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The Use of Geomorphic Principles in Natural Channel Design: The State 5f“River Restoration Practice in Southern Ontario, Canada

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Abstract

River restoration and natural channel design attempt to (re)construct channels to emulate the self-sustaining geomorphic and ecologic function of natural watercourses. The practice of river restoration and natural channel design has occurred in Ontario for over two decades, but there has not yet been a review of design approaches and methodologies utilized to achieve the aforementioned function and the overall state of stream design practice. Using the stream design projects in rivers within the jurisdiction of Toronto and Region Conservation Authority and Credit Valley Conservation, two Ontario watershed-based river management agencies, forty-six stream design projects were reviewed and analyzed to assess how and for what extent geomorphic principles are incorporated into the designs. The review and analysis indicated that: 1) project objectives were vague and lacked quantitative baseline data; 2) channel designs were undertaken at the reach scale and did not include watershed conditions; 3) constraints primarily impacted the plan-form of the channel and the degree of natural geomorphic functionality allowed; 4) designs are not influenced by legislative control or specific design methods and requirements, and; 5) that project design was undertaken using a variety of methodologies and approaches (some of which are proprietary), but relied heavily on existing field conditions for design discharges and other parameters. Geomorphic design is done by well-trained and experienced fluvial geomorphologists who are central to ongoing improvement in design methods. There is a strong emphasis on continuing education from junior practitioners working towards their Professional Geoscientist designation, to keeping up with academic research via peer-reviewed journals. Post-project monitoring typically occurs for a maximum of three years. The absence of long-term monitoring hampers the ability of practitioners and scientists to learn from previous designs.

Keywords: River restoration, channel design, fluvial geomorphology, southern Ontario.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

> "We in the stream restoration world are currently in the untenable position of spending more than a billion dollars of taxpayer money a year on restoration projects with no real idea whether or not they are succeeding. Thus supporters and critics of Natural Channel Design [the Rosgen Approach] should work together to develop a broadly comparable national study evaluating the outcomes of restoration projects based on a variety of approaches. This should give a better sense of what combinations of available tools are working, and indicate the areas where practitioners and researchers need to work together to develop better tools"
>
> (Lave, 2009)

Successful river restoration can be defined as the achievement of project objectives, and in particular, where objectives include the improvement of river form and function, and the creation of a dynamically stable channel, and thus the successful design of river restoration works should include local geomorphology (Levell and Chang, 2008). Dynamically stable channels are relatively stable and resilient and reflect the current hydrologic and sediment regimes of the watershed. Geomorphological approaches to channel design are more holistic (Brookes and Sear, 1996). Geomorphology informs the design and is an appropriate lens through which to approach river and watershed management, and as a monitoring tool (Yates, 2008). These approaches should lead to more sustainable watershed management (Newson and Large, 2006).

This thesis aims to connect the science of fluvial geomorphology with the practice of river restoration and natural channel design (NCD) in southern Ontario. Through the analysis of the current practices, this research will identify ways in which channel design is impacting rivers and the landscape. Furthermore, this research will aid in the identification of potential areas of improvement, and areas where the practice is succeeding in the creation of sustainable, dynamically stable geomorphically functional channels. In order to understand how channel design is carried out in southern Ontario, I will explore the practice by reviewing channel designs and interviewing practitioners.

This project was inspired in part by the National River Restoration Science Synthesis (NRRSS) (Palmer *et al.*, 2007; Bernhardt *et al.*, 2007; Hasset, 2006), which catalogued restoration practices throughout the U.S.A. to assess the state of restoration practice, the scientific basis of current practice, and identification of exemplary projects. The NRRSS focused on ecological success and synthesized a variety of types of restoration efforts in many regions of the country. Results were disseminated via summary fact sheets on the project's website. Using the NRRSS concept, an inventory and analysis was completed for NCD projects in southern Ontario. The inventory and analysis of projects was also guided by scientific and engineering literature and restoration guidebooks/handbooks available from the United States, European Union, and Australia.

Given the physiographic diversity of southern Ontario and the wide range of conditions (landscape disturbances) under which restoration might occur (e.g. urban versus suburban versus rural), specific methodologies would likely not be applicable over a wide enough range of conditions to be of actual use to practitioners. Although there are currently no guidelines, handbooks or standardized recognized design methodologies for channel restoration in southern Ontario, a regional handbook (with regional relationships) may be beneficial, particularly as a way for experienced practitioners to share their findings. This type of handbook would allow greater learning from previous projects, which would aid in evolving the practice. A guidebook with specific methodologies would be less useful in southern Ontario than a handbook with recommended techniques that have proven to be useful in previous designs and under what conditions they proved successful.

Given the lack of design guidance provided by the regulatory agencies or otherwise, it is unclear on what basis, and with which methods, the design process is actually undertaken in southern Ontario. Specifically, there is the question of what, if any, geomorphic principles are being incorporated into design, under what circumstances, how they are being applied, and for what types of projects. At present, there is no general information on the extent to which practitioners and regulators have adapted NCD methods to semi-alluvial conditions, or what constrains the application of these principles.

1.1 Objectives

It is not the intention of this project to provide a standardized approach to NCD in southern Ontario, nor is it suggested that a standardized approach is required. The purpose of this thesis is to: 1) compare and contrast existing methods proposed in the science and engineering literature, and other design manuals, with those being applied to projects typical of the region; and 2) identify the extent geomorphic design principles are being used and the factors limiting their application. The objectives of this thesis are to determine:

- The types of projects typically undertaken, including project drivers and objectives;
- Which methods are used to incorporate geomorphic principles into NCD;
- What constraints practitioners face when designing NCD projects and how this impacts the application of geomorphic principles; and
- How practitioners consider the semi-alluvial nature of streams in their design.

The study will:

- Provide information to benefit stream design and restoration activity in the region; and
- Identify future areas of research for applied fluvial geomorphology in southern Ontario.

By understanding the state of practice in relation to the state of the science, both practitioners and academics can improve their knowledge of this evolving field.

Chapter 2: Background and Literature Review

2.1 Introduction

Natural channel design, as defined by the Toronto and Region Conservation Authority (TRCA), is the "practice used in stream realignment and restoration projects that attempts to reconstruct channels to emulate the self-sustaining geomorphic and ecological functions of natural watercourses" (p. 1,TRCA, 2009). Channel design is a biophysical process that incorporates social, political and economic aspects (McDonald *et al.,* 2004). Successful and sustainable projects are multidisciplinary, and include geomorphology, ecology and engineering. This thesis will focus on the geomorphic aspects of channel design, and therefore, ecology and engineering are beyond the scope of this project.

The background information presented in this chapter is intended to illustrate what constrains and/or guides channel design and the implementation process. Constraints or guides may include legislation, issues arising from urbanization, management issues and approaches, and design approaches. Geomorphic principles of NCD are explained through the description of their purpose and use, methods for utilizing these principles in the design process, and the limitations of these principles. Additionally, practices in other countries (with a focus on developed countries) in relation to how the practice has evolved in Ontario are reviewed. This background information will be used to support findings and results, presented in Chapter 5 and discussed in Chapter 6.

2.2 Understanding fluvial systems for channel design and management

The goal of this section is to provide the reader with a basic understanding of key fluvial geomorphology concepts that apply to channel design, approaches used in channel design, and geomorphic principles which guide NCDs.

2.2.1 Fluvial geomorphology basics for NCD

Channel adjustments are driven by the flow and sediment regimes and are the result of spatially complex, process-form feedbacks. Alluvial channel types exist along a continuum, which corresponds to the energy of the system. There are certain energy thresholds above which a channel may braid and below which a channel may meander. If a channel is close to an energy threshold it is particularly sensitive to changes in flow or sediment supply or to engineering works (Charlton, 2008).

There are three primary driving variables that govern channel shape; flow regime, sediment regime, and the balance between stream power and sediment supply (Charlton, 2008). The flow regime of a given channel is unsteady and fluctuates through time. Discharge influences stream power, velocity, and bed shear stress, which drives sediment transport (Charlton, 2008). Channel morphology is significantly influenced by the bankfull discharge, which is the discharge at which the channel is completely filled. Bankfull discharge is a representative flow for channel-forming conditions, which controls overall channel morphology. The overall geomorphic effectiveness of a given discharge depends on the magnitude and frequency of channel-forming flows, as well as the cumulative effect of the discharges over time.

The sediment regime, which includes the volume and size of the sediment delivered from upstream, is the second driving variable in channel change. Surficial geology, topography and erosion processes in the watershed influence the sediment supply (Charlton, 2008). Consequently, land cover change, including urbanization, have an important effect on sediment supply in southern Ontario.

The third driving variable is the balance between stream power and sediment supply, which is essentially the combination of discharge and sediment supply. Stream power is the rate at which work is carried out along a given length of channel and increases with channel slope and discharge. When stream power and sediment supply are in balance there is no net deposition or erosion within the reach. When stream power and sediment supply are at an imbalance, there is an increase in volume or size of sediment load in relation to stream power (Charlton, 2008). Sediment size is important because it determines flow competence required to initiate transport (Charlton, 2008).

There are four boundary conditions that impact the degree to which driving variables influence channel shape. The valley slope determines the overall rate at which potential energy is expended along a given reach. The degree of valley confinement influences the degree of slope-channel coupling, channel substrate determines how erosion resistant the channel is and how quickly channel shape changes in response to the flow regime. Riparian vegetation is the final boundary condition as it protects and strengthens banks, increasing the erosion resistance of the banks (Charlton, 2008).

Different components of channel morphology change over different time scales (Figure 2.1). However, morphological adjustment tends to lag behind changes that cause them (Charlton, 2008). This, in part, explains why channels in southern Ontario are continuing to adjust to urbanizing influences even when the watershed has been urbanized for an extended period of time. The form and behaviour of the channel reflect the driving variables and the boundary conditions. There are four degrees of freedom that can be modified. These include: 1) cross-sectional geometry, specifically width and depth; 2) slope, which can increase or decrease by degradation/aggradation or by changing sinuosity; 3) plan-form, including lateral migration, meander bed development, reworking bars; and 4) wholesale shifts to a new channel course or channel type; and 5) bed roughness (Charlton, 2008). Understanding driving forces, boundary conditions and degrees of freedom is essential for effective geomorphic design.

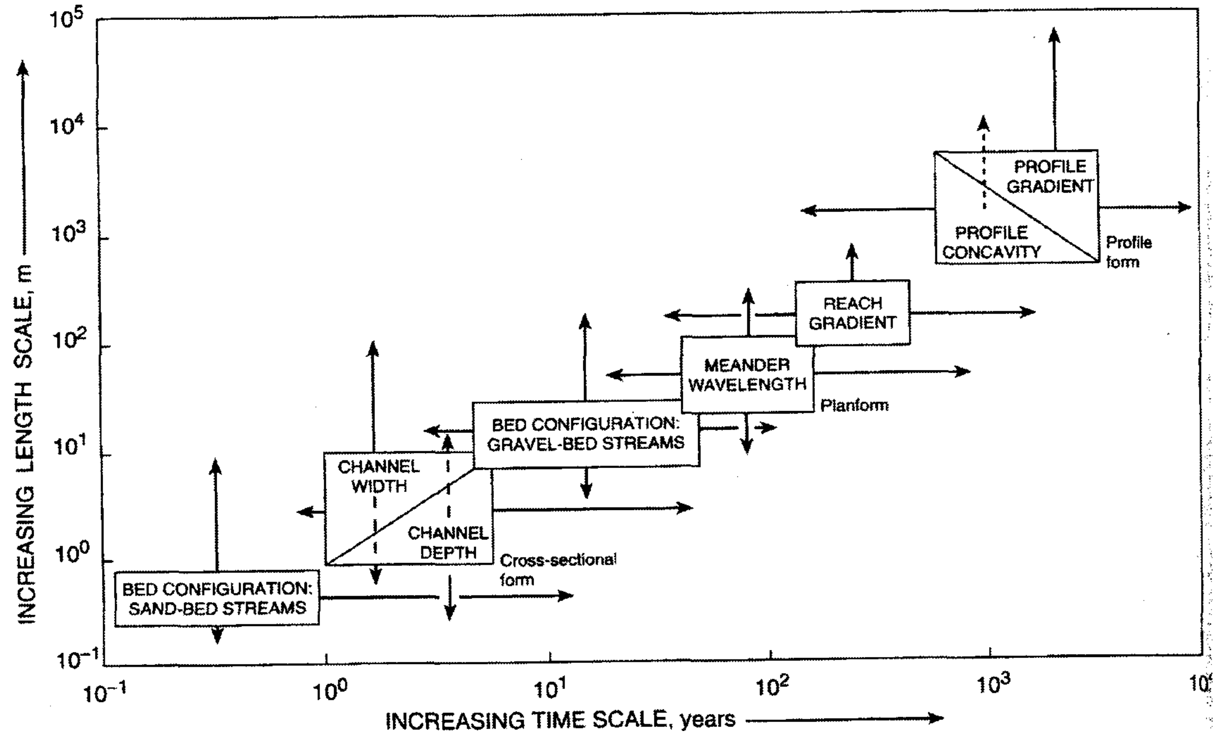

Figure 2.1: Time scales of adjustment of various channel form components (Charlton, 2008).

For meandering channels, there are three important factors to consider when designing channel plan-form. These include the sinuosity ratio, the meander wavelength and the radius of curvature. The sinuosity ratio is the channel length divided by the valley length and indicates how 'wiggly' a channel is. Meander wavelength is determined by measuring the straight-line distance from one bend to the next. Wavelength is more strongly related to channel width than bankfull discharge. Meander formation in channels with cohesive banks allows for the development of a narrower cross-section with tighter bends. Also significant in meander formation is secondary circulation, which is also controlled by channel size. The radius of curvature (r_c) is the 'tightness' of the individual bends in a meandering channel. The influence of channel controls reflects the close correlations that exist between wavelength, mean radius of curvature, and channel width. Because width is related to discharge, meanders are scaled to a range of discharges that shape the channel (Charlton, 2008). Meander wavelength is also correlated with sediment load and channel slope. This implies the importance of understanding the through flow of sediment in order to determine an adequate meander wavelength (Charlton, 2008).

Channel bed forms form at the sub-channel scale and affect hydraulic processes. Riffle-pool sequences are large-scale undulations in the bed topography and are commonly found in gravel-bed channels with low to moderate slopes. In channel design, it is important to understand that the spacing from pool to pool or riffle to riffle is related to the width of the channel, and hence the flow discharge. However, geometry and the relationships that govern the formation of bed forms may be different for semi-alluvial channels. When determining critical bed shear stress for designs, riffles and pools should be considered separately because of local variation in bed material size and bed shear stress within a pool-riffle unit. Steps and pools and rapids and cascades may also be used in channel design, as they provide considerable energy dissipation. In nature they are typically associated with steep channel gradients and are not characteristic of southern Ontario.

The glaciated history of southern Ontario means that the parent material underlying the channel may be glacial till, alluvium, or bedrock. Because channels in the study area do not solely work through previously deposited alluvial sediment, they are termed semi-alluvial channels. Semi-alluvial channels respond differently to driving variables than alluvial channels. Therefore, it is reasonable to assume that the semi-alluvial nature of the channels in the study area would impact the design.

In southern Ontario, unchanneled valleys that exist in headwaters are referred to as swales. Swales are shallow and ephemeral in nature and the fluvial transport in these headwater valleys is relatively ineffective at transporting sediment. Under current conditions, undefined headwater systems have insufficient flow to initiate and maintain a channel (Montgomery and Buffington, 1998). In low-gradient landscapes, such as those found in the headwaters of southern Ontario streams, this type of unchanneled valley is likely the result of long-term climate change (Montgomery and Buffington, 1998), such as the transition from glaciation to a more temperate climate.

2.2.2 Issues arising from urbanization

Urbanization of all or part of a watershed will have significant hydrological and sediment regime impacts. Hydrological impacts include increases in runoff volume; accelerated rate of runoff delivery; increased size of and accelerated arrival of flood peaks; decreased recession time of peak flows; and increases in the frequency of lower magnitude flood returns (Burns *et al.*, 2005; Andrews and Nankervis, 1995; Niezgoda and Johnson, 2005; Annable *et al.*, 2010a). The result of rural to urban/suburban land use conversion is greater surface runoff and reduced sediment supply (Wolman, 1967; Chin, 2006; Annable *et al.*, 2010b).

The extent of the imperviousness and other changes in watershed conditions depends on the density of the development and the type of land use, with effects more pronounced for commercial and industrial developments. Modifications to drainage systems may have significant impact on runoff dynamics and hydrologic regime. Drainage system modifications increase drainage density, connectivity, flow velocity and decrease rainfall-discharge lag times by limiting infiltration. Channels adjust to increases in hydrologic flow regime by enlarging the channel, which may alter channel pattern characteristics. With an increase in discharge, combined with possible channel pattern changes, stream power increases, which leads to greater erosion potential (MacDonald, 2011).

Sediment supply initially increases with the onset of urbanization, which includes road construction and the removal of vegetation (Niezgoda and Johnson, 2005; Riley, 1998). After the completion of construction, impervious surfaces prevent erosion causing post-construction sediment supplies to decrease below pre-urbanization levels (Niezgoda and Johnson, 2005).

Changes in channel morphology have been observed at 5% impervious surface area within the watershed and substantial changes in channel morphology have been observed at 30% (Bravard and Petts, 1996). Channel morphology reflects the sediment transport rate of the stream, which is systematically related to runoff frequency (Richards, 1982). Channel morphology adjusts either vertically or laterally, or both, in response to changes in the hydrologic and sediment regimes through bed erosion or deposition (Niezgoda and Johnson, 2005). Long-term erosion and deposition of the bed-load is directly related to sediment transport and sediment supply. Sediment yield may also be increased from changing channel shape (Riley, 1998). Decreased sediment supplies, coupled with increased runoff volume and velocity, increases stream competence. Increased competence increases sediment transport rates by increasing the incidence of removal of the armor layer leading to channel incision and degradation (Rosgen, 1997). Incision is caused by activities that decrease sediment loads, increase annual discharge and peak discharges, concentrate flow and increase channel gradient. The type and magnitude of morphological change caused by urbanization is better understood if channel evolution is considered over the medium term (tens of years), as the channel will evolve in response to any future changes in the hydrologic and sediment regimes (Surian *et al.,* 2009).

Urbanized watersheds present restoration practitioners with a set of constraints that must be taken into account during the design and implementation process. Beyond the hydrologic and sediment regime impacts, urbanization typically decreases the amount of floodplain space available for channel construction, particularly in areas that have been settled for longer periods of time (e.g. in higher energy, lower reaches in the Greater Toronto Area (GTA) watersheds). In these areas, it is important to protect public and private property, as well as infrastructure that runs along or across the valley corridor, as public sensitivity to disturbance is greater than the morphologic sensitivity of the watercourse (Downs and Gregory, 2004). Additionally, urbanized watersheds preclude the use of historical channel morphologies in the design process. Historical channel morphologies, associated pre-urban hydrologic and sediment regimes, and morphologies associated with this time period may no longer be operating in the watershed or stable. In highly urbanized watersheds, particularly in areas where the floodplain has been developed, restoration practitioners do not have the flexibility required to design a functional channel because an important aspect of naturally functioning channels is overbank flooding and floodplain deposition (Personal Communication, Aquafor Beech, 13 April 2011). Additionally, when the floodplain is developed the plan-form does not have the freedom to migrate across the floodplain. Examples of highly urbanized watersheds in the study area include Highland Creek (85% developed), Etobicoke Creek (71%), and Mimico Creek (97%) (TRCA, 2010).

2.2.3 Approaches to NCD

Channel design may be selected as an appropriate management option when channel instability impacts private property or infrastructure, or there is an increased risk of impact. Channel realignment may be selected as a management option to accommodate new developments or infrastructure. Approaches to channel design depend on available data, the current and predicted state of the channel at the reach scale and the watershed scale, and the expertise of the design practitioner.

The goal of NCD in Ontario is to introduce a dynamically stable channel configuration that is compatible with the current and predicted water and sediment inflow (TRCA, 2009). Three general methods exist that can be used, individually or in combination, in the design process. Choice of method depends on the available data, the regulatory requirements and the designer (Ness, 2001). This section will discuss three approaches to design: analogue, empirical, and analytical. The choice of design approach depends on local regulations, expertise of the designer, quality and quantity of available data, and the location of the project.

2.2.3.1 Analogue

There are two types of analogue approaches: historical channel morphology and reference reaches. The use of historical channel morphology aims to return the subject watercourse or reach to its historical state, typically pre-European colonization. The use of historical channel morphology requires that current hydrologic and sediment regimes are similar to historical conditions and that the historical channel geometry was dynamically stable. Historical morphology is determined from maps, aerial photos, and geomorphological evidence. Land use changes within the watershed, such as urbanization, create hydrologic and sediment conditions that are incompatible with historical conditions and thus preclude the use of this approach (Ness, 2001). The return of a channel to its historical condition is true 'restoration' (i.e. a return of the channel to pre-disturbance conditions). Under definitions utilized in academia, most of the work that is undertaken in southern Ontario is rehabilitation, however, this thesis will use restoration as a synonym for rehabilitation, as this is the terminology typically used in the industry.

The reference reach method utilizes the dimensions of nearby reaches, either within the same watershed or in a similar watershed, as the basis for design. The idea of using a reference reach to determine the dimensions of the subject watercourse is a controversial one. The choice of an appropriate reference reach is crucial to the success of the eventual design. The reference reach must be stable, correspond with the stream type, have the same valley type, be in the same hydrophysiographic region (Hey, 2006), and have a high degree of similarity in surficial geology. Furthermore it must be subject to similar hydrologic and sedimentological influences, as this impacts the response and magnitude of effects of storm events. Hey (2006) used the width:depth ratio and the sinuosity from the reference reach and scaled them to determine the design. For channels that are similar and differ only in scale, the boundary conditions would differ (Hey, 2006), which impacts their response to wet weather events. The Rosgen approach (discussed in more detail in Section 2.4.2) relies on the reference reach approach when determining the dimensions of the project reach; dimensionless ratios for streams of the same type and similar valley type are used to determine dimensions for the project reach. Regional curves and regime equations are used in the design process and the data obtained from the reference reach can be used to validate and sort appropriate regime equations by stream type prior to the implementation of the design (Rosgen, 1998).

