Fishes are considered the most jeopardised vertebrates worldwide with the 2009 IUCN Red List reporting 1147 of 3120 assessed species (37%) as at risk of extinction (as cited in Tyus 2012). Holmlund and Hammer (1999) identified several ecosystem services generated by fish populations which they grouped into two major categories: 1) fundamental ecosystem services, which are essential for ecosystem function and resilience and; 2) demand derived ecosystem services, which are formed by human values and demands. Fundamental ecosystem services include: regulating services such as food web and nutrient dynamics/balances, sediment processes and carbon flux; linking services via actively and passively transferring nutrients, and genetic storage between years and different ecosystems, essentially linking different spatial and temporal scales (Holmlund and Hammer 1999). The concept of ecological memory is similar to a 'remember' cross scale interaction in the complex social-ecological systems framework of Holling (2001). Such interactions allow processes and resources operating at a larger spatiotemporal scale, for instance a meta-population of riverine fish, to contribute to the renewal of processes operating at a smaller scale by emigration into habitats post-disturbance. Maintaining these cross scale connections is extremely important to maintaining the resilience of riverine ecosystems. Demand-derived ecosystem services include: information services, such as using fish as indicators of water quality (Karr, J.R. 1991), and as historical environmental records of climate change; Cultural services, as important sources of food and other goods, recreational activities like fishing and scuba diving, aesthetic values in natural settings and aquaria, and improving human health as sources of medicines and bio-control (i.e. mosquito fish to control aquatic disease vectors and plants) (Holmlund and Hammer 1999). Biodiversity must be maintained in order for such ecosystem services to be upheld. The genetic diversity of individuals and populations aid in the maintenance of ecosystem function in fluctuating environmental conditions, and complex natural systems have greater community stability than simple ones because they generally recover more quickly from environmental perturbations (Tyus 2012).

Large Prairie rivers provide several demand driven services including domestic and industrial water supply, hydropower production, irrigation, and transportation, all of which play key roles in the decline of aquatic biodiversity (Pracheil *et al.* 2013). Habitat degradation or loss due to land use practices, damming, and water extraction, are among the most prevalent threats to prairie fish biodiversity. Many of these threats can be mitigated by altering existing management practices. Improved storm water and drainage management efforts and the implementation of buffer strips in riparian zones may help reduce sediment inputs and increased runoff in both urban and agricultural areas (Allan and Castillo 2007, Palmer *et al.* 2009). Dams can be regulated so peak flow timing and variability more closely reflect historic flows (Poff *et al.* 2007) and fish ladder technology improved to allow migration barriers to be passed more readily. Improved river restoration efforts that seek to restore natural channel shape, sediment loads, and structural features such as boulders and large wood may help increase habitat availability (Allan and Castillo 2007). An important part of implementing such efforts is being able to characterize the current state of habitats within extensive, trans-boundary river networks. This is a demanding undertaking, with traditional management approaches requiring considerable financial and labor commitments over long time periods. Various documents outlining management goals and actions in the systems presented in this thesis consistently point to a lack of: 1) existing information about riverine habitats and 2) a system to classify them. For example, one of the key objectives of the Water Security Agency's South Saskatchewan Watershed Source Water Protection Plan is to "Restore fish habitat and passage in key locations throughout the watershed" with an associated action to "…evaluate and restore fish habitat in the South Saskatchewan River Watershed" (Saskatchewan Watershed Authority 2007). Similarly, Manitoba Water Stewardship has stated that one of their conservation issues is that "a classification system for fish habitat and a co-ordinated process for the protection and enhancement of fish habitat in the design of drainage systems is not currently available". Key strategies for dealing with this are to "Develop integrated resource planning to allow for habitat and resource conservation to be incorporated early in the planning process" as well as "Develop workable, practical means to harmonize with the Fisheries Act of Canada Section 35(1), including a fisheries habitat classification system". Though there are some protocols available for fish habitat assessments in rivers they are usually designed for a specific purpose at a localized area, for example such as assessing and monitoring fish habitat at watercourse crossings (Government of Alberta Transportation 2001). Though these assessments allow consistent classification on a small scale they are difficult to transfer to entire watersheds or incorporate into early planning processes because they require intensive data collection. When management goals are on a larger, watershed or system wide scale a generalized classification system that can guide the planning process and contribute to well-rounded monitoring programs is more desirable.