Reference reaches are difficult to locate within disturbed urban environments due to instability and changes in water and sediment inflow (Ness, 2001; Copeland *et al.,* 2001). Most urban reaches are not in geomorphic equilibrium, which academics say should preclude the use of analogs or reference reaches for monitoring, assessment, and design (Schwartz *et al.*, 2009).

Definitions of 'natural' and 'reference' conditions are derived from the concept of 'damage' and may be too static to form sustainable design, management and implementation strategies (Newson and Large, 2006). The definition of 'damage' to a system is highly anthropocentric. Humans may consider a large magnitude storm damaging to a watercourse, however this is a natural disturbance. Watercourses are in a constant state of adjustment, at various spatial and temporal scales. Damage is defined in terms of the decrease in the value we place on the watercourse and its ability to do work for us. It is possible to create a river with all the value-making entities and interrelationships that are present in a natural, functioning riverine system (Brook, 2006). The relationships present within the fluvial system drive the sustainability and successful implementation of channel designs. The use of a purely form-based design does not attempt to recreate or mimic these relationships but puts structures in place to encourage the development of these relationships. Fluvial relationships and processes are not fully understood and thus they are subject to a certain level of uncertainty. It is important to understand that the fluvial system is constantly changing and that change occurs on a variety of interacting time and spatial scales that need to be considered during the design of a project (Figure 2.1).

2.2.3.2 Empirical

Empirical methodologies utilize regression equations to aid in the determination of equilibrium channel morphology. Cross sectional form and channel slope are calculated from relationships to independent variables, such as discharge and sediment inflow (with discharge used more commonly) (Hey and Thorne, 1986). These relationships have been established for a number of different regions and uncertainty is reduced if the relationships used have been specifically developed for the study region (Hey and Thorne, 1986). Rosgen-based regional relationships for rural southern Ontario streams are available from

Annable (1996a). Experienced practitioners may have developed these relationships for urban and suburban streams. Changes in physiography and hydrological conditions caused by urbanization, impact the reliability and availability of empirical relations for urban areas. Land use and runoff characteristics vary widely (even within a single watershed) in urbanized areas (Copeland *et al.,* 2001). NCD practitioners may choose to develop these relationships for their project but that is typically beyond the scope of the project and not feasible within the project budget (Ness, 2001). While this is the case for individual projects, practitioner experience and multiple projects within a single watershed may lead to the development of these relationships over time.

2.2.3.3 Analytical

The analytical method is based on traditional physical relationships developed in river engineering and analytical fluvial geomorphology. These methods use channel hydraulics and sediment transport principles based on discharge, sediment size, bank strength, bank vegetation, bank materials, and cross-sectional width and depth. The utilization of analytical methods is recommended in many of the design manuals produced for the US and in some other jurisdictions. Some analytical methods describe an engineering geomorphology, where traditional engineering methods are informed by basic geomorphic theory. Other analytical methods are more empirical in nature, but quantify local conditions (Ness, 2001). The analytical method may be difficult to apply in cases with bank vegetation and heterogeneous and cohesive bank material. Heterogeneous and cohesive bank materials are common in semi-alluvial streams in Ontario, and therefore, it is important in this region to adequately consider these variables (Ness, 2001).

2.2.4 Geomorphic principles of NCD

NCD cannot be sustainably accomplished by applying a 'cookie cutter' approach to the design process (i.e. using a single design applied blindly in more than one location). Restoration techniques that have been used successfully in one location may not be feasible in others (Skinner *et al.,* 2008). This is due to the high variability in fluvial systems and large-scale hydrologic and climate variability. The appraisal, design, and implementation processes need to incorporate local geomorphology and other local environmental factors to decrease the level of uncertainty associated with the design and increase the long-term sustainability of the project (Levell and Chang, 2008; Brookes and Sear, 1996). Geomorphological approaches yield the most cost effective and sustainable outcomes for channel works (Newson *et al.,* 2001). At the local reach scale, geomorphic context is key to understanding the actual/effective disturbance regime associated with a particular hydrologic regime (Poff *et al.,* 2006). Engineered solutions are still required, but are no longer sufficient when used in isolation. Engineered solutions are best (and increasingly) being used nested within a multidisciplinary framework (Newson *et al.,* 2001).

In order to effectively recreate the river's functional character, the dynamic geomorphic character of the system must be taken into account (Lemons and Victor, 2008). The indeterminate nature of the fluvial system, as well as the incomplete scientific understanding of the physics governing fluvial processes leads to high levels of uncertainty in the design of restored channels. Particularly at the microscale, science cannot exactly: 1) predict sediment loads; 2) predict channel change; 3) predict morphology; 4) understand the scaling of morphology; and 5) select the appropriate sediment size for a dynamically stable channel (Brookes and Sear, 1996). Incomplete morphological information should not preclude an attempt at applying geomorphic knowledge to all restoration projects as substrate, stream power, and location in the watershed can be used to suggest what range of morphology and relative activity of channel processes to expect, prior to detailed design (Brookes and Sear, 1996).

There are three primary geomorphic elements of channel design: 1) sediment continuity, 2) design discharge, and 3) cross-sectional and plan-form geometry. In order for a design to be sustainable and successful (i.e. a design that produces dynamically stable channel dimensions and configuration), these three principles must be incorporated into the design (Soar and Thorne, 2001; Shields Jr. *et al.,* 1996, Brookes and Sear, 1996; Biedenharn and Copeland, 2000). A dynamically stable channel, however, may not be a desirable end result, depending on the location of the project.

2.2.4.1 Design discharge

The design discharge is defined as the discharge, or range of discharges, restoration practitioners use to aid in the selection of appropriate features, particularly cross-section dimensions, plan-form geometry, substrate size, and gradient. Ideally the design discharge would be equivalent to the natural channel forming discharge (Q_{cf}), on the conceptual basis that this single discharge, if held constant over time, would produce the same bankfull channel morphology that a range of discharges has produced over time (Soar *et al.,* 2005). A range of discharges determines channel dimension, morphology (bed forms, pools and riffles, cascades) and other physical characteristics. Therefore, it is important for practitioners to consider a range of flows in the design process because every competent flow (flows with the ability to initiate bed-load transport) influences channel form and a range of channel forming discharges is important in the dynamic stability of the channel (Soar and Thorne, 2001; Andrews and Nankervis, 1995).

Although Q_{cf} is the ideal parameter to base design discharge, it is not directly measureable. Channel forming discharge can be estimated from hydrological models, for example, by estimating discharge of a particular recurrence interval. There are three surrogate measures of Q_{cf}, bankfull discharge (Q_{bf}), effective discharge (Q_e), and recurrence interval discharge (Q_{ri}). These surrogates are related and may be equivalent to one another under certain circumstances, but the relationship between Q_{cf}, Q_{bf}, Q_e, and Q_{ri} remains uncertain (Soar *et al.,* 2005).

Other factors that should impact the selection of a design discharge include the identification and defining of Q_{cf} in ephemeral or degraded reaches, such as those found in headwater areas (ephemeral) and highly urbanized areas (degraded). In these areas, the identification of Q_{cf} is complicated by the frequent absence of consistent field indicators of bankfull stage (Annable *et al.,* 2010b). Channel design, specifically the selection of design discharge, relies heavily on field identification of bankfull flow (a surrogate measure of channel forming discharge). Other significant flows that usually occur more frequently than the 2-year flow (which is assumed to be equal to the bankfull discharge) are flushing flows and mobilizing flows. Mobilizing flows and flushing flows are particularly significant in the southern Ontario context and are unique to each channel as a result of variability in local sediment conditions (Villard and Ness, n.d.). Practitioners must also consider low flow and habitat requirements, particularly where project objectives include aquatic habitat improvement. In Ontario, low flow and habitat requirements are necessary in the design process as part of the HADD approval process.

Bankfull discharge is the discharge at which the flow just barely overtops the banks of the watercourse (Doyle *et al.,* 2007), and is considered to be equivalent to Q_{cf} because the channel is adjusted to accommodate that discharge. Channel designs rely on the field identification of Q_{bf} for the existing reach or a reference reach. Field identification of Q_{bf} is difficult and can be ambiguous. In highly disturbed watersheds, it is difficult to find adequate numbers of stable reference sites to obtain data for regional hydraulic regression analysis (Shields Jr., 1996). Identifying the Q_{bf} by return interval is complicated by the return interval varying according to flow regimes and the lack of flow data for unguaged streams in southern Ontario (Newson and Sear, 2010). Identification can be done through the application of geomorphic criterion, or from vegetation or sediment zonation (Soar *et al.,* 2005; Navratil *et al.,* 2006).

The field identification of bankfull stage is further complicated by the introduction of storm water management (SWM) facilities which extend the duration of flow above critical shear conditions, altering depositional benches in urban channels (Annable *et al.,* 2010a). Interactions between storm sewers, combined sewer overflows (CSO), storm water quality ponds and other infrastructure further complicate the situation by initiating complex watershed responses. This makes the detection of predictive trends between urban land use and bankfull return interval elusive (Annable *et al.,* 2010b). Despite the level of experience required and potential ambiguity of in-field Q_{bf} identification, it is preferred over the application of hydraulic theory to cross-sectional shape to determine bankfull discharge (Navratil *et al.,* 2006).

In stable watersheds, the Q_{bf} is considered equivalent to the effective discharge and occurs every one to two years. In an urban setting, the recurrence interval for Q_{bf} is typically lower than 1.5-years and is frequently found to be lower than 1.05-years (Annable *et al.,* 2010a). The annual frequencies of Q_{bf} occurrences in urban streams are significantly higher than in rural watersheds (Annable *et al.,* 2010a). This is significant because the empirical relationships that do exist for southern Ontario (Annable, 1996a; Annable, 1996b) were developed for rural watercourses. Because Q_{bf} is not equivalent to Q_e for unstable watersheds, no generalizations can be made regarding the recurrence interval of the effective or bankfull discharge (Doyle *et al.,* 2007; Soar *et al.,* 2005). Changes in channel cross-sectional geometry at urban gauge stations (which are typically located at a crossing, which impacts flow) biases Q_e predictions of Q_{cf} (Annable *et al.,* 2010). Despite all the issues facing the identification of bankfull stage, there still remains no better means of identifying the channel forming discharge than field identification of the bankfull stage during a flood event (Annable *et al.,* 2010b).

The Q_e transports the greatest volume of bed-load over time (Shields Jr. *et al.,* 2003; Emmett and Wolman, 2001). Effective discharge has been proposed as the design discharge by the United States Army Corps of Engineers (USACE) (Biedenharn and Copeland, 2000). Because the Q_e transports the largest fraction of bed-load material (an important factor in channel morphology and function), it is a good estimator of channel forming discharge. There is no single Q_e because a wide range of discharges are responsible for moving significant portions of the total sediment load, and thresholds of erosion may be modified by complex interactions of several factors (Doyle *et al.,* 2007; Wolman and Miller, 1960). The Q_e is primarily concerned with bed-load transport, as the bed-load is more responsible for bed forms and channel morphology than suspended sediment (Emmett and Wolman, 2001). Effective discharge is recommended for use in the design of restoration projects for three reasons: 1) because of difficulties in identifying bankfull discharge, particularly in incised or incising rivers, a common condition in urbanized areas; 2) the inconsistent relationship between the magnitude of flow associated with a specific time interval; and 3) Q_e is the only surrogate that considers sediment transport, an important component of dynamic stability (Andrews and Nankervis, 1995; Doyle *et al.,* 2007; Shield Jr *et al.,* 2003).

In southern Ontario, in small urban streams, Q_e is highly sensitive to changes in hydrologic and sediment regimes and is easily influenced by the method of determining Q_e, the watershed storage coefficient (reflects storage characteristics of the watershed), and the time of concentration of a watershed (Quader and Guo, 2009). When determining Q_e in small southern Ontario streams, it may be helpful to analyze the suspended sediment data, as it is suggested that the bed-load component of the total sediment load in Ontario streams is relatively insignificant (Quader *et al.,* 2008). This is particularly true in small headwater catchments as they typically have low energies and the size of the drainage area influences the frequency of sediment transport (Wolman and Miller, 1960). This is important in the restoration context because in low energy channels, morphology reconstruction may be the only feasible option within management timeframes (Downs and Gregory, 2004). Additionally, stream flows in southern Ontario streams are highly unpredictable and are strongly dependent on climate and watershed conditions. Therefore, relying on analytical solutions may result in poor estimates of Q_e (Quader *et al.,* 2008). In stream restoration design, low Q_e values should serve as a caution about the accuracy of the sediment transport data, particularly in southern Ontario (Quader *et al.,* 2008) and a range of discharges should be considered for successful restoration of physical processes (including sediment transport) and ecological functions (Barry *et al.,* 2008).

In restoration design, it is usually assumed that the bankfull discharge is equivalent to the effective discharge and that this discharge occurs approximately once every one to two years. As stated above, this relationship is not certain and should be used with caution in the design process. Additionally, southern Ontario streams with a recurrence interval of 1.5 and 2.5 years may be the most sensitive to watershed imperviousness, a significant issue in highly urbanized watersheds (Quader and Guo, 2009).

While the three surrogates of the channel forming discharge are important in the determination of the design discharge, there are other factors that should be considered before selecting the final discharge, or the range of discharges to use in the design process. A flow regime, which preserves the magnitude and frequency of the bed-load sediment transport rate, is necessary, but may not be sufficient to maintain channel resources (Andrews and Nankervis, 1995). The method to determine the regime of maintenance flows relies on identifying the magnitude and frequency of bed-load transporting discharges (Andrews and Nankervis, 1995). Flow effectiveness also involves the magnitude and frequency of the flow (Wolman and Miller, 1960). A large portion of the geomorphic 'work' in a channel is done by moderate magnitude, relatively frequent events, with the exception of the erosion of cohesive banks where a combination of conditions actually determines the frequent and magnitude of effective stress (meaning approximately bankfull discharge) (Wolman and Miller, 1960). The channel forming and bankfull discharges are not solely responsible for the channel's forms. Lower flows are also important in shaping the channel.

The duration of the flow, plus magnitude and frequency, stream power (and its distribution throughout a flood), land surface resistance, time, and degree of natural restoration or recuperation between flow events impacts whether discharges will be effective from a sediment transport perspective (Costa and O'Connor, 1995). Therefore, it is the sequencing and timing of flow events, along with the magnitude and frequency, which matters in shaping the channel.

The cumulative effects of moderate magnitude, relatively frequent flow events transport the same (or similar) amounts of sediment as large, rare events. However, there are dissimilar morphological results despite this similarity in amount of sediment transported. Channel morphology arises from a range of discharges and two modes can be conceptualized as being most important. The first is frequent, moderate magnitude events (bankfull and below) related to bed-load movement and bed forms. These types of flows are considered channel form maintenance flows. The second type is infrequent, higher magnitude events, with discharges at or above bankfull. These types of events are related to channel capacity (which in turn relates back to bankfull discharge) and meander morphology. Extreme flow events also control the erosion of cohesive banks. These types of flows are responsible for macro-scale channel changes. Unlike more frequent flows, which can occur up to a few times per year these infrequent, high magnitude events occur on a decadal time-scale and influence the shape of the banks (Lenzi *et al.,* 2006; Richards, 1982; Costa and O'Connor, 1995). There is no complete relationship between morphology and sediment transport, which must be taken into consideration when designing an equilibrium channel (Emmett and Wolman, 2001). In channel design, if a certain form is being preferentially designed for, this supports the use of a single design discharge instead of a range of discharges.

2.2.4.2 Cross-section and plan-form geometry

The goal of channel design is to introduce a stable channel configuration that is compatible with the current and predicted water and sediment inflow. The design of channel dimensions can be approached in three ways: 1) using nearby stable reaches (reference reach approach); 2) empirical approaches, such as regime theory and hydraulic geometry; and 3) analytical approaches, where for geometry parameters there are more unknowns then the equations can solve for (Shields Jr., 1996). The direct relationship between discharge and channel width requires design discharge to be selected prior to determining cross-sectional geometry parameters. Plan-form geometry is also determined using the selected design discharge but may be modified based on constraints, such as available floodplain space (Personal Communication, Parish, 16 May 2011). Projects aimed at restoring form and function of river ecosystems increasingly recognize the importance of channel geometry for dynamic equilibrium and the role of bed-load transport in forming and maintaining it (Barry *et al.,* 2008).

In natural rivers, cross-sectional form is considered to be the most adjustable component of channel geometry. Width and depth can adjust rapidly but the scale and rate of adjustment varies considerably from site-to-site. A river's cross-section adjusts to isolated flow events (e.g. high magnitude, low frequency floods) as well as sustained changes in hydrologic and sediment regimes, such as those caused by urbanization.

Given the adjustability of the channel cross-section, it is difficult to maintain a stable width and depth. This has important implications in channel design. In urban areas, constraints such as private property and municipal infrastructure protection make channel stability an important component of the design even when the goal of a project is to restore form and function to the reach.

Channel morphology adjustment occurs in three main phase: 1) residual; 2) active; and 3) overbank (Knighton, 1998). Residual adjustment occurs when discharge is below the threshold for entrainment and the cross-sectional form left over from previous high flows largely determines the flow characteristics in the channel. Active adjustment occurs when the bed is mobile but discharge is less than bankfull discharge. Overbank adjustment occurs as flow inundates the floodplain. As flow over tops the banks, there is a marked discontinuity in the response of hydraulic variables; width expands rapidly which may occur because of bank slumping (resulting from saturation) during the receding phase of the flood (Knighton, 1998).

Channel cross-section dimensions adjust to accommodate the discharge and sediment from the drainage basin spatially through the channel network. Factors that affect the degree of adjustment of channel form to discharge and sediment regimes include boundary composition, bank vegetation, and valley slope. Boundary composition has a significant influence on cross-sectional geometry, as the cohesiveness of the boundary influences its erodibility. Well-defined width-depth-discharge relationships are expected if bank materials remain uniform downstream. In channel design, Q_{bf} is used to define the width and depth of the downstream geometry. Channel response to downstream changes in cohesiveness varies depending on the region of investigation, river type, and floodplain conditions. Typically, if banks become more cohesive downstream, width increase more slowly and depth increases more rapidly in response to changes in discharge, creating a more box-like cross-section and potentially leading to incision (Knighton, 1998).

2.2.4.3 Sediment transport and sediment continuity

In order for a restored channel to neither aggrade not degrade, equilibrium sediment transfer and sediment continuity through the system must be maintained over the entire river course for the lifespan of the design (Bravard *et al.,* 1999). Sediment continuity depends upon the magnitude and frequency of the flow and the bed and boundary materials themselves, particularly with non-cohesive sediments (Bettess, 1994). Channel design must also appreciate the significance of the connectivity, linkages, feedback loops, and insight regarding how rivers of difference types characteristically evolve through time, adjusting for extreme events and response to changes in flow and sediment regimes (Thorne *et al.,* 2010). Sediment transfer is one of the most important determinants of dynamic channel stability, as the long-term erosion and deposition of the bed-load is directly related to sediment transport capacity and incoming sediment supply (Andrews and Nankervis, 1995; Niezgoda and Johnson, 2005). Excess flow energy, shear stress, and stream power are proportional to sediment supply, therefore it is important to understand the relationship between discharge and sediment mobility, particularly in terms of designing erosion resistance channels (Simon and Darby, 1999; Newson *et al.,* 2002). When sediment continuity is maintained, it precludes the need for extensive maintenance of implemented channel designs over the short to medium term. Maintenance may be required over the longer term, but if sediment continuity is maintained throughout the lifespan of the design, maintenance requirements will likely be minimal (Soar and Thorne, 2001).

In self-formed alluvial channels the channel size reflects the quantity of water and the size and characteristics of sediment delivered to if from the drainage basin (Emmet and Wolman, 2001). However, our ability to predict the absolute values of the sediment load is poor, although we are able to define the order of magnitude of transport. There is uncertainty regarding the timing, rates, and type of adjustment a channel will experience based on sediment transport (Brookes and Sear, 1996). Additional complications arise when dealing with meandering channels as it is difficult to directly relate hydraulic parameters, such as channel width, to bank erosion processes (Niezgoda and Johnson, 2005). This is significant in the design process because most streams in the study area naturally meander. It is also significant if applying form-based design methodologies, such as the Rosgen Approach. In urbanized watersheds, sediment continuity may no longer exist. Using a watershed-scale approach, sediment continuity may be restored through the assessment of the sediment budget as determined by the magnitude and frequency of all sediment transporting flows (Soar and Thorne, 2001). The effects of downstream sediment yields may take decades to emerge due to lags in sediment transport and sediment storage within the system (Shields Jr. *et al.*, 1999).

2.3 Other factors impacting geomorphic channel design

This section will discuss the impact of provincial legislation and policy and river and watershed management approaches in Ontario. NCD practices have been utilized for over a decade in southern Ontario (Villard and Ness, 2006b). A range of factors influences the design and implementation of these types of projects. Effective restoration and channel design requires clearly set objectives and requires that the design is consistent with prevailing geomorphological and ecological processes at the reach scale, with a sound understanding of the site's larger spatial and temporal context (Kondolf, 1998; Kondolf and Downs, 1996; McDonald *et al.*, 2004). True restoration (the return of a site to a desired historical conditions) is usually impractical due to changes in land use and in the hydrological and sediment regimes (Shields Jr. *et al.*, 1999).

Restoration is an emerging science and improvements are needed in the science and decision-making process to improve effectiveness and decrease uncertainty as conventional research methods are often insufficient for gaining adequate ecosystem understanding to support effective decisions for river-specific restoration and management (Polster *et al.*, 2010; Poff *et al.*, 2003).

2.3.1 Legislation and permitting

In Ontario, no single regulatory agency administers the permitting process for river restoration projects. This section will review three pieces of provincial legislation (*Conservation Authorities Act, Environmental Assessment Act, and Endangered Species Act*) and one piece of federal legislation (*Fisheries Act*) that impact the restoration process. Within these four pieces of legislation there are not any explicit references to channel design, or river restoration in general, as there is limited mandated permitting in Ontario (Villard and Ness, 2006a). Figure 2.2 illustrates selected provincial and federal legislation that impacts stream corridors.

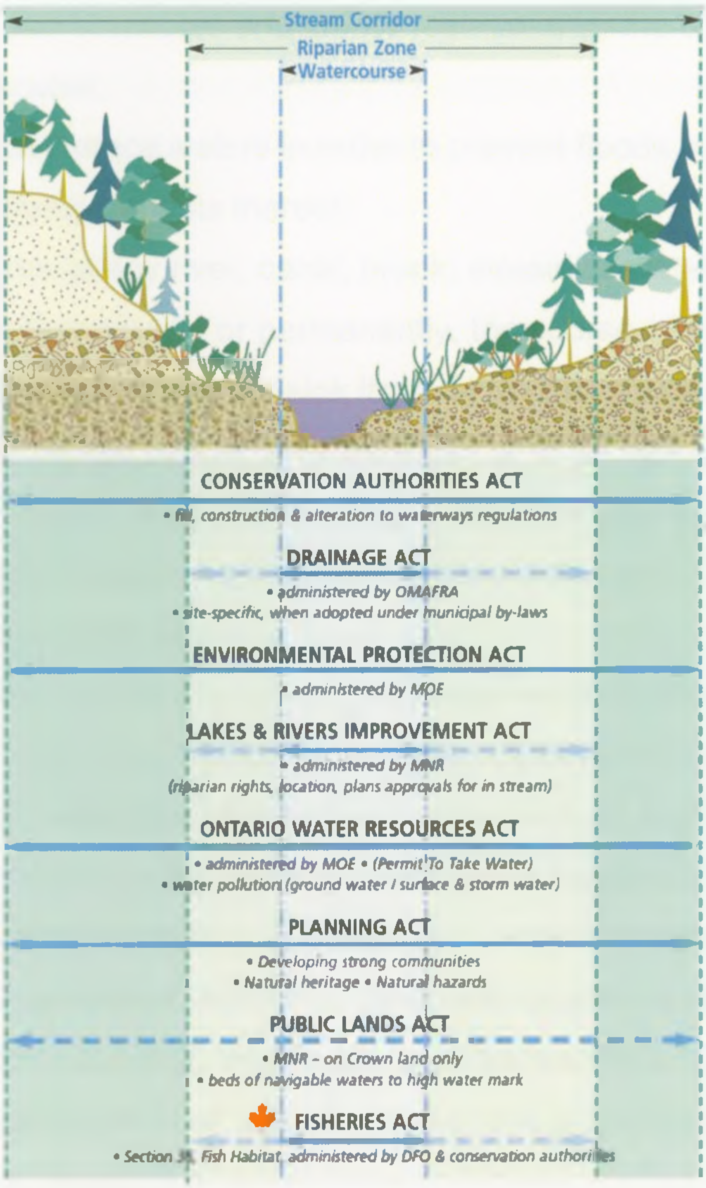

Figure 2.2: Selected legislation affecting stream corridors (MNR, 2002)

The objective of the *Conservation Authorities Act* is to allow a CA to establish and undertake, within its jurisdiction, a program to further the conservation, restoration, development and management of natural resources (excluding gas, oil, coal and minerals). This Act gives a Conservation Authority a number of powers including the power to:

- Study and investigate a watershed and determine a program whereby the natural resources of the watershed may be conserved, restored, developed and managed;
- Enter into agreements with owners of private lands to facilitate the due carrying out of any project;
- Erect works and structures and create reservoirs by the construction of dams or otherwise;
- Control flow of surface waters in order to prevent floods or pollution or to reduce the adverse effects thereof;
- Alter the course of any river, canal, brook, stream or watercourse, and divert or alter, temporarily or permanently, the course of any river, stream, road, street or way, or raise or sink its level to carry it over or under, on the level of, or by the side of, any work built or to be built by the authority, and to divert or alter the position of any water-pipe, gas-pipe, sewer, drain or any telegraph, telephone or electric wire or pole; and
- Cause research to be done.

Prior to proceeding with any project, a Conservation Authority (CA) is required to file plans and a description of the project with the Minister of Natural Resources in order to obtain the Minister's approval. In turn, the CA may grant approval to projects, which undertake any of the above listed actions by an outside agency, business or individual. The *Conservation Authorities Act* also indicates that works on lakes or rivers that have been approved on the Act do not require approval under the *Lakes and Rivers Improvement Act.* Approval from the local CA is a requirement of all natural channel design projects, as they have the power to alter the course of a watercourse and therefore have the power to grant permission for others to alter a watercourse. CAs and CA staff are an important component of obtaining permission to carry out a project. The knowledge and expertise of approval staff at a CA can impact the overall design, and are therefore an important part of the design process.

The Ontario *Environmental Assessment Act* was enacted for the purpose of the betterment of the people of the whole or any part of Ontario by providing for the protection, conservation, and wise management in Ontario of the environment. Channel works may be subject to an Environmental Assessment if initiated by the provincial or municipal government, however most projects proposed by members of the private sector are exempted (as of January 1997) from the EA process. Proponents must receive approval from the Minister of the Environment in order to proceed with an undertaking. This approval to proceed does not preclude an undertaking from a contravention of the *Environmental Protection Act* or the *Ontario Water Resources Act* or a regulation made under either Act.

Undertakings not subject to a full EA may be subject to a Class Environmental Assessment. Class EAs typically only apply to certain classifications of projects, such as municipal water and wastewater treatment and transportation corridors. Therefore, the Class EA does not apply to channel design works.

The *Canadian Environmental Assessment Act* (CEAA) normally applies when there are specific federal decisions or approvals that must be made or granted in order for a project to proceed. This includes when the proponent is the federal government, the federal government is providing funding for the undertaking, the land on which the undertaking is proposed has been provided by the federal government, or the federal government exercises a regulatory duty by issuing a permit, approval, authorization, or license.

The Ontario *Endangered Species Act* (ESA) is the newest piece of legislation which may impact the design and implementation process of river restoration and NCD projects. The Act was updated in 2007 and now provides for the broader protection of Species at Risk and their habitats. The purpose of the ESA is to:

1) Identify Species at Risk based on the best available scientific information, including community and aboriginal traditional knowledge's;
2) Protect species at risk and their habitats, promote recovery of Species at Risk; and
3) Promote stewardship activities to assist in protection and recovery of Species at Risk.

Under the updated version of the ESA, habitat, not just the species themselves, is given special protection. Habitat includes the area prescribed by the regulation as habitat and the area on which the species depends, directly or indirectly, to carry on its life processes.

As the ESA is a newer piece of legislation, the permitting process practitioners must navigate is not yet fully formalized (as of Spring 2011) (Personal Communication, Villard, 29 March 2011). This may lead to significant delays in the permitting process as practitioners have indicated that the Ministry of Natural Resources (MNR) must first provide approval or recommendations under the ESA before the relevant CA and the Department of Fisheries and Oceans (DFO) will provide approval. The most common trigger of the ESA in the study area is Red Side Dace. The presence of this fish species has the potential to greatly impact the design and implementation of the project. The initially identified project objectives become secondary to the improvement and protection of Red Side Dace and their habitat. In Ontario, the ESA has the greatest potential to impact the design of the project.

The *Fisheries Act* is one of the oldest and more powerful pieces of legislation in Canada. The *Fisheries Act* was first established during Confederation with the goal of managing and protecting fisheries resources including all fishing zones, territorial seas, and inland waters. Given that river restoration projects have the potential to significantly alter a channel, and therefore fish habitat, the *Fisheries Act* is of particular importance. CAs and the DFO have an agreement under which the CA assumes a regulatory role for the DFO. The level to which the CA has authority over a project that would normally fall under the DFO's jurisdiction depends on the CA. The TRCA (which administers much of the study area) has a high level of authority and can provide approvals and letters of authorization. With respect to the design and implementation process, Section 35 of the *Fisheries Act* is of particular importance. Section 35 is the general prohibition of harmful alteration, disruption or destruction (HADD) of fish habitat. The DFO, or the authorizing CA, may authorize the HADD or provide a letter of advice regarding mitigation measures. The authorization of the HADD is not an approval of the project resulting in the HADD. HADD authorization requires practitioners and construction crews to consider and mitigate for fish habitat disturbance regardless of whether the improvement of fish habitat is a project objective. In general, the CA and DFO understand that the intention of these types of projects is to create an environment that is beneficial to aquatic species. Overall legislative requirements impact the implementation process more than the design process, other than the ESA.

2.3.2 River and watershed management approaches in Ontario

Ecosystem management and adaptive management theories influence river and watershed management approaches in Ontario. Effective river management must holistically address catchment-scale issues and local issues because the problems, symptoms, causes, and solutions should be viewed in context of the whole catchment (Downs and Gregory, 2004; Petts and Amoros, 1996). Adaptive management is the active learning through experience to deal effectively with systems characterized by uncertainty (Downs and Gregory, 2004). The aim of river restoration, aided by adaptive management, attempts to reverse the legacy of channel straightening, enlargement, constructed embankments, and hard engineering structures where possible (Downs and Gregory, 2004).

The MNR has produced two documents to help guide the practice of restoration in Ontario. These two documents represent two phases of development of the Provincial Natural Channel Systems Initiative. The MNR published *Natural Channel Systems: An Approach to Management and Design* in

1994 and *Adaptive Management of Stream Corridors in Ontario* in 2002. While these documents do not represent the MNR's policy, nor does the use of the documents indicate that project approval will be granted, or non-use of these documents mean approval will be denied, they are important in the planning process. These documents provide an approach to the design and implementation and overall management of these types of projects. These documents have spawned a series of conferences that bring the restoration community together to share new ideas and lessons from past projects. In this way, the MNR's Natural Channel System has created a professional community of restoration practitioners in Ontario and a forum in which they can come together to develop approaches and vision for Ontario streams.

The MNR does not provide any specific methodology with regards to the design of natural channel systems. The MNR's *Natural Channel Systems: An Approach to Management and Design* (1994) establishes the conceptual basis for natural channel systems, identifies design principles, stream evaluation and classification approaches, and proposes a design approach for projects with multiple objectives. Figure 2.3 illustrates the relationship between the design process and other processes occurring in the watershed. The MNR advocates an ecosystem-based approach and details a nine-step approach to design. These steps include:

- Defining design objectives;
- Defining existing stream conditions;
- Defining the expected natural regime;
- Identifying inconsistencies between the expected and actual regimes;
- Determining the design parameters for an unconstrained design;
- Identifying constraints;
- Identifying trade-offs that will need to be made based on constraints;
- Developing final design parameters; and
- Evaluating the design (MNR, 1994).

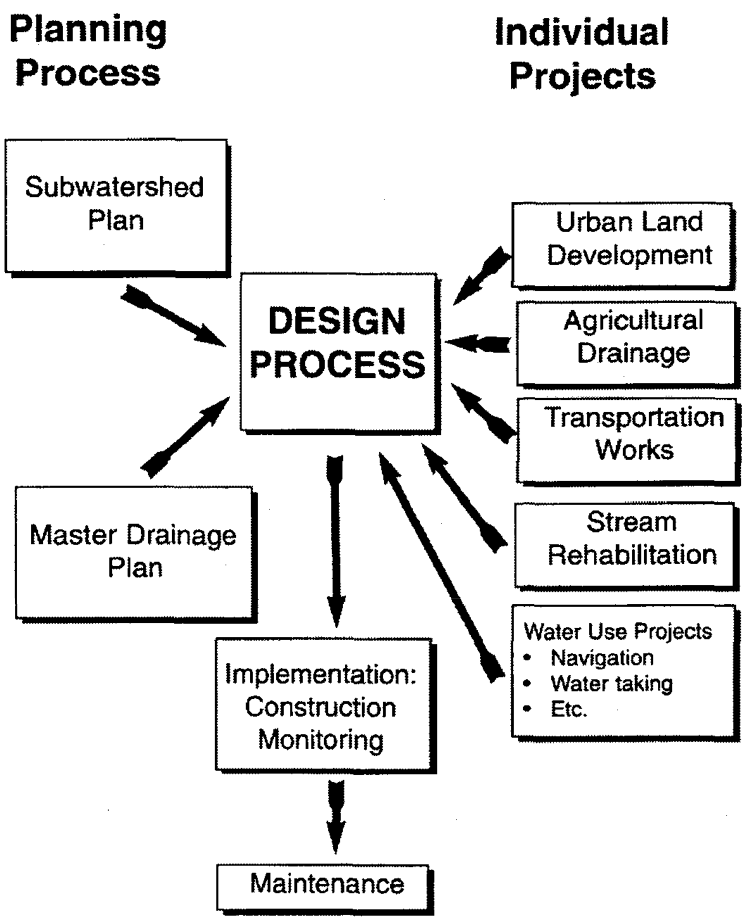

Figure 2.3: Relationship between design process and other processes (MNR, 1994)

This nine-step process allows for the additional consideration of technical, economic, ecological, financial, legal, administrative, recreational and political issues that may constrain the design (MNR, 1994). It is interesting to note that the chapter on Stream Evaluation and Classification Procedures includes the Rosgen classification system. The MNR justifies the inclusion of the Rosgen approach because it is useful for developing a process to identify appropriate combinations of channel attributes for design purposes. They do note that the classification system does not address flow regimes, habitat characteristics, or water quality, which are important influences on habitat type and health. The MNR does not endorse the use of the Rosgen approach as the sole method to design channel works.

The second phase of the Provincial Natural Channel Systems Initiative, *Adaptive Management of Stream Corridors in Ontario* (2002), provides a broad-based compilation of technical information and an explicit planning and design process model from fluvial geomorphology, engineering, and aquatic ecology perspectives. This document details the adaptive management approach that allows for subsequent iterations as more is learned about fluvial systems. The adaptive management process enables long-term management with the aid of models, which forecast when channel maintenance may be needed, continual improvement of the aforementioned models to reduce uncertainty, working with nature, and following the lowest possible cost solution to maintenance and intervention (MNR, 2002). Adaptive management requires the constant analysis and re-evaluation of project experiences, thereby embracing uncertainty at the time of decision and provides an avenue for setting flexible alternatives that can be monitored to gain information and decrease uncertainties associated with future management decisions, and allow for a more efficient management decision making process, as well as more effective environmental management strategies (Linkov *et al.,* 2006; Nagle, 2007). Figure 2.4 illustrates the steps and planning phases recommended by the MNR. The nine-steps list on the right of the document is from the 1994 report and the stages are from the 2002 report.

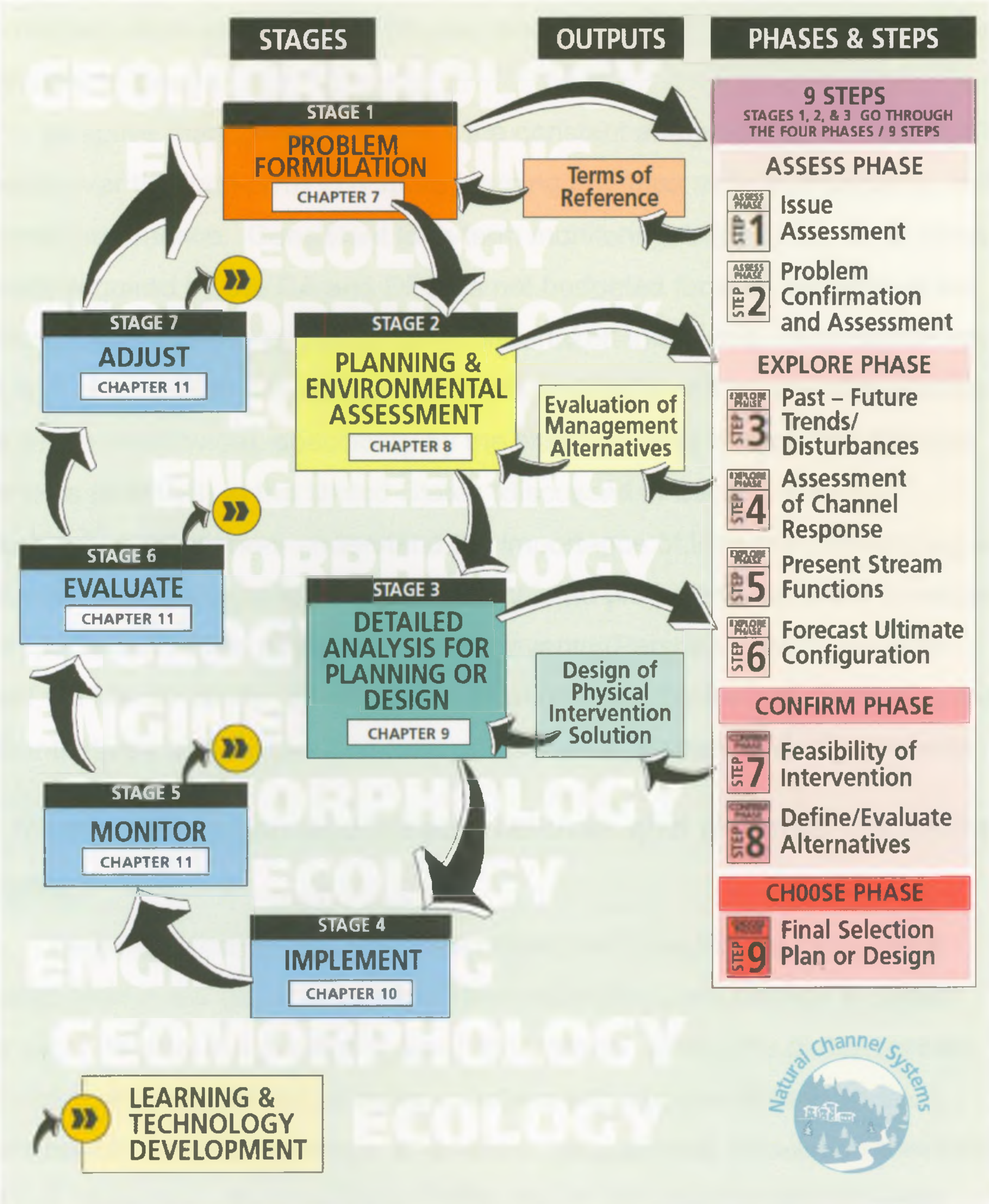

Figure 2.4: Framework for adaptive management and design for rivers and streams: Major stages and key outputs (deliverables) (MNR, 2002)

The MNR documents (1994 and 2002) were reviewed and compared against the design approach utilized in the design of channel works projects in Ontario. This was done with the aim of understanding whether or not the approaches, steps and planning phases recommended by the MNR are used in planning and design.

Adaptive management requires the constant analysis and re-evaluation of projects over the long-term to acquire learning and thus reduce uncertainty and improve the practice. Consistent long-term monitoring, beyond the three-years typically required by the CA and DFO, is not budgeted for and, because of the nature of consulting, is less likely to be undertaken in a formal, quantitative way. The lack of long-term monitoring has been identified as an issue in the practice as a whole (worldwide), specifically by the National River Restoration Science Synthesis (NRRSS) in the United States (discussed in Section 2.4.1). Accordingly, practitioners understand the importance of long-term monitoring and evaluation and occasionally visit older completed projects to qualitatively inspect them, particularly after major wet weather events (Personal Communication, Villard, 29 March 2011). Qualitative evaluations lack the level of detail required to quantitatively assess the long-term performance of channel design projects.

2.4 River restoration successes, failures and debates – a global context

The aim of this section is to understand the basis for this study, what debates exist in the global practice of river restoration, and provide a context from which to view the practice in southern Ontario. Within the global context, river channel management provides countries with opportunities to address issues related to climate change, floodwater management, population pressures, land use pressures, river channel stability issues, the improvement of water quality, and address the legacy of traditional channel engineering. River restoration is expensive and the benefits produced may not have a direct economic benefit, therefore restoration projects are typically not a priority for less developed countries.

2.4.1 National River Restoration Science Synthesis

The National River Restoration Science Synthesis (NRRSS) Project is a recently completed project (2005) that had the intention of analyzing the extent, nature, scientific basis, and success of river restoration projects throughout the US in order to provide the restoration community with a national level synthesis of these types of projects and aid in understanding what makes a project successful. The intent was that the synthesis could then be used to inform policy at the local, regional and national levels (Palmer *et al.*, 2003). Prior to the completion of the NRRSS, information on the implementation and outcome of small-scale river restoration projects was not readily accessible (Bernhardt *et al.*, 2005). The NRRSS found that in the US approximately $1 billion dollars is spent annually on river restoration efforts (Bernhardt *et al.*, 2007). Despite the high annual expenditure, only a small fraction of projects benefit from the combined insights of practitioners and scientists (Palmer *et al.*, 2003); and despite the extensive review of restoration projects compiled for the NRRSS, there was only minimal information on project motivations, actions and results, and fewer than half of the projects inventoried had set measurable objectives (Bernhardt *et al.*, 2007). Project success should be determined through ongoing monitoring and the achievement of project goals as well as improved geomorphic and ecologic performance (Kondolf, 1998). However, post-project appearance and positive public opinion were the most commonly used measures of success by practitioners and projects included in the NRRSS (Bernhardt *et al.*, 2007). To date, there has not been this national level of investigation in Canada. This thesis aims to address this on a local scale and provide more detail on the design process than the NRRSS.