More recently, research in the South Saskatchewan River basin has begun to investigate the pending impacts of climate change on water quantity and quality, as well as fish habitat (Head 2015, Islam and Gan 2015). Projected changes in flow have system wide repercussions and must be incorporated into management plans and instream flow needs (IFN) frameworks. The WSA 25 year water security report includes reference to maintaining biodiversity, ecosystem function, fisheries habitat and species at risk in their considerations for water and land use as well as impacts on fisheries and fish habitat in water allocation and reservoir operating plans in the Province of Saskatchewan, though no clear frameworks for classifying and quantifying fish habitats are discussed (Water Security Agency 2012). IFN frameworks often include fish habitat and channel structure as some of the main categories for IFN determination and monitoring (Alberta Environment and Fisheries and Ocean Canada 2007, Alberta Environment 2013). Understanding the possible habitat complexity and connectivity in different IFN reaches can improve monitoring and assessment of the possible impacts on habitat availability due to flow manipulation and withdrawals by ensuring sample sites reflect the possible diversity of habitats in impacted reaches. As aforementioned, the GRU method can improve the efficiency and efficacy of river management efforts through the *a priori* classification of river reaches based purely on GIS derived measures of geomorphic character. The GRU method is a valuable tool that has the potential to increase our understanding of habitat availability, complexity, and connectivity and provide valuable insight for monitoring programs, habitat restoration efforts, and sustaining riverine fish populations on the Prairies.

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APPENDIX A: Supplemental Information for Chapter 2

Table A-1. Results of post-hoc pairwise multiple comparison of geomorphological variables in each Type using Dunn's Method

	Sinuosity			**Slope**			**Fractal Dimension**			**Width**		
Type	Z value	P value	P value adjusted	Z value	P value	P value adjusted	Z value	P value	P value adjusted	Z value	P value	P value adjusted
1-0	-7.5824	<0.001	<0.001 *	-14.9667	<0.001	<0.001 *	-7.2197	<0.001	<0.001 *	13.3785	<0.001	<0.001 *
2-0	23.3361	<0.001	<0.001 *	-0.5512	0.582	1.000	10.8243	<0.001	<0.001 *	5.1718	<0.001	<0.001 *
2-1	19.5712	<0.001	<0.001 *	13.4487	<0.001	<0.001 *	12.4787	<0.001	<0.001 *	-9.4937	<0.001	<0.001 *
3-0	-25.2115	<0.001	<0.001 *	-55.8730	<0.001	<0.001 *	-9.7889	<0.001	<0.001 *	63.8639	<0.001	<0.001 *
3-1	-3.6863	<0.001	0.027 *	-9.9692	<0.001	<0.001 *	2.7574	0.006	0.699	15.0479	<0.001	<0.001 *
3-2	-40.2537	<0.001	<0.001 *	-39.8480	<0.001	<0.001 *	-17.2948	<0.001	<0.001 *	41.2578	<0.001	<0.001 *
4-0	19.1053	<0.001	<0.001 *	4.3469	<0.001	0.002 *	-28.4245	<0.001	<0.001 *	2.6264	0.009	1.000
4-1	15.5502	<0.001	<0.001 *	16.6472	<0.001	<0.001 *	-4.8196	<0.001	<0.001 *	-12.1390	<0.001	<0.001 *
4-2	-9.2554	<0.001	<0.001 *	3.5902	<0.001	0.040 *	-30.4934	<0.001	<0.001 *	-3.1809	0.001	0.176
4-3	41.2487	<0.001	<0.001 *	57.1836	<0.001	<0.001 *	-16.2769	<0.001	<0.001 *	-58.5191	<0.001	<0.001 *
5-0	-13.5707	<0.001	<0.001 *	-29.9146	<0.001	<0.001 *	-64.5165	<0.001	<0.001 *	24.6257	<0.001	<0.001 *
5-1	1.2065	0.228	1.000	0.9606	0.337	1.000	-22.2929	<0.001	<0.001 *	-1.8194	0.069	1.000
5-2	-31.5808	<0.001	<0.001 *	-21.4885	<0.001	<0.001 *	-57.4638	<0.001	<0.001 *	13.3220	<0.001	<0.001 *
5-3	9.8073	<0.001	<0.001 *	21.8816	<0.001	<0.001 *	-50.4561	<0.001	<0.001 *	-33.7737	<0.001	<0.001 *
5-4	-29.6121	<0.001	<0.001 *	-32.3983	<0.001	<0.001 *	-36.9683	<0.001	<0.001 *	21.2689	<0.001	<0.001 *
6-0	33.9150	<0.001	<0.001 *	-10.5156	<0.001	<0.001 *	-2.8867	0.004	0.467	7.8256	<0.001	<0.001 *
6-1	24.7210	<0.001	<0.001 *	8.4734	<0.001	<0.001 *	5.2253	<0.001	<0.001 *	-8.3937	<0.001	<0.001 *
6-2	7.3995	<0.001	<0.001 *	-7.8687	<0.001	<0.001 *	-11.3133	<0.001	<0.001 *	1.8849	0.059	1.000
6-3	50.9106	<0.001	<0.001 *	32.3861	<0.001	<0.001 *	4.6934	<0.001	<0.001 *	-40.9555	<0.001	<0.001 *
6-4	18.7694	<0.001	<0.001 *	-13.3960	<0.001	<0.001 *	18.1710	<0.001	<0.001 *	5.6454	<0.001	<0.001 *
6-5	41.5794	<0.001	<0.001 *	13.3268	<0.001	<0.001 *	46.9213	<0.001	<0.001 *	-11.7337	<0.001	<0.001 *
7-0	-21.9739	<0.001	<0.001 *	-68.6522	<0.001	<0.001 *	-67.6223	<0.001	<0.001 *	73.6077	<0.001	<0.001 *
7-1	-0.9467	0.344	1.000	-11.7244	<0.001	<0.001 *	-19.1092	<0.001	<0.001 *	15.2528	<0.001	<0.001 *
7-2	-38.3909	<0.001	<0.001 *	-45.3914	<0.001	<0.001 *	-56.2467	<0.001	<0.001 *	44.0189	<0.001	<0.001 *
7-3	6.4306	<0.001	<0.001 *	-3.3945	0.001	0.083	-49.7578	<0.001	<0.001 *	-0.4205	0.674	1.000
7-4	-40.2871	<0.001	<0.001 *	-68.9167	<0.001	<0.001 *	-34.2266	<0.001	<0.001 *	66.3926	<0.001	<0.001 *
7-5	-4.7827	<0.001	<0.001 *	-27.7243	<0.001	<0.001 *	8.5792	<0.001	<0.001 *	37.3517	<0.001	<0.001 *
7-6	-49.9876	<0.001	<0.001 *	-37.7742	<0.001	<0.001 *	-44.8022	<0.001	<0.001 *	44.0070	<0.001	<0.001 *