2.4.2 Debates in river restoration

The practice of river restoration and the design of channel works projects has driven the privatization and commercialization of the science, which has begun to substantively affect the practice and the content of public sector science (Lave *et al.*, 2010). This has shifted the methods, organization, and context of research across the natural sciences including in the field of fluvial geomorphology. The most widely reported on debate in the restoration of rivers is between supporters of the Rosgen Approach and critics (typically academics) who oppose the use of the Rosgen Approach. The Rosgen Approach is synonymous with NCD in the US. The term natural channel design, when used by Ontario practitioners does not indicate the use of the Rosgen Approach (see definition of NCD, Section 2.1). The Rosgen Approach is seen as a departure from the current consensus in fluvial geomorphology with its focus on stability, the Rosgen Approach does not allow the river to behave naturally (Lave *et al.*, 2010; Lave, 2009; Lave, 2008), which is part of the goal of NCD in Ontario. Critics say that Rosgen ignores the complexity and specificity of stream channels. This point, in particular, illustrates why Ontario restoration practitioners may favour other approaches. The glaciated history and the process of European colonization have created a wide variety of stream channel conditions under which restoration must occur.

There are three main components of the Rosgen Approach: 1) a 'universally' applicable alphanumeric classification system, 2) a set of structures for implementing designs (these perform many of the same functions as traditional hydraulic engineering structures, and 3) a standardized 40-step design process (Lave *et al.,* 2010). Rosgen's work is promoted by federal agencies in the US, such as the Environmental Protection Agency (EPA), the United States Fish and Wildlife Service (USFWS), the Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA), and the United States Forest Service (USFS), as well as state-level natural resource departments in over a dozen states (Lave *et al.*, 2010; Lave, 2008). Part of the reason for the popularity in the US of the Rosgen Approach is the standardized approach, which works well for permitting agencies, and the message of do-ability. Many scientists were slow to embrace a more interventionist focus and tended to concentrate on the uncertainty inherent in the fluvial system (Lave *et al.,* 2010, Lave, 2008). Rosgen, and his message of do-ability have moved the entire field of fluvial geomorphology more in the direction of thinking about how to solve practical problems. Despite its general non-use in Ontario, the message that rivers can be 'fixed' has impacted the evolution of the practice in Ontario.

The result of the debates in the US, as well as the NRRSS, have led to a call for a national certification program, as well as more funds to be allocated to long-term monitoring programs (Lave, 2008; Palmer *et al.,* 2007). The call for long-term monitoring studies has been echoed in Ontario (TRCA, 2009), but the diversity of the Canadian landscape and the drivers of restoration projects across the country seem to indicate that a national certification program would not find favour among practitioners.

2.4.3 Common approaches and results from around the world

2.4.3.1 United States

In the United States, population and land use pressures, floodwater management, and stability concerns have led to a proliferation of river restoration projects. Similarly to Canada, there is no single agency or governmental department at the state or federal level, which regulates or permits activities related to restoration. In the US, the USACE, EPA, USFWS, state water quality, fish and wildlife, and cultural resources agencies; and relevant local agencies provide permits for the construction of channel restoration projects. There are a variety of programs, handbooks and guidebooks designed to aid practitioners in the design and management of river channels and river restoration projects. Some of these handbooks or guidebooks have been issued by the aforementioned agencies. Others are the products of private citizens and may or may not be endorsed by the regulatory community or the academic community.

2.4.3.2 European Union and the Water Framework Directive

In the 1990's, there was a global recognition of the need for sustainable environmental management. The European Water Framework Directive (WFD) responded by turning their attention to environmental restoration (Petts, 2000) focusing on preventative and recovery measures (Smits *et al.,* 2000). WFD documents focused on larger rivers and international cooperation. This differs from Ontario, where the focus is on smaller watercourses. In Europe, channel restoration began with shorter reaches, typically 2 km or less, and has expanded in scope in the last decade (Petts, 2000). The WFD focuses on incorporating all user needs, meeting social, economic and ecologic goals (Petts, 2000).

Prior to the Industrial Revolution, and the subsequent creation of the railway, boats were the primary means of transportation and shipment of goods in Europe. Since the Industrial Revolution, rivers in Europe have had to accommodate larger vessels. This requires a greater draft, thus requiring dredging. Rivers in Europe have been seriously modified, especially over the last century (Petts, 2000; Nijland and Cals, 2000). For example, the Danube, which begins in Germany and flows across central Europe to the Black Sea, became important for trade in the early 19th century (Danube River, 2011) and is now a priority transport corridor as part of the Trans-European Network for Transportation. Flow is regulated throughout most of Germany and through all of Hungary (World Wildlife Federation, n.d.). Another example of a heavily modified river is the Rhine, which begins in Switzerland and flows into the Black Sea. The Rhine is navigable for 880 km of its 1320 km length. Major modifications over the last century have allowed for its navigability. The Rhine is heavily canalized and was a major corridor for chemical industries and other industries, which lead to heavy water pollution (The Rhine, n.d.). Since modifications began around 1840, the floodplain has become heavily populated, with 85% of the floodplain having been suppressed since the beginning of development.

Each region of Europe has its own degradation characteristic. In Western Europe, habitat destruction is the central issue; in Central and Eastern Europe it is water pollution; and in Southern Europe water shortages and the modification of seasonal discharge patterns are the central issues (Nijland and Cals, 2000). River restoration in the EU is guided by the WFD, which embraces a variety of measures and aims to restore natural functions as well as the multifunctional use of rivers by adjusting human use to the natural system (Nijland and Cals, 2000). Currently, many rivers in Europe serve one primary function (e.g. shipping or hydroelectric power generation, river restoration aims to restore multifunctional uses) (Nijland and Cals, 2000).

Changing environmental, economic, and social preferences of European society, as reflected in EU water policy, exerts much influence on river management approaches in Europe. The EU's WFD establishes a legal framework to protect and restore clean water across Europe, ensures the long-term sustainable use of water resources, and a recently added goal of improving channel function and morphology. The goal of the EU's WFD is to get polluted waters clean again, and ensure clean waters are kept clean. The WFD is an operational tool that is used by Member States of the EU to set objectives for future water protection and requires that Member States coordinate efforts to manage international watersheds. The primary goal of the WFD is to achieve 'good ecological status' in all European waters by 2015. This will be achieved through approaching management at the watershed scale and ensuring there is cooperation and joint objective setting across Member State boarders. Practitioners in Europe believe that river restoration can be achieved using an integrated approach coupled with negotiated agreements, interactive planning, and by involving public and stakeholder opinions (Nijland and Cals, 2000).

2.4.3.3 Australia

In Australia, river restoration is defined as returning the watercourse to its historical condition, which in most cases, due to watershed development, is no longer a viable option. The focus in Australia is on rehabilitation and improving the most important aspects of the stream environment. This section uses the same language of the Australian literature to more accurately reflect the state of the Australian practice.

Land and Water Australia, a division of the Australian federal government, governs river restoration in Australia. The federal government of Australia advocates a 12-step rehabilitation planning process. The first four steps are designed to aid planners in identifying what needs to be done, the next four narrow down what needs to be done and sets priorities and feasible objectives, and the final four steps are focused on the actual rehabilitation. The government advocates careful planning, setting clear measurable objectives, and promotes a 'protect first, restore and rehabilitate second' framework. The Australian government also provides a *Rehabilitation Manual for Australian Streams (Volumes 1 and 2)*, produced by the Cooperative Research Centre for Catchment Hydrology at the Land and Water Resources Research and Development Corporation (Rutherfurd *et al.*, 2000). Volume 1 concerns itself with the concepts and planning of river rehabilitation projects and Volume 2 with planning tools and invention tools.

Another example of an approach to river management and restoration/rehabilitation is the River Styles Framework, which embraces a range of social, cultural, political, moral, and aesthetic qualities in its approach to river management (Brierly and Fryirs, 2005). This watershed-scale planning tool aids river managers in coping with the uncertainty that is inherent to the process of river restoration (Brierly and Fryirs, 2005). The River Styles Framework considers:

- River forms and processes;
- Contemporary river dynamics viewed through the historical context;
- The trajectory of the reach in relation to the downstream pattern of river types;
- The landscape connectivity at the catchment scale to interpret geomorphic river recovery potential; and
- The differing implications for reach and catchment-scale rehabilitation planning that prompt the 'manage with nature' approach (Brierly and Fryirs, 2009).

Australian rivers, while different from Ontario rivers in physiography and morphology (Australia having more pond chains, Ontario having more pool-riffle morphology), they have faced similar development pressures since European colonization. Stream management involves a mix of goals, balances requirements of economic production, asset production, aesthetics, recreation, and the environment (Rutherfurd *et al.*, 2000). Prior to 2007 there was very little scientific guidance and little to no post project monitoring or effectiveness evaluation (Brooks and Lake, 2007). Now there is mandatory, statewide reporting and an increased emphasis on project design and post-project monitoring (Brooks and Lake, 2007).

2.4.3.4 Elsewhere in Canada

The restoration of streams in Canada is no more pervasive in any other province as it is in Ontario, specifically southern Ontario and the Greater Toronto Area (GTA). That is not to say that river restoration does not occur in other provinces, just the majority of projects are located in southern Ontario. British Columbia (BC) is the only other province that has some form of river restoration program or policy in place. From 1994 to 2002, the Watershed Restoration Program, a provincial government initiative run by the Ministry of Water, Land and Air Protection; the Ministry of Sustainable Resource Management; and the Ministry of Forests, published ten Watershed Restoration Management Reports to accelerate the restoration of logging impacted watersheds (Keeley and Waiters, 1994). The primary difference between river restoration in Ontario and BC, other than the diverse physiographic settings, is the driving force behind the need for restoration. In Ontario, river restoration is driven by watershed changes caused by urbanization. In BC, restoration is done in response to logging. Programs in BC, such as Streamkeepers, provide guidance for people who wish to help protect and restore local waterways in BC. The Streamkeepers Handbook was published in 1995 (Taccogna and Munro, 1995). In Manitoba, watershed restoration projects focus more on wetlands and lakes for waterfowl habitat. Projects are typically done in response to changes/issues cause by agriculture.

The diversity of physiographic settings rivers occur in across Canada and the regionalism of the issues facing watersheds explains why there is no national program or approach for river restoration in Canada. Additionally rivers fall under provincial jurisdiction, excluding fisheries resources, which are covered under the *Fisheries Act*, and as a consequence, river and watershed management approaches are decided on a province-by-province basis.

Chapter 3: Methodology

To understand how geomorphic principles are incorporated into the design, technical briefs, design reports and as-built (as available) drawings were reviewed and practitioners were interviewed. Through the review of design documentation an inventory of projects was created. Case studies were selected from the inventory and analyzed to determine objectives, constraints, design approaches, and use of geomorphic principles in the design. Further insight into the design process was sought through semi-structured interviews with practitioners. The purpose of these interviews was to gain a better understanding of the design process from the practitioner's point of view and add a narrative of the state of the practice that is not readily evident from the project analysis. This was intended to provide some insight into why certain design approaches are used, how constraints impact the design process, and generally better understand how the design process is undertaken.

3.1 Study area selection and study time frame

In order to achieve the objectives of this study, it was necessary to select a study area with a similar regulatory environment, but with a variety of different watershed conditions and a range of projects, in order to understand how different watershed conditions and constraints might impact the design process. It was also important that the study area capture complete watersheds. A thorough understanding of watershed issues should, at least in part, guide the design process. Individual watersheds or subwatersheds may be subject to watershed plans, which should to be considered when planning and designing local channel works.

The areas under the jurisdiction of the TRCA and Credit Valley Conservation (CVC) were selected as the study area. This is a region of extensive stream restoration activity. For example, between 2003 and 2007 the City of Toronto (a member municipality of the TRCA) restored over 65 km of stream channel at an approximate cost of $34 million (City of Toronto, 2003). This, coupled with the highly urbanized and degraded and/or engineered nature of the streams within the City of Toronto, as well as the semi-alluvial nature of the streams, indicated that there were a large number of potential cases that could be used in developing a picture of the state of practice of river restoration. The City of Toronto is located within the jurisdiction of the TRCA, and thus, along with the six other member municipalities, is subject to a uniform regulatory process for watershed management. The City of Toronto is heavily urbanized and in order to capture a range of restoration project types, including suburban sites, it was important to include the entire jurisdiction of the TRCA. Additional projects were inventoried within the CVC to increase the number of projects available for inventory and to determine if the two adjacent conservation authorities differ in their approach to design approval. The CVC and TRCA face similar development pressures and are both part of the Lake Ontario watershed.

The TRCA has jurisdiction over seven watersheds and has six member municipalities. These include: the City of Toronto, Regional Municipality of Durham, Regional Municipality of Peel, Regional Municipality of York, Town of Mono, and the Township of Adjala-Tosorontino. The CVC is located adjacent and to the west of the TRCA and has jurisdiction over the Credit River watershed and has ten member municipalities including: Region of Halton, Region of Peel, City of Brampton, City of Mississauga, Town of Caledon, Town of Erin, Town of Halton Hills, Town of Mono, Town of Oakville, Town of Orangeville, Township of Amaranth, and Township of East Garafraxa.

Projects undertaken within the boundary of a CA are subject to the same regulatory process. Each CA has a different level of agreement with the DFO, and therefore selecting the entire CA to be included in the study area ensures that all projects have been subject to the same review process. The TRCA and CVC boundaries limited the number of watersheds included in the study and eliminated the possibility of including partial watersheds.

River restoration and channel design was occurring prior to 1994 in southern Ontario (MNR, 1994). Given the number of projects that have been completed within the TRCA and the CVC in the past 20 years, it was necessary to select a study period, which would yield a reasonable number of case studies (with relatively complete project files) and illustrate the evolution of the design process. Projects constructed and completed between 2000 and 2010 were selected. Due to the occasionally lengthy design and approval process, some of these projects may have been initiated in the 1990s. The decade of 2000-2010 also covers a period of active development of the science, and debate, on geomorphic design and stream restoration that will have influenced and changed the approaches used in the design of channel works.

3.2 Data collection

The TRCA, CVC, and the private-sector consulting companies Geomorphic Solutions (a member of the Sernas Group), Aquafor Beech, and Parish Geomorphic, provided access to project files, which included a variety of design documents (i.e. Technical Design Briefs, design drawings, permit applications, and communication between the CA and the design company). Design briefs are particularly important as they represent an important medium to document pre-construction conditions, conceptual design objectives, design methods and assumptions, and performance criteria (Villard and Ness, 2006b). Each organization provided a number of project files for review. Because a goal of this project is to provide an understanding of the practice of channel design in southern Ontario, inclusion of projects designed by a number of different practitioners offers the possibility of a more robust understanding of the design process in southern Ontario.

3.2.1 Project inventory

Projects were catalogued to create an inventory of projects completed in the TRCA and the CVC. This inventory complimented and built upon the inventory completed by the TRCA and Geomorphic Solutions in 2009. Project data were catalogued via an inventory database (Appendix A) and standard 'factsheets' for case studies (Appendix B). The categories of the factsheets and database were determined through a review of categories used in the NRRSS project and through a review of the literature pertaining to channel design.

Research questions identified in Chapter 1 were used to guide the types and categories of data collected and compiled as part of this inventory. This thesis focused on the geomorphic aspect of channel design. Through the inventory, projects that incorporated geomorphic principles in their design process were identified. If geomorphic function was not a project objective, the document review determined what constraints were in place to prevent the application of geomorphic principles.

3.2.2 Case study selection and analysis

The inventory database and associated project files were reviewed to aid in the selection of case studies. Some project files did not contain enough information on the actual design process or the final design and were not selected as case studies. Other projects were not selected because, based on the inventory, they did not include cross-sectional and plan-form geometry parameters compatible with the idea of natural channel design, as defined by the TRCA. Projects designated as a NCD, or projects that indicated that the application of NCD principles, or fluvial geomorphological principles were used to guide the design, increased a project's appeal as a potential case study. The company responsible for the design was also considered when selecting case studies to avoid selecting too many case studies from one company. Case studies were critically appraised to determine the design approaches used, how constraints influenced the design, and evaluate the appropriateness of certain design structures. Further analysis was undertaken to determine common objectives to understand the drivers of the projects, how legislation and regulatory agencies impacted the design process, and, most importantly, case studies were analyzed to determine the use of geomorphic principles in design and what constrained their application. Based on analysis of the use of geomorphic principles in designs, a comparison of the established NCD methods for fully alluvial channels (as identified in the available literature) was undertaken to determine whether the semi-alluvial nature of the watercourse was considered in the design (either implicitly or explicitly), and if any of the methods recommended in the literature were used in the design.

3.2.3 Semi-structured interviews

Semi-structured interviews were conducted with practitioners to: 1) gain further insight into the practice of river restoration and NCD; 2) gain a better understanding of the design process from the practitioners' point of view; 3) add a narrative of the state of the practice that is not readily evident from the project analysis; 4) provide some insight into why certain design approaches are used; 5) understand how constraints impact the design process; and 6) generally better understand how the design process is undertaken. Currently, the information needed to advance the practice of restoration lies in the minds and unpublished notes of restoration practitioners (Palmer *et al.,* 2007). This provides further rationale for the use of semi-structured interviews.

Professionalization of the practice of river restoration and geomorphology has developed substantially in the past 10-15 years. Semi-structured interviews were used to gain a more thorough understanding of NCD in southern Ontario. Semi-structured interviews allow the interviewer to approach the world from the subject's perspective (Berg, 2004). Semi-structured interviews also allow participants the chance to explore the issues they feel are most important and allow for a conversational, informal tone and open response (Longhurst, 2010). In this case, interviews were used to supplement other methods (i.e. the analysis of selected case studies). The aim of interviews is to not be representative, but to understand how individual river restoration practitioners perceive their design methods (Longhurst, 2010; Berg, 2004).

Appendix C contains the list of prompting questions used in the semi-structured interviews. Practitioner interviews were used to further inform findings. This was particularly important given the nature of the consulting business, as practitioners typically do not provide in-depth details regarding their design methods in their design documents because of the need for competitive advantage among a limited number of companies and practitioners within the study area.

The study methodology was focused on the design process and methodologies utilized in the study area. Case study analysis specifically focused on how objectives and constraints impact the design process, the type of design approach utilized, how legislation, policy and permitting agencies impact the process, and most importantly how designs incorporate geomorphic principles.

Chapter 4: Inventory and Case Study Analysis

4.1 Introduction

The goal of this thesis is to gain an understanding of how the process and practice of channel design in southern Ontario is undertaken, specifically focused on how geomorphic principles are applied in the design process. This chapter provides the inventory of reviewed projects, analysis of selected case studies, and a summary of the semi-structured interviews conducted with selected practitioners.

4.2 Inventory

A total of 46 separate projects were inventoried, which were represented in 49 project files. Three projects had two separate project files. Appendix A contains the inventory, including a breakdown of projects by watershed and whether or not the project was a good case study candidate (refer to Chapter 3 for case study selection rationale). Of the 46 projects inventoried, four were located in the Humber River watershed, six in the Etobicoke Creek and Mimico Creek watershed, ten in the Rouge River watershed, three in the Highland Creek watershed, one in the Don River Watershed, four in the Duffins Creek and Carruthers Creek watershed, and ten in the Credit River watershed. Figure 4.1 illustrates the location of all inventory and case study projects. Inventoried projects are labeled in white with the numbers corresponding to the identification number used in Appendix A. Case studies are indicated by red icons, with numbers corresponding to identification numbers from Table 4.2. Three projects were associated with storm water management projects, ten with erosion, stabilization and infrastructure protection, seventeen with development (i.e. new subdivisions), eight with infrastructure such as bridges, crossings, and culverts, and ten classified as 'other'. Table 4.1 summarizes the results of the inventory.

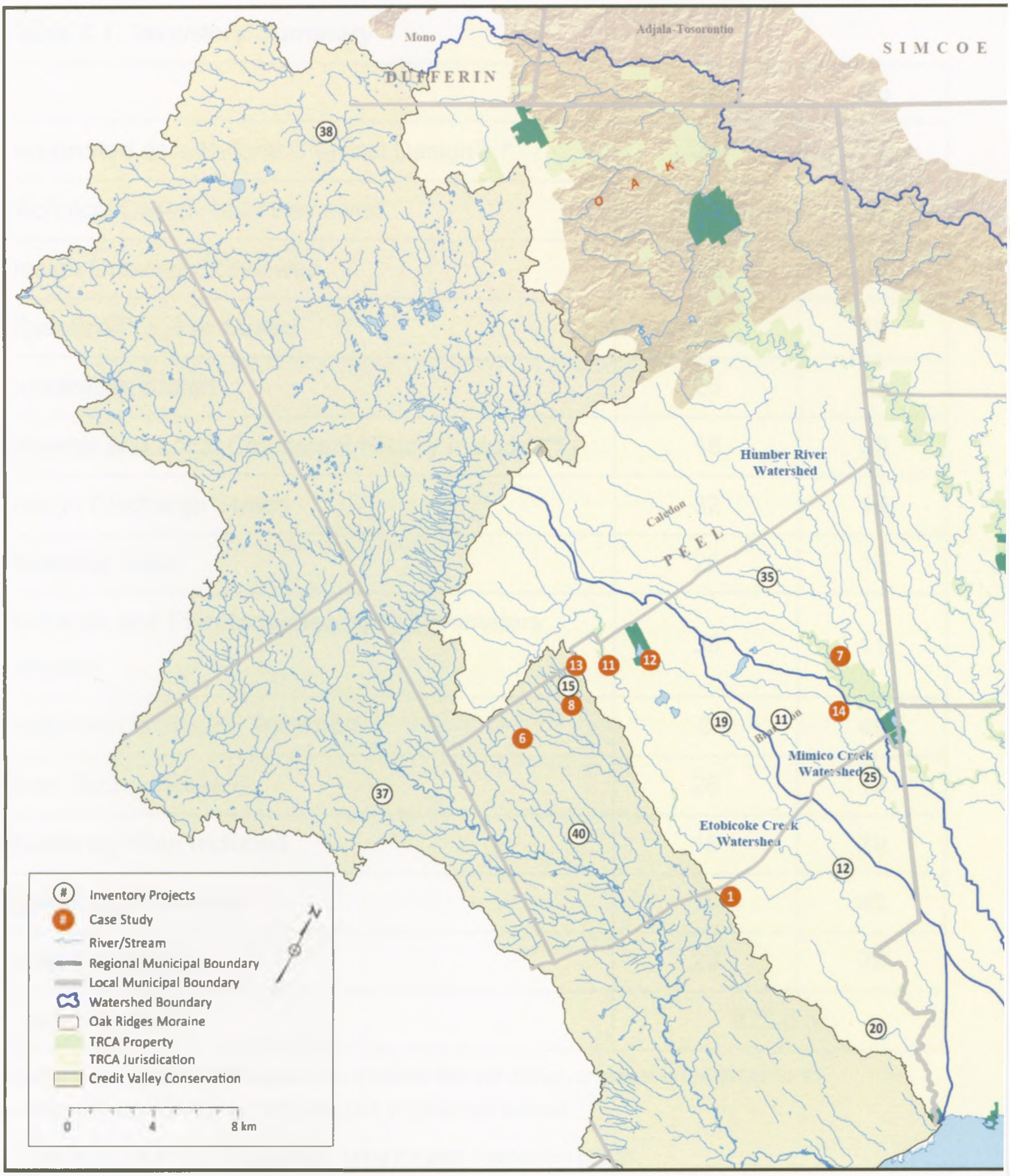

Figure 4.1: Study area map

Source: Toronto and Region Conservation Authority, Jurisdiction Map. Modified by Nina Sampson and Karen VanKerkoerle

Table 4.1: Inventory Summary

	Yes	**No**
Designated as a Natural Channel Design? *	24	22
Technical Design Brief Reviewed	24	22
Design Drawings Reviewed	22	24
Objective/Purpose Stated	28	18
Constraints Stated	25	21
Channel and Local Catchment History Included**	18	28
Design Discharge Stated	32	14
Modelling Used	26	16
Hydraulic and Plan-form Geometry Parameters Included	35	11
Sediment Continuity/ Transport	0	49
Grain Sizing Included	26	19
Monitoring Plan Included	16	29
Project Cost Included	3	43
Length Specified	29	20
Average Length	876.6 m	

*Project files that referred to a project as a natural channel design, or indicated the use of fluvial geomorphology principles or NCD principles in the design process.

**Referring to watershed development during the post-colonization period

The Technical Design Brief is a document that explains the design process (in some cases) and provides the client with an understanding of what the final design will look like. The exact content of design briefs varies by company, but typically includes objectives, constraints, existing conditions, and proposed conditions. Whether or not Design Briefs or design drawings were reviewed depended on the availability of the documents. Project files that were obtained from the private sector companies typically included both design briefs and design drawings. Project files obtained from the CAs often included a wider variety of documents, including permit applications and approvals, but may not have included design briefs.

4.3 Case studies analysis

This section provides details for each of the selected case studies. Appendix D lists the sources used for each of the case studies. Of the fourteen case studies selected, one was associated with storm water management, two with erosion control, two with crossings, one with stabilization, seven with development, and one with the creation of a dynamically stable channel (Table 4.2). The case studies, represent six different companies, with twelve of the projects coming from three companies. This was considered to be representative of the current state of the industry, with the majority of natural channel designs being undertaken by companies who specialize in this type of work. Appendix B provides summary tables of each of the case studies with basic details on location, objectives, constraints, existing conditions, and a design description. The goal of this section is to provide a critical appraisal of the design approaches used, discuss how constraints influenced the design, and evaluate the appropriateness of certain design structures. Appendix E contains the photo record for selected case studies.

Table 4.2: Case Studies and Type of Work

#	Project Name	Type of Work	Length
1	Etobicoke Creek West Branch, Tributary 3	SWM, Stabilization	Not specified
2	Upper Milne Creek Restoration Project	Erosion/Flooding	505 m
3	Village Parkway Outfall Channel Restoration	Erosion Control	35 m

Table 4.2: Case Studies and Type of Work

#	Project Name	Type of Work	Length
4	West Highland Creek at Markham Road	Stabilize	Not specified
5	Gore Road Tributary Natural Channel Design at Pannahill Drive and Cottrelle Blvd	Crossings	Not specified
6	Stanford Channel	Culvert/Crossing	440 m
7	West Humber River in Woodlands Golf and Country Club	Development	Not specified
8	East Branch of Fletcher's Creek Headwater Stream Realignment and Enhancement, Phase 1	Development	475 m
9	Miller Creek Realignment and Natural Channel Design	Development	1400 m
10	Morningside and Neilson Tributaries Valley Design	Development	2000 m
11	Naturalized Corridor of Tributary H2 of Humber River	Development	Not specified
12	Spring Creek Tributary of East Etobicoke Creek	Development	Not specified
13	McLaughlin Road Tributary Channel Design, Phase 2	Development	600 m
14	Upper Mimico Creek Natural Corridor Project and Upper Mimico Creek Aquatic Restoration Project	Create dynamically stable channel	1700 m

4.3.1 Realignment and Renaturalization of Tributary 3 of Etobicoke Creek, West Branch

This project was designated as a NCD and was associated with improvements to a nearby storm water management facility. Constraints included upstream and downstream tie-in elevation and the requirements to include wetland/wet meadow features and replication of the function of natural swale corridor. A 'soft' design approach was used – indicating that no armoring was sought and that dynamic stability (i.e. movement of the plan-form) would be allowed. This project is a good example of the use of NCD principles in an urban context. It addresses SWM infrastructure needs and aims to improve natural function and the quality of the aquatic environment.

4.3.2 Upper Milne Creek Restoration Project

The design of Upper Milne Creek is highly constrained by development, particularly commercial and light industrial development in the corridor. A lack of upstream storm water management has resulted in flashy flows and soil erosion.

Stable sections of Upper Milne Creek were used to determine the bankfull discharge, which compared reasonably well with the results of the area-based calculations for the size of the watershed. A HEC-2 model was used to determine hydraulic conditions. The design included the creation of plunge pools, vortex weirs, pool-riffle sequences, a meandering plan-form, and riparian wetland cells with bioengineering techniques that were used to stabilize the banks. The design was based on the Rosgen classification system, despite the TRCA indicating to the design company that the Rosgen classification system was not applicable in Ontario (as reflected in communication in the project file). This is one case where the design of the channel was not altered at the local CA's request. There was no further explanation of how the design was approached other than the targeted channel was a Rosgen C4 channel.

4.3.3 Village Parkway Outfall Channel Restoration

This project, located in the Rouge River watershed, was initiated to restore a storm water outfall channel, which discharges into Berczy Creek. This approximately 35 m long channel was originally constructed in 1971 and was gabion lined (now failing) and contained several weirs for grade control. The design of the channel was constrained by the request of the TRCA to minimize the loss of mature vegetation, and by the downstream tie-in elevation. Plan-form was constrained by the pedestrian walkway to the north, and mature vegetation to the south and north where the pedestrian walkway was not adjacent to the channel.

While the goal of this design was to create a stable channel, the design intended to incorporate natural channel design principles into the design. The design drew upon principles of fluvial geomorphology and flow hydraulics as well as field observations, specifically of the interaction between the flow regime and the existing channel, and was designed using an iterative approach. The iterative approach is not fully explained. It is assumed that based on the selected design discharge, channel dimensions are varied within a reasonable range until a desired velocity is reached – at which the selected/anticipated bed material will not be subject to erosional velocities. It is also assumed that the dimensions are varied within proprietary models/spreadsheets of the design companies. Designs considered flow hydraulics, shear stress, and geomorphically stable forms that are suitable to the channel setting. The existing channel was used as the reference reach with the profile of the existing watercourse mimicked in the proposed design with the inclusion of a plunge pool and an enlarged cross-section. Analytical results determined that the existing cross-section was too small to accommodate the design flow. The design discharge was determined from the flow capacity of the outfall, which was determined from the diameter and grade because flow data was unavailable from the City of Markham. The design widened the cross-section and included a plunge pool (for energy dissipation) at the outfall. These two measures reduced stress on the new bank protection measures. The plunge pool was designed using MTO and DFO guidelines.

4.3.4 West Highland Creek at Markham Road

This project was initiated to stabilize a section of west Highland Creek, as well as improve fish passage and local habitat through the removal of in-stream barriers. This project was initiated prior to the August 2005 storm, a large magnitude storm which exceeded the 1/100-year storm in the north part of the City (Snodgrass, 2005). The storm significantly altered Highland Creek's morphology and exacerbated existing issues, such as erosion and instability. Highland Creek's watershed is one of the most heavily urbanized in the TRCA (TRCA, 2011), resulting in significant impacts to flow and sediment regimes, which must be taken into consideration when designing channel works in the area. Within the study area, the bridge at Markham Road determines local hydraulics and the form and structure of the bridge needed to be considered in the placement of bank treatments and grade control structures.

During field assessments completed prior to the August 2005 storm, down-cutting was evident in the upstream reach and gabions were exposed approximately 10 m upstream of Markham Road. The gabions were in place to protect a sanitary line and act as a grade control structure. This promoted scouring immediately downstream. The downstream reach contained a weir 4 m downstream of the bridge, which provided grade control, but impeded fish passage. The majority of the channel was lined with armourstone, with unprotected sections showing evidence of down-cutting and widening. Following the August 2005 storm, field assessment noted that the bed scour upstream of the Markham Road bridge was more evident, till exposure had increased and there was an increased level of exposure, failure, and general deterioration of the gabion structures which protect the sanitary sewer line and the banks. The weir structure downstream of the bridge failed during the storm.

This project was not a true natural channel design project, as the primary object was to stabilize the reach. However, it was designed to allow a certain level of natural adjustment, albeit very minimal. The project was approached from a 'worst-case scenario' perspective with a high engineering safety factor. Due to the highly urbanized nature of the watershed and the impacts of the 2005 storm, the channel was designed to accommodate large flow events. Geomorphic and hydraulic analyses were used in combination with the results from the field investigations to determine the appropriate channel form and elements. HEC-RAS (v. 3.1.3) modelling was used to determine stream hydraulics, and stone sizing was based on 25-year flows. Deep pools were incorporated into the design for energy dissipation and three new elevation control points (rock vortex weirs) were included to limit additional scour. Banks were protected using materials large enough to resist entrainment, vegetated buttresses, and the armourstone was realigned and extended to protect municipal infrastructure. The result of this design is a very hard, stable channel. Due to the heavily urbanized nature of the Highland Creek watershed, it is not unexpected that available floodplain space, required to allow for dynamic stability and some plan-form adjustment, is unavailable. The plan-form of the final design is not expected to adjust due to the nature of the bank treatments. The longitudinal profile may adjust as the riffles and pools adjust to the rock vortex weirs.

4.3.5 Gore Road Tributary Natural Channel Design at Pannahill Drive and Cottrelle Boulevard Crossings

This project was initiated at the proposed construction of the Pannahill Drive and Cottrelle Blvd crossings, as it provides an opportunity to replace the existing online ponds with watercourse features. Since the watercourse has adjusted to the existing backwater conditions, they must be replicated. The existing character of the channel was to be maintained in the design and the in-channel vegetation was planned and accounted for in the design.

The design of the Gore Road Tributary is constrained by the low energy environment, the projected vegetation-dominated stream channel, which will impact flow velocities and shear stress, and a need to replicate backwater conditions. Additionally, the design is constrained by the tie-in elevations, which are required to maintain a continuity of channel form, function and processes and avoid unduly compromising the design through unanticipated erosion or aggradation.

This natural channel design was guided by the principles of fluvial geomorphology and observations of the existing watercourse. The 2-year flow was modelled, however the design discharge was significantly different from the modelled value. For Pannahill, the modelled value was 5.13 m^3s^{-1} and the design discharge was 1.55 m^3s^{-1}; and for Cottrelle the modelled value was 5.13 m^3s^{-1} and the design discharge was 2.99 m^3s^{-1}. No explanation was provided as to why there was such a discrepancy between the two values, or why it was decided that the modelled value was inappropriate.

Paved inverts were removed and existing ponds were backfilled. In channel vegetation was planned and accounted for in the design. Channel dimensions at Cottrelle Blvd replicate those at Pannahill Dr. The channel profile was constrained by the tie-in elevations and considered the need to dissipate energy and promote flow conveyance. The profile incorporated pool-riffle morphology, a deeper online pool, and wetland features. The section at Pannahill Drive included one pool and one riffle, and the section at Cottrelle Blvd included two riffles and one pool. It was stated that wetland features and aquatic features were to be included in the design. Details on what these features would look like, or how they would function or affect the function of the channel was not provided.

4.3.6 Stanford Channel Alteration and Natural Channel Design

Stanford channel is a tributary of Fletcher's Creek in the Credit River watershed. The channel is a vegetation-controlled, headwater swale with intermittent flow. The design of the Stanford Channel was constrained by the CVC's requirement to maintain a minimum of a 0.3 m freeboard from the top of the valley to the Regional Storm water surface elevation, and the requirement that the existing conditions were to be mimicked. The channel was designed to have steeper side slopes (ranging from 2.5:1 to 5:1) which were deemed necessary to transition the proposed channel with the local topography, while providing the required invert, meander belt width, and freeboard during a Regional Storm event.

Due to the low energy conditions of the channel, the rules of alluvial channel sinuosity, meander plan-form and thalweg definition did not apply. The design utilized the principles of natural channel design to restore the form and function of the channel. The principles of natural channel design used in this project are not defined. The design was undertaken iteratively and utilized regime relationships for the length and spacing of pools, riffles, inter-pools and inter-riffles, and hydraulic modelling was done to ensure all designed storm flows met the minimum freeboard constraint. The channel was lowered for future upstream servicing and a more natural, meandering plan-form was used. A proprietary geomorphic design model was used to iteratively design the hydraulic geometry of the pool and riffle cross-sections for the lower part of the channel. In the lower reach, a simple pool-riffle-run morphology was utilized in the design. The upper part of the channel is steeper and therefore step-pool morphology was used to aid in the dissipation of energy. Appropriate sinuosity was determined based on the proposed valley gradients needed for the floodplain storage and conveyance. The lower reach's cross-sections were mimicked in the upper reach after they were checked for design capacity and stability. The proposed cross-sections in the upper reach have extra capacity given the steeper slope and differences in velocity and depth. The design discharge was determined from the Meander Belt Width report, produced by Aquafor Beech (2002) prior to the initiation of this project and from design discussions with the CVC. This indicates that the CVC has influence in how projects are designed. Field investigations were undertaken to ground truth the design discharge determined in the Meander Belt Width report. Field observations, based on snowmelt conditions, indicated that the flow should be greater and therefore the design discharge was increased from 0.66 m^3s^{-1} (the 2-yr flow) to 0.9 m^3s^{-1}. In general, the methodology for the design was not sufficiently explained in a way that would allow an adequate understanding of how and why the design was undertaken in the way it was.

4.3.7 West Humber River in Woodland Golf and Country Club

The West Humber River was realigned and naturalized as part of the redevelopment of the Woodland Golf and Country Club into a residential subdivision and included a dam removal. The purpose of this project is to remove the dam located within the study area, reinstate a channel in the head pond and remove fish barriers, which also impede bed-load transport. The design was constrained by the upstream and downstream tie-in points (which aid in the continuity of channel form, function and processes), the maintenance of grade control points, the maintenance of a large pool along the channel, and that the bedrock layer was not to be excavated as it may have induced incision. This project was designed according to the principles of natural channel design and fluvial geomorphology. These principles are not specified, nor was there an explanation of how they differ for a semi-alluvial channel with exposed bedrock. Geomorphic and hydraulic analyses were completed to ensure that the low flow channel had a similar flow capacity as the reference reach, which was a nearby section of the West Humber, unaffected by the backwater conditions created by the dam. The design replicated the 20 m wide channel with similar depth to the upstream sections. The cross-section is 2-tiered, with a low flow channel set within a larger channel with width varying spatially along the channel. The low flow channel is slightly sinuous within the larger channel with a large radius of curvature to reduce shear on banks during high flow events.

Reference reaches unaffected by the backwater conditions caused by the dam were used in the design. Channel capacity was calculated using HEC-RAS assuming a 20m wide channel and using the 10-yr flood.

4.3.8 East Branch of Fletcher's Creek Headwater Stream Realignment and Enhancement, Phase 1

The realignment of the East Fletcher's Creek system, undertaken in three phases, has an ultimate drainage area of 360 ha and a length of 452 m of realigned channel for Phase 1. The design was based on HEC-2 cross-sections and a 2-year storm peak flow rate, determined in the 'Master Servicing and

Storm water Management Report'. The reviewed design documentation (of which the aforementioned storm water management report was not a part) did not indicate how the 2-yr storm peak flow rate was determined. Cross section dimensions were based on reference data for cohesive soil channels and known regime relationships. The dimensions were iteratively tested. The cross sectional design was used to layout the plan-form, specifically using the bankfull width, sinuosity, and channel length. A 'blended' design was determined to be the most appropriate. This indicates that the final design was not a fully dynamically functional system and some hardening (i.e. necessary stone treatments, likely on banks to prevent erosion) will be part of the design. However, neither specific nor general details on any hardening were provided in the reviewed design documents.

There were three primary constraints that impacted the design of the East Branch of Fletcher's Creek:

1. Upstream and downstream tie-ins
    - Proper grade control allows the design to function as intended
2. Accommodate flow increases
    - Required due to upstream development
3. Maintain existing Regional Storm floodplain storage
    - Required by the CVC

4.3.9 Miller Creek Realignment and Natural Channel Design

This 2000m of natural channel design is non-continuous, with three reaches lying between the three reaches subject to realignment and natural channel design. Reaches 6, and 1 & 2 were subject to redesign with Reaches 3, 4, 5 and 7 remaining in their existing states. The purpose of this development-associated realignment was to allow for 'more efficient community design', remove fish barriers, and restore channel form and function

The biggest constraint faced in the design of Reaches 6, 1 & 2 is the presence of a beaver dam in Reach 5. The dam affects the channel processes upstream in Reach 6 and affects function and sediment supply in Reach 1-2.

Backwater effects immediately upstream in Reach 6 have caused channel widening and sediment deposition. This deposition decreases the sediment supply and the size of sediment available downstream.

Modelling and reference reaches were used to guide the design process. Detailed field data were obtained from nearby unaltered reaches and included bed morphology and plan-form pattern. Post-development flows (2-yr flows) were modelled by a different company (Cosburn Patterson Mather) as part of an Environmental Master Drainage Plan for the area. It was determined through a comparison of the estimated and modelled 2-yr bankfull flow values that the bankfull values were similar in Reach 6 but estimated values were lower for Reach 1-2. Based on this, the bankfull discharge value used in the design was less then the modelled value. No analysis or rationale was provided explaining whether the 2-yr bankfull flow was appropriate to use as the design discharge. Cross-sectional parameters were determined from a range of geomorphologic and hydraulic analyses, however it was not specified which relationships were used. This design took into account what channel boundary materials would be like when the new channel was cut into the floodplain. No other case studies indicated whether a change in boundary materials was considered in the cross-sectional and plan-form design of the channel. This does not mean that future boundary conditions were not considered, only that is was not a part of the final design discussion as evidenced by the design documents. This illustrates a deficiency in the design documents and their usefulness in allowing an outsider to understand the design process from the design briefs.

4.3.10 Morningside and Neilson Tributaries Valley Design

This project was associated with a 290 ha upstream development and was designated to accommodate increase in flow volume, as a result of increases in impervious surface area upstream. The design is formulaic and reads like it would produce a very regular channel with repeating sections of pool-riffle sequences and transitions in each reach. Existing conditions were used to determine cross-sectional shape, meaning that the channel acted as its own

reference reach. Throughout my review of academic literature, there were no articles discussing using existing conditions as a reference for designing channel shape and dimensions, or the appropriateness of such. Logically, if the channel capacity needs to be increased to handle increases in flow volume there is a question as to whether using the existing dimensions is in anyway appropriate.
In a description of pre-existing conditions Neilson Tributary was indicated as not having sufficient capacity to convey the bankfull flow and therefore would not have sufficient capacity to convey the increased flows as a result of upstream development.

4.3.11 Naturalized Corridor for Tributary H2 of Humber River

Prior to design and construction, Tributary H2 was a swale with an intermittently defined channel. The channel was designed iteratively and included swale and intermittent channel morphology. The design of the channel was constrained by upstream and downstream tie-in elevations and channel crossings, such as bridges, which confine the path and alignment of the designed channel. However, there was no indication in the technical design brief of how the channel design was altered or impacted by this constraint. When constraints impact the layout of the channel, it is important to quantify the appropriate meander belt width and radius of curvature in order to adjust the design to compensate for potential increased erosional forces.
Upstream of Countryside Drive the invert is higher due to servicing requirements. Cascade morphology was used as a temporary linkage because as upstream land development continues the upstream channel will likely have to be altered to accommodate post-development flows. Particular attention needs to be paid to the sizing of materials used in the cascade feature to prevent the feature from being compromised during high flow events.

Design discharge and cross-sectional parameters were included in the design. Calculations used to determine radius of curvature in the defined channel sections were not provided. Design discharge was estimated from geomorphic relations (it was not indicated which relations were used). Previous work undertaken by Aquafor Beech (2004) provided the bankfull flow, which was based on proprietary regional relations. The post-development increases to bankfull discharge were estimated based on the assumption that runoff from upstream developments would be properly managed.

There were two distinct types of channels within the design. Part of the channel was defined, the other had swale morphology. The inclusion of swales or wet meadow features was due to their presence in the pre-constructed channel, their ability to provide sediment and flow retention and detention functions, provide additional pockets of coarse sediment in the long-term, and provide 'added diversity' to the corridor. It was not specifically indicated whether the added diversity was geomorphic or ecologic, however it can be assumed that wet meadows would increase both types of diversity. Wet meadows also enhance the spilling of flows on the floodplain. This allows for increased infiltration opportunities and will slow the flow velocity during wet weather events. The wet meadow is designed to mimic the geomorphic function of a swale. Based on the inventory and case study analysis, the use of wet meadow or wetland features is prevalent in many designs, particularly those that occur in developing, headwater channels. Overall, the redesign and realignment of Tributary H2 shares many characteristics and design features with other projects undertaken in headwater systems and associated with development.