8-0	-5.9104	<0.001	<0.001 *	14.9166	<0.001	<0.001 *	-8.1114	<0.001	<0.001 *	8.6978	<0.001	<0.001 *
8-1	2.2547	0.024	1.000	22.1194	<0.001	<0.001 *	0.4960	0.620	1.000	-5.1286	<0.001	<0.001 *
8-2	-20.1160	<0.001	<0.001 *	13.5408	<0.001	<0.001 *	-14.0788	<0.001	<0.001 *	4.3906	<0.001	0.001 *
8-3	7.7673	<0.001	<0.001 *	44.3840	<0.001	<0.001 *	-2.6254	0.009	1.000	-25.7603	<0.001	<0.001 *
8-4	-15.6413	<0.001	<0.001 *	12.4597	<0.001	<0.001 *	6.6186	<0.001	<0.001 *	7.2180	<0.001	<0.001 *
8-5	1.7934	0.073	1.000	30.7566	<0.001	<0.001 *	27.6964	<0.001	<0.001 *	-5.1988	<0.001	<0.001 *
8-6	-26.3081	<0.001	<0.001 *	19.9640	<0.001	<0.001 *	-5.5344	<0.001	<0.001 *	3.0091	0.003	0.314
8-7	4.5827	<0.001	0.001 *	47.9553	<0.001	<0.001 *	24.2569	<0.001	<0.001 *	-26.5366	<0.001	<0.001 *
9-0	-27.8216	<0.001	<0.001 *	-6.6527	<0.001	<0.001 *	-22.6886	<0.001	<0.001 *	37.2131	<0.001	<0.001 *
9-1	-11.2392	<0.001	<0.001 *	8.4148	<0.001	<0.001 *	-8.2910	<0.001	<0.001 *	12.3012	<0.001	<0.001 *
9-2	-39.9902	<0.001	<0.001 *	-5.3971	<0.001	<0.001 *	-27.0371	<0.001	<0.001 *	28.7711	<0.001	<0.001 *
9-3	-12.2700	<0.001	<0.001 *	25.8753	<0.001	<0.001 *	-16.2317	<0.001	<0.001 *	-1.0097	0.313	1.000
9-4	-37.9614	<0.001	<0.001 *	-8.9540	<0.001	<0.001 *	-6.4805	<0.001	<0.001 *	35.1004	<0.001	<0.001 *
9-5	-18.4569	<0.001	<0.001 *	11.3881	<0.001	<0.001 *	16.6166	<0.001	<0.001 *	20.8514	<0.001	<0.001 *
9-6	-47.0962	<0.001	<0.001 *	1.0366	0.300	1.000	-18.2388	<0.001	<0.001 *	27.8738	<0.001	<0.001 *
9-7	-16.6223	<0.001	<0.001 *	29.0627	<0.001	<0.001 *	12.3450	<0.001	<0.001 *	-0.8083	0.419	1.000
9-8	-15.5603	<0.001	<0.001 *	-16.6000	<0.001	<0.001 *	-10.0934	<0.001	<0.001 *	20.1879	<0.001	<0.001 *
10-0	22.7295	<0.001	<0.001 *	14.9691	<0.001	<0.001 *	17.7590	<0.001	<0.001 *	19.0063	<0.001	<0.001 *
10-1	18.4413	<0.001	<0.001 *	21.6033	<0.001	<0.001 *	15.6371	<0.001	<0.001 *	-3.2804	0.001	0.124
10-2	-2.7540	0.006	0.706	12.0256	<0.001	<0.001 *	4.2888	<0.001	0.002 *	10.1646	<0.001	<0.001 *
10-3	41.3940	<0.001	<0.001 *	58.7797	<0.001	<0.001 *	24.3885	<0.001	<0.001 *	-33.5661	<0.001	<0.001 *
10-4	6.9093	<0.001	<0.001 *	11.0238	<0.001	<0.001 *	39.4756	<0.001	<0.001 *	16.2709	<0.001	<0.001 *
10-5	31.6799	<0.001	<0.001 *	37.9224	<0.001	<0.001 *	68.5947	<0.001	<0.001 *	-2.7630	0.006	0.687
10-6	-10.8782	<0.001	<0.001 *	21.0220	<0.001	<0.001 *	16.7130	<0.001	<0.001 *	8.5217	<0.001	<0.001 *
10-7	39.8046	<0.001	<0.001 *	67.2510	<0.001	<0.001 *	69.3139	<0.001	<0.001 *	-36.3833	<0.001	<0.001 *
10-8	18.9329	<0.001	<0.001 *	-4.9325	<0.001	<0.001 *	18.0247	<0.001	<0.001 *	3.2124	0.001	0.158
10-9	39.8440	<0.001	<0.001 *	15.5792	<0.001	<0.001 *	31.9997	<0.001	<0.001 *	-21.9318	<0.001	<0.001 *
11-0	-17.4864	<0.001	<0.001 *	-25.4673	<0.001	<0.001 *	-7.6657	<0.001	<0.001 *	67.8972	<0.001	<0.001 *
11-1	-0.3902	0.696	1.000	3.2649	0.001	0.131	3.6347	<0.001	0.033 *	17.2072	<0.001	<0.001 *
11-2	-34.5936	<0.001	<0.001 *	-18.0084	<0.001	<0.001 *	-15.7221	<0.001	<0.001 *	44.5411	<0.001	<0.001 *
11-3	6.7227	<0.001	<0.001 *	27.0200	<0.001	<0.001 *	1.8108	0.070	1.000	4.5041	<0.001	0.001 *
11-4	-33.6836	<0.001	<0.001 *	-28.1766	<0.001	<0.001 *	17.9618	<0.001	<0.001 *	62.4778	<0.001	<0.001 *
11-5	-3.1796	0.001	0.177	4.5629	<0.001	0.001 *	51.6543	<0.001	<0.001 *	37.7682	<0.001	<0.001 *
11-6	-44.8880	<0.001	<0.001 *	-9.5865	<0.001	<0.001 *	-3.1448	0.002	0.199	44.3776	<0.001	<0.001 *
11-7	1.2181	0.223	1.000	33.7017	<0.001	<0.001 *	51.0524	<0.001	<0.001 *	5.4748	<0.001	<0.001 *
11-8	-3.7498	<0.001	0.021 *	-28.1824	<0.001	<0.001 *	3.6881	<0.001	0.027 *	28.3245	<0.001	<0.001 *

11-9	16.5103	<0.001	<0.001 *	-8.4717	<0.001	<0.001 *	17.3119	<0.001	<0.001 *	3.8853	<0.001	0.012 *
11-10	-35.0700	<0.001	<0.001 *	-34.3502	<0.001	<0.001 *	-22.5635	<0.001	<0.001 *	37.2402	<0.001	<0.001 *
12-0	13.1344	<0.001	<0.001 *	27.6513	<0.001	<0.001 *	-32.8763	<0.001	<0.001 *	15.1061	<0.001	<0.001 *
12-1	13.2650	<0.001	<0.001 *	26.9531	<0.001	<0.001 *	-7.6098	<0.001	<0.001 *	-6.3321	<0.001	<0.001 *
12-2	-12.3167	<0.001	<0.001 *	20.6321	<0.001	<0.001 *	-34.0616	<0.001	<0.001 *	6.1420	<0.001	<0.001 *
12-3	34.6568	<0.001	<0.001 *	75.4762	<0.001	<0.001 *	-21.1928	<0.001	<0.001 *	-43.6509	<0.001	<0.001 *
12-4	-4.4502	<0.001	0.001 *	22.5307	<0.001	<0.001 *	-6.1088	<0.001	<0.001 *	12.0849	<0.001	<0.001 *
12-5	23.9113	<0.001	<0.001 *	51.5573	<0.001	<0.001 *	29.3387	<0.001	<0.001 *	-8.9357	<0.001	<0.001 *
12-6	-21.5834	<0.001	<0.001 *	30.8335	<0.001	<0.001 *	-22.3306	<0.001	<0.001 *	4.2091	<0.001	0.003 *
12-7	32.6025	<0.001	<0.001 *	88.1393	<0.001	<0.001 *	25.1981	<0.001	<0.001 *	-48.6268	<0.001	<0.001 *
12-8	12.8135	<0.001	<0.001 *	0.5520	0.581	1.000	-9.9510	<0.001	<0.001 *	-0.2284	0.819	1.000
12-9	34.3758	<0.001	<0.001 *	22.5228	<0.001	<0.001 *	2.5985	0.009	1.000	-26.9130	<0.001	<0.001 *
12-10	-10.3658	<0.001	<0.001 *	8.5020	<0.001	<0.001 *	-42.8998	<0.001	<0.001 *	-5.3416	<0.001	<0.001 *
12-11	27.6143	<0.001	<0.001 *	47.9039	<0.001	<0.001 *	-22.7391	<0.001	<0.001 *	-47.6012	<0.001	<0.001 *
13-0	-33.1330	<0.001	<0.001 *	-5.8000	<0.001	<0.001 *	-70.1486	<0.001	<0.001 *	63.5278	<0.001	<0.001 *
13-1	-5.7257	<0.001	<0.001 *	12.6314	<0.001	<0.001 *	-20.9522	<0.001	<0.001 *	12.1373	<0.001	<0.001 *
13-2	-45.9101	<0.001	<0.001 *	-3.4061	0.001	0.079	-58.6640	<0.001	<0.001 *	38.1707	<0.001	<0.001 *
13-3	-4.3582	<0.001	0.002 *	50.5912	<0.001	<0.001 *	-52.7263	<0.001	<0.001 *	-7.1363	<0.001	<0.001 *
13-4	-50.2889	<0.001	<0.001 *	-9.8034	<0.001	<0.001 *	-37.7548	<0.001	<0.001 *	57.2537	<0.001	<0.001 *
13-5	-14.8852	<0.001	<0.001 *	24.8809	<0.001	<0.001 *	4.2020	<0.001	0.003 *	29.9319	<0.001	<0.001 *
13-6	-57.6659	<0.001	<0.001 *	6.3360	<0.001	<0.001 *	-47.4979	<0.001	<0.001 *	37.8105	<0.001	<0.001 *
13-7	-12.3039	<0.001	<0.001 *	62.4731	<0.001	<0.001 *	-5.0082	<0.001	<0.001 *	-7.7982	<0.001	<0.001 *
13-8	-10.4133	<0.001	<0.001 *	-17.7641	<0.001	<0.001 *	-26.4461	<0.001	<0.001 *	22.5989	<0.001	<0.001 *
13-9	10.0941	<0.001	<0.001 *	3.5481	<0.001	0.047 *	-14.8171	<0.001	<0.001 *	-3.2350	0.001	0.146
13-10	-48.1591	<0.001	<0.001 *	-19.4039	<0.001	<0.001 *	-71.6445	<0.001	<0.001 *	29.8469	<0.001	<0.001 *
13-11	-11.6506	<0.001	<0.001 *	20.3221	<0.001	<0.001 *	-53.9642	<0.001	<0.001 *	-11.9627	<0.001	<0.001 *
13-12	-42.2048	<0.001	<0.001 *	-32.6896	<0.001	<0.001 *	-28.7919	<0.001	<0.001 *	40.7125	<0.001	<0.001 *
14-0	37.1902	<0.001	<0.001 *	12.1625	<0.001	<0.001 *	3.9368	<0.001	0.010 *	12.7184	<0.001	<0.001 *
14-1	26.9293	<0.001	<0.001 *	20.3103	<0.001	<0.001 *	8.7622	<0.001	<0.001 *	-5.5042	<0.001	<0.001 *
14-2	10.9426	<0.001	<0.001 *	10.2259	<0.001	<0.001 *	-5.6279	<0.001	<0.001 *	6.0238	<0.001	<0.001 *
14-3	53.4666	<0.001	<0.001 *	52.2162	<0.001	<0.001 *	10.8518	<0.001	<0.001 *	-34.5726	<0.001	<0.001 *
14-4	22.5672	<0.001	<0.001 *	8.7294	<0.001	<0.001 *	23.9937	<0.001	<0.001 *	10.4901	<0.001	<0.001 *
14-5	44.4423	<0.001	<0.001 *	33.4361	<0.001	<0.001 *	51.5056	<0.001	<0.001 *	-6.5154	<0.001	<0.001 *
14-6	3.8619	<0.001	0.013 *	18.4992	<0.001	<0.001 *	5.5755	<0.001	<0.001 *	4.3303	<0.001	0.002 *
14-7	52.6208	<0.001	<0.001 *	58.7914	<0.001	<0.001 *	49.7440	<0.001	<0.001 *	-36.8850	<0.001	<0.001 *
14-8	28.8319	<0.001	<0.001 *	-5.5318	<0.001	<0.001 *	9.6987	<0.001	<0.001 *	0.3425	0.732	1.000