4.3.12 Spring Creek, Tributary of East Etobicoke Creek

This development-associated project required an increased capacity to accommodate post-development flows and aimed to restore form and function to this previously straightened and channelized watercourse. There were two primary constraints; the need to increase capacity; and the accommodation of the existing tie-in invert elevations with special consideration for the upstream tie-in with a transition channel that is proposed to be lower in the future.

Natural adjustments in the channel form were expected and anticipated. This indicates that the channel is designed to geomorphically function and will not be armoured or stabilized in a manner that would eliminate the possibility of erosion or migration of the plan-form.

Design discharge was determined through field estimates (based on existing bankfull cross-sectional dimension channel gradient and an estimation of Manning's n) and flood modelling. Greater consideration was given to the field bankfull discharge values as modelling results provided a discharge that was inappropriate for design purposes. The design channel has the capacity to convey the bankfull flow before spilling onto the floodplain, which is by definition the bankfull flow. A frequency or recurrence interval for this flow was not indicated in the reviewed design documentation. Hydraulic analyses minimized flow energy and inhibited erosion while 'still allowing for the transport and conveyance of sediment through the system'. Neither sediment conveyance nor transport was quantified or qualified in the reviewed documents. The assumption of sediment conveyance through the system implies a solid understanding of upstream channel and watershed conditions (existing and proposed future conditions) and upstream sediment sources and sinks. However, the reviewed documentation did not indicate the level of research or fieldwork necessary to quantify or adequately qualify upstream conditions.

Hydraulic analyses and the resultant understanding of conditions guided the sizing of substrate materials. Modelled radius of curvature values were used to guide the initial channel plan-form layout and were derived from relationships determined from c-type stream channels in southern Ontario (Annable, 1996).

4.3.13 Proposed McLaughlin Road Tributary, Phase 2 Channel Design

This development associated channel design was designated as a natural channel design and was based on the principles of fluvial geomorphology and flow hydraulics. The purpose of this project was to relocate and amalgamate the drainage courses that form the McLaughlin Road Tributary of Fletcher's Creek. The new channel incorporated an increased conveyance capacity, which resulted from the merging of watercourses, and wetland features, which were included at the request of the CVC. Other constraints impacting the design also included the upstream and downstream tie-in points and the requirement that the design maintain a minimum of a 0.3 m freeboard during a Regional Storm, meaning floodlines cannot be altered by the channel design.

The design was completed iteratively. Design discharge was derived using a range of methods, as a nearby reference reach could not be located. Design discharge was determined using drainage area, from which bankfull flow was estimated (Annable, 1996), modelling of the anticipated 2-yr flow of the merged watercourses, and from pro-rating the hydrograph from an adjacent tributary of Fletcher's Creek. The final design discharge was less than the 2-yr modelled value, and similar to both the drainage-area relationship value, and the hydrograph pro-rating approach.

The meander belt width was determined via four empirical relationships; 1) Annable, 1996, Type-E channels, 2) TRCA, 2001, Meander Belt Delineation Procedures; 3) Williams, 1986, equations derived from 153 data points; and 4) physically-based relation based on Canadian and US data. The design incorporated wetland features at the request of the CVC, which constrained the ability of the channel to meander or migrate across the floodplain. Wetland pockets are included to act as detention and retention of sediment and water and allow for increased infiltration. These features are most commonly included in headwater channel designs in southern Ontario. The CVC requests their inclusion in most headwater channels under their jurisdiction reviewed as part of this thesis. An adequate explanation for the inclusion of wetland features is not given in any of the design documents. It is stated that they are a natural part of headwater systems in this area of Ontario; however, no references are given to justify this statement. This may be due to a lack of published academic research corroborating this statement but it is justified by the experience of the practitioners and their mentors.

4.3.14 Upper Mimico Creek Natural Corridor Project & Upper Mimico Creek Aquatic Restoration Project

This project was driven by watershed priorities identified in 'Greening Our Watersheds: Revitalization Strategies for the Etobicoke and Mimico Creek Watersheds'. This project is the only case study driven primarily by environmental factors. Due to the setting of the project location, a true natural channel design could not be undertaken. The design was considered a hybrid natural channel design with a meandering riffle-pool sequence.

The design utilized a number of different approaches and methodologies. Modelling was undertaken to determine design discharge, radius of curvature, and meander belt width. The value for the radius of curvature was determined for an Annable Type C channel. The Annable categorization was also used to determine riffle length and pool length. The design discharge was modelled on the specifications of the reference reach, and the modelled discharge value was used to derive bankfull specifications of channel design. Riffle spacing was based on Hey and Thorne (1986) for vegetated channels with 5-50% tree/shrub cover. Hydraulic analyses (not specified) were used to minimize flow energy and inhibit erosion while allowing sediment transport. The reviewed design documentation does not specify quantitatively or qualitatively how much sediment may be transported through the system.

Constraints accounted for in the design included the removal of instream barriers, grade control issues, the impact of storm water runoff, and the need to add capacity for urban flows. These constraints impacted the design, particularly the cross-sectional and plan-form dimensions.

Two types of features were included in the design. Wet meadow/ wetland features were included at storm water outfalls to decrease the velocity with which storm water enters the system. The inclusion of these features was justified by stating that wet meadows/wetland features are 'commonly found in natural channel systems, particularly those in the context of southern Ontario', no literature was cited to backup this claim. Oxbow features were included for the purposes of water and sediment storage when the channel overflows its banks.

These features also offer added protection for nearby development from over bank flows.

4.4 Project analysis

4.4.1 Natural channel design in the TRCA and the CVC

Within the inventory, a total of 22 projects were designated as NCD, or indicated that the principles of NCD or fluvial geomorphology was used to approach the design. Table 4.2 summarizes basic project information for the selected case studies. Of the 14 selected case studies, nine projects (Upper Mimico Creek, Morningside and Neilson Tributaries, Spring Creek, Fletchers Creek – Phase 1, Miller Creek, McLaughlin Road Tributary – Phase 2, West Humber River, Gore Road Tributary, and Stanford Channel) were designated as NCDs, or the principles of NCD were used in the design, and/or fluvial geomorphology principles were used in the design process.

These nine case studies had a number of common elements. Five were associated with developments and eight included an analysis of the selection of the design discharge. Eleven of the case studies included some computational modelling, with four projects specifying the use of HEC modelling. HEC-RAS is the Hydrologic Engineering Centers River Analysis System developed by the USACE. The current version of HEC-RAS can model one-dimensional, steady flow, unsteady flow, sediment transport/mobile bed computations, and water temperature. Flows modelled for these case studies were done for one-dimensional, steady flows. The purpose of the one-dimensional steady flows was not discussed in the reviewed design documents. Likely it was done to determine channel capacity, water levels, and estimate velocity and shear stress. Because HEC-RAS was used in these case studies, only models flows in one-dimension (i.e. width-averaged along the channel), there is no direct modelling of the hydraulic effect of cross-sectional shape changes, bends, or other two and three-dimensional aspects of flow, or the effect of structures used in the design, like rock vortex weirs or wetlands, on local secondary flow characteristics. HEC-RAS modelling requires an independent discharge to be input into the model.

For most case studies, it is assumed that the value was derived from field data (bankfull conditions). However, no indication was given as to whether or not gauge data or rainfall-runoff models were used to determine the discharge.

Of the five case studies not designated NCD (Etobicoke Creek West Branch Tributary 3; Naturalized Corridor of Tributary H2 of Humber River; Upper Milne Creek Restoration; Village Parkway Outfall Channel Restoration; and West Highland Creek at Markham Road), two (Etobicoke Creek and the Village Parkway Outfall) were primarily concerned with stability, but it was indicated that natural function was incorporated into the design where possible. Natural function in these cases included the improvement of aquatic habitat conditions, and allowing for a mobile bed (where infrastructure protection didn't take precedence). Natural function does not include plan-form adjustments in these channels. A fully functional channel has the ability to adjust its plan-form, has sufficient width to accommodate the migration of riffles and pools, and has a sufficient meander belt width to decrease velocity and shear stress thereby reducing erosion risk.

In some cases, where floodplain space or available valley width did not allow for a fully functioning channel, a low flow channel with a more natural meandering plan-form, pools and riffles (where appropriate), and other cross-sectional and plan-form geometry features, were incorporated into the design allowing some natural form, even in a constrained system. Case studies generally indicated that, where appropriate, the design would include a dynamically stable channel. In geomorphic terms, dynamic stability signifies stability or the equilibrium conditions where the amount and size of the hydraulically controlled sediment being delivered from upstream is in balance with the transporting power of the stream such that there is no net change in channel dimensions over time (Simon, 2008). Dynamically stable channels are highly desirable, as over the management life cycle, which is typically 10-30 years, a minimum amount of direct intervention or management will be required, thus justifying the cost of the project. Based on the degree of hardening evident in some designs, as well as the 'factor of safety' used in determining sediment size, it is unlikely that these channels will truly be 'dynamically stable' in the same way that natural streams are. These constructed channels will likely be stable at most flows up to and including the bankfull flow.

4.4.2 Design approaches

Designs reviewed for this study and interviews with practitioners indicated that NCDs are approached scientifically, quantitatively, and analytically. Geomorphic function was considered in the design, and academic literature was used to improve designs (as indicated through practitioner interviews, see Section 5.5). Within that broad categorization, multiple approaches are used, even within the same project. The approach(es) used must reflect the appropriateness of a given approach to the unique set of objectives and constraints of the project, as well as geographical setting, which varies across the study area. Approaches include the use of hydrodynamic modelling to determine design discharge, the use of analogues (i.e. reference reaches), other types of modelling for plan-form parameters such as meander belt width, relying on field data, regional curves, regime relationships for cross-section dimensions, and experience-guided proprietary models.

Multiple approaches were used in each project. None of the case studies or inventoried projects included specific sediment transport equations or calculations, although some used discharge and shear stress to aid in the determination of appropriate bed material sizing. Regardless of approach used, an iterative approach is taken, which attempts to get the cross-sectional, plan-form, discharge and sediment sizing (where applicable) values closer to values that will provide for the dynamic stability of the channel.

Data availability is a key consideration in the approach used for the design. Data on bed-load transport is unavailable for streams in southern Ontario, as there is no provincial monitoring network of gauging stations, and flow data are typically only available for larger watercourses and most natural channel design projects are undertaken on small, unmonitored watercourses. Additionally, flow monitoring devices are typically located at or near infrastructure, such as bridges or other crossings, for ease of access, but crossings can influence flow velocity and shear stress, as well as other hydraulic parameters, due to the constriction of flow at the crossing. Where flow data are used in the design, presumably for modelling purposes, these data sets or their use in a model are usually not referenced. This may be due to modelling being undertaken by a sub-consultant, the project proponent, or being done previously. Field data and modelling are particularly important in the selection of design discharge, which is important in the selection and design of the cross sectional and plan-form geometry. A more in-depth discussion regarding design discharge and its selection can be found in Section 4.4.6.1.

Reference reaches were used as a basis for design in four case studies. Two case studies used their own pre-design dimensions as a reference reach, meaning that the channel acted as its own reference reach. Various other approaches were used to determine final design dimensions. These included: modelled and calculated belt width analysis, regime relationships, Annable empirical relations (Annable, 1996a; Annable, 1996b), physically based relations, reference data for cohesive soil channels, geomorphic and hydraulic analyses (often used in tandem, but occasionally presented as separate approaches), the Rosgen approach (a type of NCD approach popular in the US, which uses a standardized classification scheme and associated methods and structures to create a specific class of channel), proprietary geomorphic design models, numerical modelling, field results, and Geomorphic Referenced River Engineering (GRRE). GRRE is used where physical limitations exclude the use of the natural channel design approach. GRRE uses geomorphic principles to design a stable channel form, including riffles and pools, and claims that the channel will look and function like a natural, meandering pool-riffle system while the plan-form is fixed in place through a fixed non-erodible bed and banks.

Historical morphology (which can be ascertained from historical aerial photographs) was not used in any case study or inventoried project as urbanization and proposed developments have altered the hydrologic and sediment regimes too greatly, making historic channel dimensions incompatible with current hydrologic and sediment regimes. If used, it will not aid in the creation of a dynamically stable channel, as the channel will have to adjust to the difference in the regimes. Approximately half the case studies included some historical analyses of the project site. Only a site history was included, the watershed context was not explicitly considered. The site history typically encompasses the last 50 years and uses aerial photos available for the study site. Unfortunately, 50 years is not a long enough time span to capture pre-colonization conditions. Where a site history was not included in the design documentation it is suggested that what is carried out is not strictly restoration but more natural design/construction. Without history, restoration is only occurring in the generic sense of improvement.

4.4.3 Objectives

The case studies reviewed for this project had multiple objectives. Objectives set in the reviewed design documents tended to be vague and ambiguous and did not provide quantitative measures for improvement, nor was it defined as to what was meant by improvement in aquatic habitat or geomorphic form and function. The most common objective was to provide diverse aquatic habitat or improve aquatic habitat through the removal of barriers to fish movement (nine projects). Seven projects had the geomorphic objective of restoring form and function to the channel, and four projects indicated that, due to the development associated with the projects, the channel would have to accommodate the anticipated post-development flows or be moved to accommodate said development.

Over the decade of reviewed designs, objectives have evolved to include more specific objectives regarding geomorphology and fish habitat. In the past (10-20 years ago), projects were primarily focused on drainage, flood control/flood conveyance, stability and erosion prevention. Very few environmental goals (ecologic or geomorphic) were included in the past, often resulting in hard channels. In the past decade channel designs have changed to include 'natural' forms in highly regular patterns (often resulting in highly regular 'coffee-cup' sinuous channels, see Figure 4.2), to including the forms necessary to create certain processes, resulting in a more diverse, functional channel that includes spatial non-uniformity in the design. None of the case studies indicated how the achievement of these objectives would be measured, although eight projects included a post-project monitoring plan. Despite the commonality of the objective of improving fish habitat, the link between habitat quality and geomorphic function has not been proven in the literature. It is generally assumed that 'if you build it, they will come', that is if you improve the function of a watercourse the fish will return and the habitat will improve. The link has not been proven due to a lack of research into the connections between fluvial geomorphology and aquatic ecology.

Figure 4.2: Highland Creek constructed meander (Google Earth, 2004).

4.4.4 Constraints

Constraints were considered to be factors that impacted the physical layout of designed channel or factors that diverted the design from a more 'natural' approach. Of the 14 case studies, only three did not explicitly discuss constraints faced in the design process. Eight projects stated that matching the elevations of the upstream and downstream tie-in points were a constraint when determining the cross-sectional and plan-form geometries. Matching tie-in elevations are required to maintain the continuity of channel form, function, and processes and avoid compromising the design through degradation or aggradation. This constrains the gradients possible in the design by setting the maximum possible gradient. Matching inverts allow for sediment continuity throughout the system, regardless of whether or not sediment continuity is considered in the design. In discussions with practitioners, it was indicated that matching elevations of the tie-in points is the most important aspect of the channel design in order to create a sustainable and maintainable channel. Five case studies indicated that valley width and alignment was sufficient to accommodate natural migration tendencies and provide a functional corridor. In four of these five cases the projects were associated with development. In other cases the width of the available corridor was not indicated as a constraint or otherwise. In development-associated projects, it is expected that the valley width would be sufficient to accommodate the projected natural migration tendencies of the channel. Development-associated projects typically have fewer overall constraints including valley width constraints and lower energies due to their location in currently less-developed headwater areas. This is a function of the geography of development in relation to the hydro-geography of the region.

Overall in the design process, few constraints were mentioned that directly impacted the design, particularly the plan-form layout, but there were a number of considerations that impacted the designs. These included the addition of wetland features along the floodplain (four projects), the removal of existing structures within the channel (four projects), the consideration of how in channel vegetation will impact the flow (three projects), and the replication of current corridor function (two projects). In the cases of West Highland Creek at Markham Road, Tributary H2 of the Humber River, Village Parkway Outfall Channel Restoration, and the Morningside and Neilson Tributaries, structures (outfalls, culverts) and crossings impacted the design of the channel. In the cases of West Highland Creek and Tributary H2 of the Humber River channel crossings determine local hydraulics and may confine the path and alignment of the channel. For the Village Parkway Outfall, the local conservation authority (TRCA) wanted mature vegetation to be preserved and for the Morningside and Neilson Tributaries hydro towers were present in the corridor and the channel had to be aligned away from them. For the Morningside and Neilson Tributaries this impacted the overall layout of the channel but not the basic principles of the design.

4.4.4.1 Cost of natural channel designs

None of the case study documents included any cost estimates, but three of the inventoried projects did. A 2 km reach of Highland Creek was rehabilitated at a projected cost of $1.825 million. This included $1.575 million for construction and $250,000 for engineering and contingency. The cost per 100 m of channel was $91,250. Approximately 340 m of Milne Creek was redesigned at an estimated cost of $170,780, including $52,720 for site preparation, $37,640 for channel restoration, and $80,420 for planting and bank stabilization. The cost per 100 m of channel was $50,230. A 90 m reach of Salt Creek was restored with an estimated budget of $14,500. Cost per 100 m varied widely. Differences in per-length cost is due to the constraints present in the project's study area. For example, Highland Creek was the most costly due to its highly urbanized and developed watershed and development within the floodplain and the size of the channel, thus limiting the floodplain space available to create a dynamically stable channel. Additionally, Highland Creek is a large channel. Due to these limitations, the design for Highland Creek had to be more engineered (i.e. 'harder'). Engineered channels are more expensive to build both in terms of construction material and the actual construction of the channel. For example, armourstone used for bank stabilization and erosion prevention is more expensive than the gravel used in riffle construction.

4.4.5 Legislation and NCD in Ontario

This section addresses the impact of legislation on the design process, as well as how the required consultation with permitting agencies impacts the design. Because final copies of Technical Design Briefs were the most commonly reviewed document, the impact of the consultation process, if any, was difficult to discern from design briefs alone. Practitioner interviews shed much light on the topic, see Section 5.5.5. Projects pertaining to Phase 1-3 of the East Branch of Fletchers Creek and the McLaughlin Road Tributary of Fletchers Creek indicated that the CVC (the local conservation authority) requested the inclusion of wetland features as these creeks represent headwater channels.

Based on the practitioner interviews, the permitting process should not impact the design of a project, however the consultation process, which occurs over the life of project, can impact the design. The degree of impact the consultation process has on the project depends on the reviewer and their level experience with these types of projects and their knowledge and comfort levels with the approaches typically used by practitioners. This indicated that the relationship between the permit applicant and the permitting official has an effect on the process. The consultation process aids in easing the approval process. Projects that have gone through the consultation process and involved the permitting agencies from the beginning of the project are able to obtain the necessary permits without significant design alteration because the permitting agencies understand what the design is trying to achieve and why the project was designed using those approaches and methods.

None of the case studies indicated that MNR approval was required under the ESA. This is a reflection of the fact that many of the projects contained within the inventory and selected as case studies were constructed prior to the implementation of the new ESA.

None of the projects, either in the inventory or selected as a case study explicitly used the MNR's nine-step ecosystem-based approach to NCD. This is not to say that an ecosystem-based approach was not used in any of the cases, just that the approach was not explicitly employed. Each of the nine steps in the Assess, Explore, Confirm, and Choose phases (Figure 2.4) is implicitly addressed in design process.

Section 2.4 discussed in detail the relevant pieces of legislation. The three Acts discussed in Section 2.4.1 are each administered by a different agency. The local CA administers the *Conservation Authorities Act*; the Ministry of the Environment (MOE) administers the *Environmental Assessment Act;* and the DFO administer the *Fisheries Act.* Additionally, if a species at risk is identified in the project reach the MNR becomes involved through the ESA. Environmental assessments, or environmental impact assessments were only available for two of the 49 projects reviewed for this study.

The complexity of the legislative jurisdiction governing the restoration process can lead to a complex, long, drawn-out approval process, although this is not often the case. Most projects go through the process with relative ease, with delays in implementation and construction, due to the fisheries windows, being the area where the approvals process has the greatest impact. The river restoration process in southern Ontario is dependent upon the approvals required by legislation in terms of implementation and project timing. However, the actual design process is not greatly impacted by policy or legislation, unless the ESA is triggered by the presence of a Species at Risk. Design is driven mainly by scientific analyses, (i.e. the training, knowledge of practitioners) and by design literature and principles, project objectives and constraints, practitioners experience, geomorphic setting, and consultation with the CA's, DFO and MNR, where appropriate.

4.4.6 Role of Conservation Authorities in channel design

Projects reviewed for this study were constructed between 2000 and 2010. Older project files typically had less, or incomplete, information regarding design methodology. This may have been the result of the project files coming from the TRCA, as even newer project files seemed incomplete and poorly organized. Case studies were evenly spread throughout the decade with 6 of the 14 projects selected as case studies being constructed prior to 2005.