14-9	49.3758	<0.001	<0.001 *	14.0155	<0.001	<0.001 *	22.4370	<0.001	<0.001 *	-23.8466	<0.001	<0.001 *
14-10	14.5776	<0.001	<0.001 *	-1.0909	0.275	1.000	-10.3923	<0.001	<0.001 *	-3.7474	<0.001	0.021 *
14-11	47.6516	<0.001	<0.001 *	30.0803	<0.001	<0.001 *	9.3124	<0.001	<0.001 *	-37.9337	<0.001	<0.001 *
14-12	25.1698	<0.001	<0.001 *	-8.9145	<0.001	<0.001 *	27.8201	<0.001	<0.001 *	0.8154	0.415	1.000
14-13	59.9816	<0.001	<0.001 *	16.1453	<0.001	<0.001 *	52.2821	<0.001	<0.001 *	-31.0839	<0.001	<0.001 *
15-0	-5.5324	<0.001	<0.001 *	-34.5611	<0.001	<0.001 *	-53.0693	<0.001	<0.001 *	67.2984	<0.001	<0.001 *
15-1	4.7021	<0.001	<0.001 *	-1.8357	0.066	1.000	-18.0014	<0.001	<0.001 *	18.7601	<0.001	<0.001 *
15-2	-25.2350	<0.001	<0.001 *	-25.4212	<0.001	<0.001 *	-49.5801	<0.001	<0.001 *	45.7975	<0.001	<0.001 *
15-3	16.3281	<0.001	<0.001 *	15.6219	<0.001	<0.001 *	-40.6166	<0.001	<0.001 *	7.7741	<0.001	<0.001 *
15-4	-21.2871	<0.001	<0.001 *	-36.8122	<0.001	<0.001 *	-27.1751	<0.001	<0.001 *	62.4074	<0.001	<0.001 *
15-5	6.6899	<0.001	<0.001 *	-5.3174	<0.001	<0.001 *	7.7913	<0.001	<0.001 *	39.2278	<0.001	<0.001 *
15-6	-34.6693	<0.001	<0.001 *	-17.6155	<0.001	<0.001 *	-38.9128	<0.001	<0.001 *	45.6199	<0.001	<0.001 *
15-7	12.1886	<0.001	<0.001 *	20.4271	<0.001	<0.001 *	0.6790	0.497	1.000	9.0005	<0.001	<0.001 *
15-8	2.4569	0.014	1.000	-33.6989	<0.001	<0.001 *	-22.3995	<0.001	<0.001 *	29.9083	<0.001	<0.001 *
15-9	22.7111	<0.001	<0.001 *	-14.8209	<0.001	<0.001 *	-11.0645	<0.001	<0.001 *	6.1178	<0.001	<0.001 *
15-10	-24.6111	<0.001	<0.001 *	-41.7151	<0.001	<0.001 *	-59.4449	<0.001	<0.001 *	38.7576	<0.001	<0.001 *
15-11	9.8725	<0.001	<0.001 *	-9.8104	<0.001	<0.001 *	-41.8926	<0.001	<0.001 *	3.4815	<0.001	0.060
15-12	-16.2570	<0.001	<0.001 *	-55.1348	<0.001	<0.001 *	-20.3714	<0.001	<0.001 *	48.5204	<0.001	<0.001 *
15-13	21.6945	<0.001	<0.001 *	-29.7364	<0.001	<0.001 *	4.6470	<0.001	<0.001 *	14.9960	<0.001	<0.001 *
15-14	-37.7240	<0.001	<0.001 *	-37.1078	<0.001	<0.001 *	-43.6875	<0.001	<0.001 *	39.4288	<0.001	<0.001 *