The Rosgen design approach was uncommon in the inventoried projects, with only 6 of 49 project files indicating use of any part of the Rosgen approach. It is interesting to note that five of these projects were constructed in 2000 and the single case study that utilized the Rosgen approach was constructed in 2004 and was not designed by one of the three companies that specialized in channel design. This is very different from the restoration done in the US where a large number of projects are designed using the Rosgen approach with some states requiring that it be used, and agencies such as the USDA promoting the approach by including it in their design manuals. In discussions with TRCA staff, it was stated that the Rosgen approach was inappropriate for southern Ontario (Personal Communication, Ness, R. July 28, 2010). Many practitioners, at least those successful in winning projects, seem to agree with the TRCA, evidenced by the fact that few projects utilize the Rosgen approach. In fact, none of the projects reviewed for this inventory completed since 2006 used the Rosgen approach. However, practitioners do agree that Rosgen classification system can be useful as a communication tool with those who are unfamiliar with the science of channel design (Personal Communication, Aquafor Beech, April 13, 2011) Practitioner and informal consultation with CA staff indicated that those who deal with channel design on a regular basis do not consider the Rosgen approach to be applicable in the urbanized/urbanizing watershed context of southern Ontario. Rosgen has not found favour in southern Ontario because the practitioners typically hold advanced degrees in fluvial geomorphology and engineering. The Rosgen approach is perceived to best teach novices, who may or may not have any background geomorphology knowledge, how to do channel design in a series of short courses (Lave, 2009). As Ontario practitioners already posses this knowledge, the Rosgen short courses do not attract many attendees in Ontario. Rosgen-based designs are considered too restrictive and hard, specifically Rosgen instream structures and bank protection measures. Some practitioners use Rosgen-like instream structures, such as rock vortex weirs in their designs, often without directly referencing or acknowledging this. A softer approach is favoured (where constraints do not limit the introduction/continuation of dynamic stability of a channel) for NCD in Ontario.

In discussions with practitioners, it was indicated that design approach has evolved over the past decade. Designs draw upon the practitioners experience and education. In Ontario, practitioners are educated in fluvial geomorphology or engineering, typically holding advanced degrees. In Ontario, most practitioners with an engineering background work to understand where their knowledge gaps lie in terms of geomorphology in order to adequately address the geomorphology of the channel. All interviewed practitioners indicated that they continue their education by keeping up with the academic literature pertaining to various aspects of channel design. Practitioners pride themselves in providing scientifically based designs to their clients.

4.4.7 The use of geomorphic principles in NCD

Of the three geomorphic principles outlined in Chapter 2, cross-sectional and plan-form geometry were the most commonly included, with 35 of the 46 projects including some channel geometry. Design discharge was included in 32 of the 46 projects. None of the projects included an analysis or quantification of sediment continuity and sediment transport, although there were 26 projects that included some sort of grain sizing analysis which was usually included to aid in determining the stability of the design. Even if a project was designated as dynamically stable, elements of long-term stability were important in the design, hence the inclusion of sediment sizing. Some project files indicated that sediment conveyance was sought in the design, but a quantification or method for determining sediment conveyance was not included.

As discussed in Section 2.4, the geomorphic principles which, when incorporated into a channel design, aid in the development of a sustainable design of a dynamically stable channel are the inclusion and calculation of an appropriate design discharge, the use of cross-sectional and plan-form geometry parameters in determining channel dimensions and the inclusion of sediment transport and sediment continuity calculations to ensure the sediment received in the study reach can be transferred through the reach(es) over an appropriate timeframe. This section discusses the application of geomorphic principles in the selected case studies and how constraints may impact the application of these principles to a design.

4.4.7.1 Design Discharge

There is a heavy reliance on field data in the design of natural channels, particularly in the selection of the design discharge. Field identification of bankfull flow in the existing channel is often used in the selection or justification of the selection of design discharge. Field identification of bankfull discharge can present a challenge, particularly in degraded, incised channels and in poorly defined channels. Degraded, incised streams and watercourses with poorly defined channels are two situations under which river restoration is often undertaken. For this reason, expertise and experience is required when identifying bankfull discharge in the field. Identifying bankfull discharge in urban channels requires prior field experience and utilizes undercutting, bar height, changes in vegetation, long profiles of reference reaches (as available) – typically 20x the width of the study reach, bed profiles, bankfull profiles, cross sectional surveys, average depth, bankfull width and maximum depth. Based on my experience and through discussions with practitioners, there is typically a dedicated field team who has been trained and is experienced in the identification of bankfull flow. Field identification of bankfull flow was used, at least in part, to determine the design discharge in eight of the inventoried projects, including four case studies. Modelling was used in 26 projects, of which 14 projects utilized HEC-RAS or HEC-2, four others utilized different hydrological modelling, and 32 projects stated a design discharge.

The selection of design discharge seems to be unclear. In some cases, the existing channel dimensions (even when existing cross-sectional area was inadequate to convey the desired flow) were used as the template for the design.

Designs refer to bankfull discharge most often but may indicate that the channel capacity is not adequate to convey the bankfull flow. The definition of bankfull discharge is the capacity of the channel. Designs likely mean the 2-year flow and have assumed that the bankfull discharge is equivalent to the two-year discharge. When the 'bankfull discharge' cannot be conveyed within the channel than the bankfull discharge is not equivalent to the 2-year discharge. This is not unexpected due to the urbanizing nature of the watersheds. Modelling was used to determine the design discharge in 13 of the inventoried projects, including five of the case studies. The method for determining the design discharge was not specified in 17 of the inventoried projects and in five projects other methods were used to determine the design discharge or alternatively the client provided the design discharge. The determination of the design discharge explicitly takes incoming flow into consideration only when upstream development or upstream storm water management facilities are driving the project. Most channels in the study area are going through adjustment to changes in the flow regime as a result of urbanization.

Design discharge is typically defined from field observations of bankfull flow. In cases where the existing channel is undefined, or the dimensions are inappropriate for anticipated future conditions, the design discharge may be estimated from geomorphic relations. These may include area-discharge curves or pro-rating hydrographs from adjacent gauged tributaries (e.g. McLaughlin Road Tributary). Where modelling, such as HEC-RAS, is used, a discharge must be independently indicated within the model, (i.e. the model does not provide the discharge, or produce a discharge as an output). Modelling is likely undertaken to determine appropriate channel dimensions, based on field identified bankfull discharge. Data used in modelling, whether hydrodynamic or other, were not specified and model calibration was not discussed.

The appropriateness of using the bankfull discharge to determine the design discharge has been questioned in the literature (Shields Jr. *et al.,* 2003). The bankfull discharge is the outcome of the channel size relative to the prevailing flows and only a few inventoried projects explicitly looked at multiple return intervals for flows. In addition, the urbanizing nature of many watersheds may mean that the bankfull discharge is not equal to the 1.5-2 year flow, or the effective discharge, which is a commonly assumed relationship (Doyle *et al.,* 2007; Soar *et al.,* 2005). It is desirable to use the channel forming discharge (of which bankfull discharge, effective discharge and 1.5-2 year recurrence interval discharge are surrogates) as the design discharge. Given the difficulties in determining effective discharge, as previously mentioned bed-load transport rates are not monitored in Ontario, bankfull discharge is the most easily ascertained measure of channel-forming discharge. This, combined with the lack of gauging stations, and thus flow data for the smaller tributaries more likely to undergo restoration, explains why field-defined bankfull discharge is used as the design discharge, it is the easiest discharge to determine that correlates with or determines channel dimensions.

4.4.7.2 Cross-Sectional and Plan-form Geometry

Cross-sectional and plan-form geometry are the most commonly and extensively included geomorphic elements used in the design of natural channel projects. All fourteen of the case studies included calculations of at least some geometry parameters. More attention was paid to designing the appropriate channel cross-section dimensions than channel plan-form. Gradient was the most commonly considered parameter that impacted the plan-form layout of the channel, and was considered in seven of the fourteen case studies. The most commonly considered hydraulic parameters were depth (eleven projects) and width (six projects). Other commonly used cross-sectional parameters included cross-sectional area (nine projects), and width:depth ratio (three projects).

Few generalizations can be made regarding the geometry parameters used in the design of a channel and the type of channel or the project drivers. Additionally, there is limited information on how the parameters that are used are calculated, as there is generally more information on how design discharge is calculated, although even that is not especially clear. In discussions with practitioners, it was noted that the design discharge was used as the basis for determining stable or sustainable cross-sectional or plan-form parameters.

Specific equations/relationships used were not indicated in the reviewed design documents. It is assumed that, while equations would likely be derived from academic research literature or experience, the mix of equations used is proprietary. In other cases, it appears that the meander belt width drove the design of the other geometry parameters.

Small, low gradient, headwater streams within the study area have very low energy and as a result channel dynamics and sediment transport are not a significant concern. However, if upstream development continues, thus increasing runoff and potential flashiness of hydrographs (depending on the quality of upstream SWM facilities), the stream will have more energy and the correct designed dimension of the channel will be more important to the long-term sustainability of the design. The most important parameter in these types of low energy systems is the valley width, particularly where a channel has been created where one did not exist before. By ensuring the valley width is sufficient to allow for plan-form adjustment across the valley and ensuring that development is not permitted within the valley, the channel will be more sustainable in the long run, even if /when runoff increases.

Other parameters that were considered in the design of the channel, which did not necessarily directly relate to the physical shape of the designed channel, nonetheless impacted the design of the shape of the channel. These commonly included boundary shear stress, roughness (Manning's n), Froude number, velocity, stream power, unit stream power, and the maximum grain size entrained during bankfull flows. These parameters show that principles of hydraulic design are almost always an element of these channels and they help ensure the channel would be dynamically stable or stable, depending on the objectives of the project, by ensuring the flows, particularly bankfull flows, would not significantly impact the designed channel by causing major changes in channel shape and layout. Parameters, such as shear stress, are essentially hydraulic calculations. Various equations would have to be used to determine the values for these parameters. Parameters are used to ensure flow energy is minimized and erosion is inhibited, while allowing transport of the sediment delivered to the channel. These calculations form the basics of geomorphic engineering and hydraulic design. The methodology for determining these values varies and the details of the hydraulically, physically-based calculations are proprietary. Many of these parameters (e.g. Manning's equation for resistance) are standard engineering hydraulic calculations. Manning's flow resistance equation is widely used but the appropriate selection of the n value is an issue. A range of factors including bed material size and vegetation controls roughness. Due to the range of factors, a single roughness or resistance equation is inadequate (Charlton, 2008). This explains the use of multiple parameters to measure resistance and roughness.

4.4.7.3 Sediment Transport and Sediment Continuity

As previously stated, sediment continuity was not calculated in any of the designs reviewed. Sediment transport rates were not calculated. However consideration was given to grain size entrained during bankfull flows. In channels where dynamic stability was the design objective, calculations of the maximum grain size entrained during bankfull flows typically included the D_{50} or D_{84}. For other projects where a higher degree of stability is required (i.e. the channel is required to be stable to protect infrastructure, private property, or to prevent erosion), a 'factor of safety' is used to ensure that all sediment used in the design will not readily be entrained by the design discharge (typically the bankfull or 2-year recurrence interval discharge).

Sediment supply to the channel tends to decrease with increasing urbanization, indicating that most watercourses in urban areas are sediment starved. This may not be the case for larger incised rivers where valley side bluffs and riparian erosion are dominant. Urban streams often lack an upstream bed-load sediment supply. Bed-load sediment is important not only geomorphically but also for ecologic function. Having a moveable bed indicates that flows will be powerful enough to remove fines from riffles and 'turnover gravel' which may aid spawning for some species. In urbanized watersheds, more fines are available for sediment transport, particularly during the construction phase of new developments. Fines impact designs in that they fill the spaces in riffles, decreasing quality aquatic habitat. By ensuring that the design discharge will remove these fines, riffles and other aquatic habitat features are maintained over a longer period. Flushing flows, which remove fines, are determined in some designs by calculating the critical velocity for the D_{50} and D_{84} sediment sizes. Bank armouring decreases, or all together eliminates, bank sources of coarser sediments that could be used to replenish riffles or are significant bed material source. In channels where stability is paramount and bank armouring is just to decrease erosion and infrastructure risks, bed-load sediment that is moved downstream by larger flows (as most channels are designed to have the bed immobile up to the bankfull flow), will not be replaced because upstream sediment sources have been cut-off. This will impact both the geomorphic and ecologic function as well as the long-term management of the design reach.

Artificial wetlands are designed to act as sediment sinks and sediment sources during various flows. Wetlands can also improve groundwater recharge and habitat. Wetland features have become more common in designs throughout the last decade. They are included in headwater channels to replicate the hydrological function of swales. In these cases, the inclusion of wetland features in the design helps the channel retain some of its existing functions while providing for the increased runoff the channel is anticipated to have by adding off-channel storage of peak flows. These features are designed to function as swales, provide some water and sediment retention and detention functions. Some ponds are meant to be permanent standing water features (less-swale like) and others are designed to have wet-dry cycles.

4.5 Semi-structured interviews

A series of semi-structured interviews were conducted with practitioners from three different companies who specialize in fluvial geomorphology and geomorphic channel design (refer to Appendix F). Two of the three interviews were conducted with a group of practitioners. The purpose of these interviews was to gain a better understanding of the practice from the practitioner's point of view, add a narrative of the state of the practice that is not readily evident from the project analysis, and provide some insight into why certain design approaches are used, how constraints impact the design process and generally better understand how the design process is undertaken.

Three interviews were completed. The first interview took place April 13, 2011 at the Mississauga Aquafor Beech office with Mariette Pushkar, Roger Phillips and Robert Amos. The second interview took place May 16, 2011 at the Parish Geomorphic office in Mississauga with John Parish, principle of the company. And finally a formal interview was completed with Kevin Tabata at Geomorphic Solutions on May 16, 2011. Informal discussions were conducted with Paul Villard at Geomorphic Solutions at various points from approximately March 2010 to August 2011.

All of the interviewed practitioners hold an advanced degree in geomorphology, excluding Kevin Tabata and Robert Amos who hold advanced engineering degrees. Educational background influences design approach and what the practitioner might consider to be important to include in the design. There is a strong emphasis on continuing education from junior practitioners working towards their Professional Geoscientist designation, to keeping up with academic research via peer-reviewed journals. Whether or not new research is incorporated into the design process depends on its perceived applicability to the project location and setting, as well as the level of knowledge and expertise of the review agency(ies), as agencies may be reluctant to grant approvals for projects utilizing previously unknown methods, or design components. This indicates there is some built-in conservatism in the design process and that experience and relationships with permitting agencies have a greater impact on the design approach of new academic research. Either a professional geoscientist or a professional engineer signs off design drawings. There is currently a push within the private sector for new practitioners to become designated as professional geoscientists.

4.5.1 NCD and types of projects in southern Ontario

NCD, as previously discussed in Section 2.0, is inconsistently defined throughout the restoration community, from academics to practitioners to community groups. The industry in southern Ontario is no exception. Regardless of the definition of NCD, all interviewed practitioners agreed that natural channels should be, dynamically stable, and allow natural processes to occur, leading to the self development of natural form.

Restoration practitioners design and build a range of different types of projects including fully functional, or full NCD, mainly associated with development, lower order streams and ongoing urbanization, hybrid designs, stabilizations and erosion protection, to agricultural drain improvements and dam removals. In a full NCD, design constraints do not impact the function or layout of cross-sectional geometry of the channel. These designs are designed to allow sediment and flow conveyance balancing erosional and depositional force to create dynamic stability. This type of project is the goal where possible. Hybrid designs attempt to incorporate NCD principles and/or fluvial geomorphology principles while addressing the needs of erosion protection and infrastructure protection. These types of projects can occur anywhere in the watershed but tend to be most common in urbanized areas and areas where development has been allowed in the floodplain, thus decreasing the space the channel has for migration and minimizing the tolerance of local inhabitants for overbank flows. Designs whose primary aim is to stabilize or protect banks are generally very hard and tend to employ traditional engineering approaches. Throughout the last decade, this type of project has become less common as most projects try to incorporate at least some natural channel principles and include some bioengineering bank treatments, such as live staking or green gabions. Fully engineered channels (i.e. piped channels) are much less common, although the use of culverts is common at road crossings. Most stabilization projects could be considered hybrids. The inclusion of NCD principles, fully or partially is driven by the involvement of geomorphologists in the design process. It is now common for CAs to request the involvement of a geomorphologist (another way in which CAs influence the design process) before they will issue an approval/permit.

Each firm has developed their own spreadsheets for design work, containing relevant equations for plan-form and cross-sectional geometry parameters. Due to their proprietary nature, these spreadsheets were not shared during the interview. Different spreadsheets exist for hydraulic stone sizing and Regional Curves to aid in the design process. Practitioners rely on their own experience along with the scientific knowledge necessary to validate the design. Experience is important because, over time, practitioners learn what equations and approaches work best in the southern Ontario context.

All practitioners utilize multiple approaches and equations in their designs. These may include the use of flow modelling, geomorphic modelling, empirical approaches such as regime relationships, and analytical approaches. Approaches vary because projects occur under a range of conditions/settings, as southern Ontario is physiographically diverse. Regardless of approach, an iterative process is used in the design development. An iterative process helps decrease uncertainty associated with the design. Specifics of what is involved in an iterative process were not discussed.

4.5.2 Design constraints

The study area, is, in general, highly urbanized and developed particularly in lower reaches of many river systems, closer to Lake Ontario. This, combined with its glaciated history, creates a wide variety of physiographic settings. The combination of these two elements, along with the business/administrative side of the industry, implies that practitioners face a range of constraints when approaching a project. The variety of conditions mean no project is straight-forward, in that the same design approach and design elements cannot be applied in a 'cookbook' fashion blindly applying the same design approach and design elements in a variety of settings without adequately considering whether it is appropriate for the setting.

Constraints fall into two broad categories: physical setting and administrative. The physical setting of the channel impacts how the design is undertaken and the design options which practitioners can utilize. As reaches are not isolated components of the channel the elevation of the channel bed must match both the upstream and the downstream tie-ins (or inverts), in order to avoid creating issues such as degradation, aggradation, or just shifting the problems of the project reach either upstream or downstream. Urban channel corridors are utilized as infrastructure corridors and as such many projects are triggered by the need to protect public infrastructure (i.e. sanitary sewers and water mains). Project design is also impacted by the need to protect private property from erosion or flooding risk. In both the protection of public infrastructure and private property, channel designs are 'harder' and do not have the dynamic stability necessary to function naturally.

Recently there has been an increasing tendency for CAs to require the protection of existing riparian vegetation, specifically mature, native tress. Non-native species are typically removed unless mature. This may impact the design, particularly in meander belt orientation and placement. In terms of habitat, aquatic habitat takes precedence over terrestrial habitat and the protection of riparian vegetation. No terrestrial Species at Risk are part of the restoration dialogue. The only aquatic Species at Risk relevant to the restoration discussion, at this time, is Red Side Dace, which will be further discussed in Section 4.5.5.

The preservation of natural and cultural heritage features impacts the overall design process as well as the implementation process. Other physical setting constraints can include; geotechnical and hydrogeological conditions such as bank conditions, soil mechanics and surface-groundwater interactions; and rights of way. Geotechnical conditions have impact on the long-term sustainability of the channel. Bank conditions have the potential to significantly impact the design, depending on objectives and constraints. Where stability, erosion protection or infrastructure protection are important to a design, or where the valley width necessary to create an appropriately meandering watercourse to reduce flow energies does not exist, soil and bank conditions may necessitate the use of harder bank treatments or bioengineering. Rights of way are more likely to impact the alignment and plan-form layout of the channel.

There is a wide range of administrative constraints, which can alter the design of a project, and the length of time the project takes to complete. Administrative constraints impact all stages of the restoration process. Budgetary constraints may restrict the use of more expensive technologies such as two and three-dimensional modelling (in terms of time, data collection, and software). Municipally initiated projects may be part of a larger project and thus be required to be implemented on a piecemeal basis due to the incremental release of capital funding (Personal Communication, Aquafor Beech, 13 April 2011). This raises the question of how much restoration work is local, reach-scale fixes and to what extent the watershed context is considered.

In general, from consultants' perspective, the review process/structure operates well, in that the approval procedure is well established (excluding the relatively new MNR approvals required under the ESA, as the process is not in place yet, discussed in Section 5.4.5). However the review process through the CA depends on who the reviewer is. CAs tend to have high staff turnover and thus if the reviewer changes over the course of a project, it will impact the design as the new reviewer may want or not want elements the other reviewer had previously accepted/rejected. A change in reviewer may also impact how long the review process takes and thus the timing of the entire project. There is also a question regarding the level of education/expertise of the reviewer. With new review staff the designer/practitioner may end up doing some indirect training to get the new reviewer up to speed on how the design as been approached thus far and what the design is trying to achieve. This requires more time, money, and effort.

Project constraints alter the practitioners' ability to create a dynamically functional reach. Physical constraints alter layout and degree of armouring. Administrative constraints, including the approvals process, can alter the design and impact all stages of the restoration process from data collection to implementation.

4.5.3 Evolution of the practice

Interviewed practitioners have been working in the industry from three to more than 10 years. Practitioners who have been working in the industry longest noted the biggest changes to the design approaches utilized. A decade ago, 'restorations' were more structured and fairly 'hard'. This was the result of a lack of confidence from permitting agencies in the science behind the design (Personal Communication, Parish, May 16, 2011). Now the science has improved and managers are more comfortable working with the inherent uncertainty of the fluvial system, at least in some ways. In the past decade (approximately 2000-2010), designs have become more empirical (i.e. based on hydraulic and geomorphic principles) and scientifically based as the industry in Ontario (in general) has moved away from more traditionally engineering approaches and classification based systems (including the Rosgen approach), and with increased levels of experience and confidence amongst practitioners, designs are 'softer' and more natural. The Rosgen approach was never fully embraced in southern Ontario. While mentioned in the 1994 MNR NCD booklet (MNR, 1994), it was not mentioned in the 2002 booklet, which focused more on management approaches. The use of the Rosgen approach was not well supported by the CAs and practice in Ontario is professionalized as a result of practitioners holding advanced academic degrees in fluvial geomorphology.

Some of the learning, which has helped propel the practice into more natural and softer designs, has been the result of monitoring. Monitoring has led to an understanding of how design elements/approaches function over time and in response to varying environmental conditions. While all interviewed practitioners agreed that monitoring is important, this importance is not reflected in the design documents in the planning for future monitoring. Monitoring was planned for a maximum of three years after project completion, as required by the DFO, but monitoring does not extend beyond that. Some practitioners indicated they occasionally visit older project sites, particularly after large flow events (Personal Communication, Villard, March 12, 2011). However, it is unlikely that formal quantitative monitoring is undertaken due to the expense.