APPENDIX B: Supplemental Information for Chapter 4

Table B-1 Results of post-hoc pairwise multiple comparisons of geomorphological variables in each Assiniboine River GRU using Dunn's Method.

	Sinuosity			**Slope**			**Fractal Dimension**			**Width**		
GRU	Z value	P value	P value adjusted	Z value	P value	P value adjusted	Z value	P value	P value adjusted	Z value	P value	P value adjusted
I vs III	62.052	<0.001	<0.001 *	0.0219	0.985	1	121.5666	<0.001	<0.001 *	-64.3929	<0.001	<0.001 *
I vs V	-18.7467	<0.001	<0.001 *	50.7004	<0.001	<0.001 *	29.9506	<0.001	<0.001 *	23.8481	<0.001	<0.001 *
III vs V	-63.8387	<0.001	<0.001 *	53.1786	<0.001	<0.001 *	-55.1098	<0.001	<0.001 *	70.8574	<0.001	<0.001 *

Table B 2 Results of post-hoc pairwise multiple comparisons of monthly velocity and depth sampled in each Assiniboine River GRU using Dunn's Method.

			Velocity			**Depth**		
Year	Month	GRU	Z value	P value	P value adjusted	Z value	P value	P value adjusted
1995	Aug	I vs V	16.436	<0.001 *	-	1.7992	0.180	-
	Sep	I vs V	1.9165	0.166	-	0.0388	0.844	-
1996	May	I vs V	12.953	<0.001 *	-	0.0326	0.857	-
	June	I vs V	3.6254	0.0569	-	0.1427	0.706	-
	July	I vs V	0.3309	0.565	-	0.0074	0.931	-
	Aug	I vs V	13.825	<0.001 *	-	0.1489	0.6996	-
	Oct	I vs V	2.9828	0.084	-	0.1022	0.749	-
2002	July	I vs III	2.4451	0.014	0.043 *	-0.0200	0.984	1
		I vs V	0.0393	0.969	1	-0.8040	0.421	1
		III vs V	-2.7899	0.005	0.016 *	-0.9711	0.331	0.994

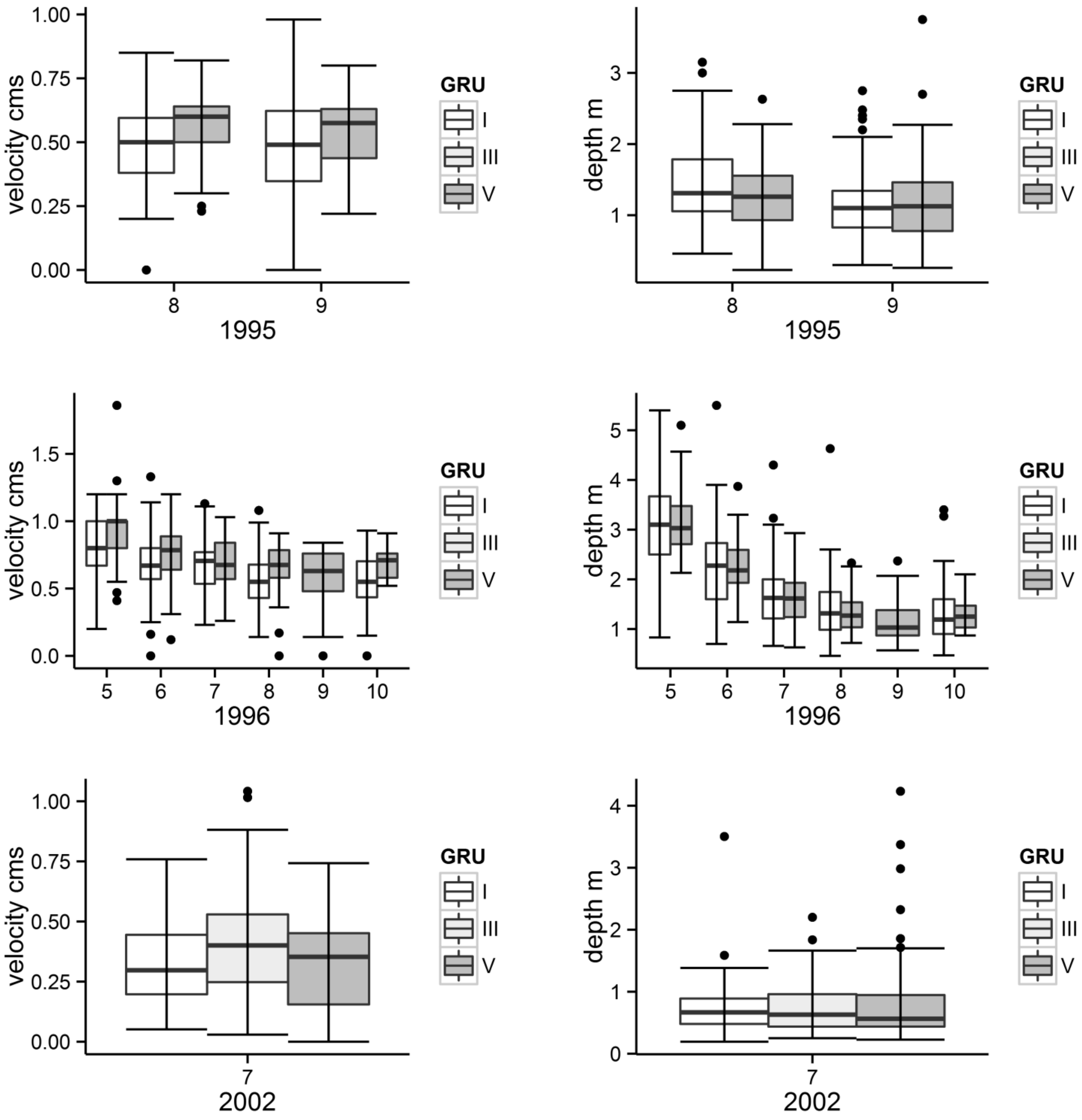

Figure B-1 Comparison of monthly depth and velocity measurements recorded in different GRUs during each year of electrofishing surveys in the Assiniboine River.