Project budgets do not allocate funds for monitoring beyond the three-year requirement. Funding for long-term monitoring is an issue that has been identified in Australia (Brooks and Lake, 2007) and through the NRRSS (Palmer *et al.,* 2007).

The practice of river restoration has also evolved in response to academic research. Academics are helping to develop tools and approaches based on existing knowledge. An example of this is the first USDA stream restoration manual (FISRWG, 1998), in which many of the design principles were based on existing research literature. More tools are available to utilize in the design process and more accurate assessments are possible.

Overall the current design approach is more holistic; encompassing watershed issues (from the reach context), water quality, and riparian conditions. Geomorphology is no longer an afterthought in the design process; it is now an important component of the design and approval process. Regulatory agencies recognize geomorphology's importance and therefore require, at minimum, the input of a geomorphologist in the design process (Personal Communication, Tabata, May 16, 2011).

4.5.4 Application of geomorphic principles

The application of geomorphic principles (sediment movement and continuity, design discharge and cross-sectional and plan-form geometry) varies from project to project (due to local physical constraints and administrative constraints). Sediment transport is important for the longevity and sustainability of the project. Most, but not all, interviewed practitioners indicated that, in general, bed-load sediment transport, specifically transport rates and continuity, are not included or not considered in enough detail, in the design process (Personal Communication, Aquafor Beech, 13 April 2011; Personal Communication, Parish, 16 May 2011). However, entrainment and stability are considered. Time and money are factors in this, as it is very difficult and time consuming to obtain, with a reasonable degree of accuracy, bed-load transport rates. In Ontario, provincial programs do not exist to effectively monitor and collect data on bed-load transport rates. However, inexpensive methods exist, including Bed-load Assessment for Gravel Bed streams (Pitlick *et al.,* 2009) and Wilcock's method (Wilcock, 2001). These methods were not discussed with practitioners so it is unknown why they are not utilized.

In urbanized and urbanizing watersheds, the sediment regime is a moving target that practitioners attempt to hit during the design process. Urban channels are supply limited, lacking upstream sediment source areas where the headwaters are fully urbanized. Where projects are full, dynamically stable NCD's, practitioners are able to plan for and include in the design, future sediment sources. Some practitioners indicated that it was more important to maintain velocities and shear stresses throughout the project reach than it was to account for sediment movement and continuity. Existing upstream and downstream conditions are reviewed to determine what the channel has moved and what it has the capacity to move. The review of existing conditions allows practitioners the insight to size the sediment in a way that is not unusual for the project reach.

The selected design discharge for NCDs is typically the bankfull discharge. All interviewed practitioners indicated that field identification was the most important tool used to identify the bankfull flow. In addition to field data, hydrologic and hydraulic modelling, rating curves, spatial relations, and reference reaches (as available) are used in the selection of the design discharge. The identification of bankfull discharge is an iterative process and utilizes all available and reasonable data. In some cases, the client may indicate what discharge is to be used in the design. This typically leads to a less geomorphically functional and harder channel.

Channel geometry parameters (cross-sectional and plan-form) vary based on the type of design and the project setting. If the project is a hybrid NCD or a more-engineered, harder design, practitioners may have to compromise regarding what parameters are included and how they're incorporated into the design. However, regardless of how the application of cross-sectional and plan-form geometry parameters may be constrained, practitioners must still determine what the ideal channel form would be in order to adequately compensate for the increases in energy caused by a less than ideal channel form (Personal Communications, Parish, 16 May 2011). In urbanized settings, infrastructure, private property and general development in the corridor may constrain the meander belt width. Initial meander geometry is a sin wave and is altered to provide a diversity of form. Artistic license, informed by experience and intuition regarding what will work, creates this diversity. In the end, the ultimate channel form is determined through an iterative process based on existing conditions, projected future conditions, and boundary conditions.

4.5.5 Permitting process

Obtaining the appropriate permits within a reasonable timeframe is an important component of both the design and implementation process. Some practitioners indicated that the permitting process shouldn't impact the design process, where others indicated that the level of impact depends on the reviewer and their level of experience and understanding of the practice. All practitioners agreed that it was important to have an open dialogue with the permitting agencies, specifically the local CA and it was vital to begin that dialogue early. By beginning the dialogue early, all red flags and confrontations are uncovered early and dealt with before they impact the completed design or the project timeline. CAs provide permits under the *CA Act*, and depending on the individual CA, the *Fisheries Act*. Each CA has a different level of agreement with the DFO and a different level of designation. This agreement between the CA and the DFO streamlines the permitting process, so practitioners do not have to approach multiple agencies to obtain the necessary permits.

More recently practitioners have had to apply for permits with the MNR under the ESA, specifically when Red Side Dace are present in the study area. Red Side Dace are a Species At Risk that prefers clear, cold water streams with gravel bottoms and a mixture of pool and riffle habitat (ROM, 2011). Red Side Dace is primarily threatened by habitat alteration and is sensitive to high levels of fines resulting from erosion. Due to the specific habitat requirements of the Red

Side Dace, their presence triggers the ESA, which is under the MNR's jurisdiction and will change the design by altering objectives to first and foremost provide for the protection and improvement of Red Side Dace habitat (Personal Communication, Parish, May 16, 2011). The MNR has only recently begun participating in the permitting process. Unlike HADDs, where CAs have some power to issue permits and Letters of Advice, thus streamlining the permitting process, the MNR provides their own approvals and the CAs and DFO will not issue their permits until the MNR issues theirs (Personal Communication, Aquafor Beech, 13 April 2011). Because the MNR is relatively new to the permitting process they do not have all of their procedures in place, which can slow down the entire permitting process (Personal Communication, Tabata, 2011).

The MOE may be involved in the permitting process as they issue permit to take water (PTTW) for dewatering and working in the dry. The process to obtain the PTTW can be a lengthy one. In addition, Transport Canada may be involved under the Navigable Waters Act, but only for larger watercourses, where restoration work is less common.

4.5.6 Semi-alluvial rivers and geomorphic function

While practitioners recognized that working in a previously glaciated landscape might impact their designs, some indicated that because nearly everything in southern Ontario is semi-alluvial, the equations and approaches utilized are adapted to this landscape. Other practitioners indicated that the semi-alluvial nature of streams is not really addressed, but this was more an issue of scale, in that issues arising from semi-alluvial rivers, particularly incision, are watershed scale issues and cannot be addressed on the reach scale.

Practitioners indicated that in order for a design to be geomorphically functional the channel must have floodplain access, water and sediment must be able to move through the system, and the channel should have the ability to migrate. Restoration projects are driven by ecologic or engineering objectives and geomorphology is the tool that brings them together (Personal

Communication, Aquafor Beech, 13 April 2011). In geomorphology, change and instability are normal elements of channel dynamics and erosion and deposition are expected. In urban areas, especially where development has been allowed to occur on the floodplain, change, instability, erosion, and deposition are undesirable. As discussed in Section 4.4.2, the physical setting of the project reach can impact the design. Geomorphologic function is typically not a main objective in these project locations. Improving the ecologic value of the reach is a common objective in restoration projects. Currently the science that links ecologic value and geomorphic function is not strong enough to propel geomorphic function to be a primary project objective. The use of science-based approaches is increasing and many practitioners pride themselves on utilizing scientific approaches. Practitioners work hard to find ways to incorporate geomorphological function into designs, regardless of the degree of engineering stability that must be incorporated into the design, which partly explains the rise in the number of 'hybrid' designs. The importance of geomorphology is now recognized and it is now expected that geomorphology will be involved in the design process.

4.5.7 Implementation

Implementation is a big challenge. Contractors are bound to implement what has been designed. All interviewed practitioners indicated that it is incredibly important that the construction/implementation of these designs be supervised and that experienced, in-house and properly trained inspectors/supervisors be on site regularly. Some practitioners indicated that there might be a substantial difference between the design drawing and what's actually in the ground. This may be due to the level of precision indicated in the design being impractical for construction machinery and methods. The length of time between design completion and implementation also impacts the degree to which the design drawings are followed. Because fluvial systems are constantly evolving, changes, for example in the downstream tie-in elevation, may require the design to be altered in field. Another important factor that can impact the implementation of the design is unforeseen physical setting issues, such as sand seams, springs, and the location of municipal infrastructure such as sewers (this is more an issue for amalgamated municipalities who's records of infrastructure locations may be poorly organized/incomplete due to amalgamations) (Personal Communication, Parish, 16 May 2011). There is a need for the design practitioners and construction supervisors to understand the design tolerances. Therefore, if a 'field fit' is required due to unforeseen circumstances the design can be altered without compromising the functionality of the design.

4.6 Conclusion

Slightly less then half of the inventoried projects were designated as a NCD. Projects reviewed as part of the inventory or as a case study employed a variety of approaches to the design process. In general, designs were approached scientifically, quantitatively and analytically using hydraulic, physically based equations. Practitioners employ proprietary models and equations in their designs therefore the details of the design process are unclear, including the identification and selection of design discharge. Where objectives were stated in design documents they were typically vague and did not provide any baseline data from which to measure any improvement over time. Practitioners face two main types of constraints in the design of these projects: physical setting constraints and administrative constraints. Both types of constraints can impact the design process and the final dimensions and layout of the channel.

The identification of design discharge relies primarily on the in-field identification of bankfull flow under existing conditions. Cross-sectional and plan-form geometry is less important in low energy, headwater environments and appropriate planning provides the channel with enough space to migrate across its floodplain without risks to private property or municipal infrastructure. In lower reaches where energy is sufficient to make cross-sectional and plan-form geometry an important aspect of the design, there is typically less room to manipulate geometries due to development in the floodplain and the use of channel corridors as infrastructure corridors. Sediment transport is not quantitatively considered in any of the reviewed designs, even though most practitioners recognize the importance of sediment transport to the sustainability of their designs.

Overall, Technical Design Briefs did not provide enough detailed information to gain an in-depth understand the design process, particularly in terms of the tools and equations used in determining the design discharge and cross sectional and plan-form layout. However, the semi-structured interviews carried out with three private-sector companies provided valuable insight into the state of the practice of river restoration in southern Ontario.

Chapter 5: Discussion

The practice of river restoration in southern Ontario is under represented in peer-reviewed academic literature. Over the past two decades, the practice of river restoration and NCD has evolved from a primarily engineering basis to one that includes consideration of geomorphic and ecologic function. Over the past two decades, river restoration has increasingly been used to address reach-scale issues such as erosion, infrastructure and property protection, and manage flow increases in response to urbanization. It is important to understand the current state of practice of river restoration and NCD in southern Ontario. This will allow the practice to continue to evolve in a way that best serves environmental needs, including geomorphic and ecologic functionality, and anthropogenic needs. Within the industry, knowledge sharing occurs at conferences (i.e. the International Conference on Natural Channels), but conference presentations tend to focus on individual projects and not general approaches appropriate for southern Ontario. An overview of the practice is needed to effectively drive the practice forward and encourage practitioners and academics to continue to work towards a better understanding of fluvial systems in the context of river restoration and natural channel design.

5.1 The design process: Approaches and methodologies

5.1.1 Objective definition

Design documents, specifically Technical Design Briefs, should provide a range of information typically including project objectives, constraints, existing conditions (at the reach-scale), design approach, and a monitoring plan. Not all design documents, however, contain this level of information. Project goals and objectives tend to be too general and fail to specifically consider individual project characteristics. For example, without adequately quantifying baseline conditions there is no way to ascertain whether objectives are compatible with the proposed design. Accordingly there is no basis for future monitoring to determine if objectives were achieved. Kondolf (1995) stressed the importance of setting specific objectives and collecting baseline data for the effective evaluation of project success. The Ministry of Natural Resources also stressed the importance of monitoring in their 1994 and 2002 Natural Stream System documents (Kondolf, 1995; Kondolf, 1998; MNR, 1994; MNR, 2002). Currently three years of monitoring is required by the DFO for projects that are subject to a HADD. Presently, monitoring is not being done beyond three years because there are no funds allocated to it and it is unclear who is responsible for the monitoring (i.e. is it the project proponent or the CA?). For long-term monitoring to take place in Ontario, funds must be allocated and there needs to be a requirement to do so from an agency such as CAs, DFO, MNR, or local municipality.

5.1.2 Project constraints

According to the literature, the key constraints to applying geomorphology in river restoration are: 1) legal framework, 2) professionalism – geomorphology cuts across the majority of traditional functions concerned with river management, 3) organizational risks, and 4) environmental risks (Newson *et al.*, 2001). There is limited mandated permitting in Ontario (Villard and Ness, 2006a), although provincial policy prohibits development in flood and erosion hazard lands (Villard, 2010). In the United States, the Clean Water Act drives restoration. Without such legislative drivers, restoration in Ontario will continue to occur on an *ad hoc* basis at the proponents' convenience. None of the individual pieces of legislation reviewed provides sufficient basis for river restoration in Ontario, nor do any require restoration in response to activity within the watershed.

Project constraints most commonly prevent the designed channels from being free to migrate within its floodplain. Channel migration may be undesirable due to development within the floodplain where channel migration results in property loss and endangers municipal infrastructure within the channel corridor. Therefore, designs are static, although aesthetically pleasing in form, and involve natural elements through bioengineering (e.g. green gabions). Lower energy headwater systems are designed with a defined channel and, in general, designed with a floodplain width sufficient to accommodate channel migration. However, due to the low energy of the system the created channel will likely remain stable unless there is a very high magnitude flow event, which statistically is unlikely to occur over the life span of the project. Lower energy headwater systems are a feature of many southern Ontario streams.

5.1.3 Semi-alluvial channels and NCD in southern Ontario

The glaciated history of the study area means that the parent material underlying many southern Ontario channels can consist of glacial till, alluvium or bedrock. Because channels in the study area do not solely flow across previously deposited alluvial sediment, but have some alluvial deposits, they are termed semi-alluvial channels. It is reasonable to assume that the semi-alluvial nature of the channels in the study area would impact the design, but in fact, there is a limited appreciation of the semi-alluvial nature of many channels within the study area, specifically the erosion of till (Villard and Ness, 2006b; Personal Communication, Aquafor Beech, 13 April 2010). The semi-alluvial nature of streams is not really addressed because of the disconnect between the scale of the projects and the scale of the problems. Currently incising, semi-alluvial streams are a watershed scale issue and cannot adequately be addressed or mitigated at the reach scale (Brookes and Sear, 1996; Personal Communication, Aquafor Beech, 13 April 2011). All of the watersheds in the study area have some form of a watershed plan developed by the local CA. However, the watershed plan was not mentioned in the reviewed design documents. During interviews, some practitioners indicated that because of their experience working in this landscape they understand what analyses work (Personal Communication, Parish, 16 May 2011) or their own databases and models are built around this type of channel (Personal Communication, Tabata, 16 May 2011). Because the proprietary models and databases were not reviewed, I cannot comment on whether or not they adequately consider the semi-alluvial nature of local watercourse. None of the projects reviewed for this study mentioned the semi-alluvial nature of the project's watercourse or indicated that this was a constraint or consideration in the design process.

5.1.4 Approaches

There are three general types of approaches to river restoration identified in the literature, 1) analogue, 2) empirical, and 3) analytical. All three approaches are utilized to varying degrees in southern Ontario and are often used in combination.

Analogues include using historical conditions and/or a reference reach to determine appropriate design dimensions. While an analysis of reach level historical conditions was undertaken for some of the inventoried projects, in no cases were historical channel dimensions actually determined and therefore were not used to guide the design of channel dimensions. The aerial photography record only extends back approximately to the 1950s in the study area, which, in general, is post-disturbance. Prior to the 1950s common land uses in headwater channels included farming, which may have altered drainage conditions. Therefore the photographs do not capture the undisturbed/ pre-colonized watershed. More importantly, the use of historical conditions to guide the design process is precluded because the water and sediment regimes have been significantly altered (as evidenced by channel responses such as incision and widening) from the regimes operating historically that it precludes the use of historical dimensions as a basis for channel design (Ness, 2001).

Reference reaches are commonly used to guide the design process. Reference reaches were chosen from either within the same watershed, where the reach was in an area that was experiencing little to no effect from the disturbance causing the issues in the study reach, or from a nearby watershed with similar conditions, that is also not experiencing any issues. One unusual example of reference reach use is in the study reach acting as its own reference reach. Throughout an extensive review of relevant academic background literature, the concept of a self-reference reach was never mentioned. At least two of the case studies used existing conditions to guide the selection of design dimensions. Using the existing channel as its own reference reach is not commonly practiced and not evidence of this approach appears in the literature. It seems inconsistent with the proposed project objectives and project drivers. If a channel cannot adequately convey the flow it receives, that flow is expected to increase or that the channel is currently unstable does not logically support the rationale behind using existing conditions as the reference reach.

Because the industry in Ontario is professionalized, practitioners have a more in depth knowledge of fluvial processes than most practitioners who utilize the Rosgen Approach (another example of an analogue approach), as they typically have only been educated in fluvial geomorphology through Rosgen's short courses, therefore Ontario practitioners can rely on better-supported science in their designs as opposed to relying on the limited knowledge the Rosgen Approach requires for the 'successful' application of this approach. Only a few of the inventoried projects utilized the Rosgen Approach, as it has never found favour in southern Ontario because CAs discourage the use of it, stating that it is not compatible with the semi-alluvial nature of streams in southern Ontario. In no other ways do CAs require NCDs to consider the unique settings of southern Ontario streams. Empirical approaches used include regime relationships and Annable relations (Annable, 1996a; Annable, 1996b).

Analytical approaches used include modelled and calculated belt width analysis, the use of reference data for cohesive channels, unspecified geomorphic and hydraulic analyses, numerical modelling and proprietary geomorphic design models. The proprietary geomorphic design models are assumed to be analytically based on analysis of physical processes and the results from these models as presented in the design documentation which include many resistance and hydraulic parameters such as shear stress and the selection of a Manning's n.

Other approaches to channel design include physically-based relations and field results. Field results were the most commonly used approach to guiding the selection of design dimensions, however it was never the sole approach used. Field data was crucial in informing the design process and occasionally provided the final design dimensions.

Methods exist in the literature that provides clear and detailed guidance on quantitative design principles and methods (Soar and Thorne, 2001; Biedenharn and Copeland, 2000; NRCS, 2007). These include bridging the gap between empirically-based and experience-based design methods and those requiring complex numerical modelling (Soar and Thorne, 2001), to providing explicit direction for the calculation of effective discharge (Biedenharn and Copeland, 2000), to providing regime equations and equations for the design of in-stream structures (NRCS, 2007). Many of the aforementioned methods require catchment scale data as well as data on sediment continuity and discharge and equilibrium sediment transfer throughout the system. The lack of available data on sediment continuity and discharge may explain why these methods do not appear to be utilized in southern Ontario. Manuals are produced by government agencies such as the USACE and the NRCS and the legislative drivers in the US may provide more funding and resources to undertake these sort of costly data collections. In Ontario, a consulting company (Parish Geomorphic) produced the only manual that provides specific details on a portion of the design process (*Belt Width Definition*, Parish Geomorphic, 2004). Additionally in the US, the United States Geologic Survey (USGS) monitors streams and provides flow data that can be downloaded from the USGS website as well as instantaneous fluvial sediment data. Unfortunately in Ontario, Water Service Canada, from whose website real time flow data can be obtained, does not have any extensive monitoring network within headwater channels/small streams. The USGS' stream gage network is more extensive then the monitoring that does occur in Ontario and currently there is no systematic collection of sediment data nationally or provincially. Without easily accessible data on fluvial sediment, and the extra fieldwork that would be required to obtain a dataset that would be similarly useful, the methods provided in these manuals are inaccessible to Ontario practitioners.

5.2 *Use of geomorphic principles in NCD*

5.2.1 Sediment transport and continuity

Despite the recognized importance of sediment transport and continuity to the long-term performance of a design, little attention is given to quantitatively incorporating sediment transport and continuity into the design. Provincial data sources for bed-load discharge do not exist, compounding the difficulties of incorporating sediment flow into the design. Although predictions are possible from 'theory', without a database from which to draw sediment flow data, practitioners would have to collect their own sediment transport data, which is difficult to do accurately, particularly over the short time span practitioners would have to collect background data before undertaking the design.

Sediment sizing is included in some of the designs, primarily to determine whether the selected bed materials will be stable at the design discharge. Including this type of calculation in the design is important, particularly where stability is a design objective (stability seems to be the primary concern for many projects) but it is not the same as sediment transport data. Knowing at which discharge bed-load transport is likely to occur is important but for the long-term sustainability of the design it is equally important to understand what upstream sources exist and to understand sediment transfer throughout the system to understand if sediment that is removed from the reach by a specific discharge will be replaced.

The inclusion of quantitative sediment transport data is an area of improvement for southern Ontario river restoration practitioners. In order for sediment transport to be included in designs, a monitoring network needs to be established and maintained by a body/agency independent of the consulting companies undertaking this type of work or an agreed upon set of predictive methods.

5.2.2 Design discharge

The NRRSS did not consider the selection of an appropriate design discharge during its evaluation of project effectiveness. The selection of design discharge for NCDs relies on field data and modelling. An experienced individual should do the identification of bankfull indicators, as identifying bankfull indicators in a degraded system may be difficult. The literature recommends (Biedenharn and Copeland, 2001) the use of the effective discharge as a surrogate for the channel forming discharge, as the effective discharge does the most geomorphic work over the long term. In areas where the effective discharge, the bankfull discharge and the 1.5-2 year discharge are approximately equivalent, the use of bankfull discharge would yield an appropriate design discharge. However, this relationship is not applicable in disturbed systems. Because of the evolving flow and sediment regimes in urbanizing southern Ontario (evolving in response to urbanization) systems are unstable and the bankfull discharge is unlikely to be equivalent to the effective discharge of the 1.5-2 year recurrence interval discharge. In the study area suburban and urban rivers are of primary concern.

That being said, because of the lack of available sediment data, calculating effective discharge is not possible without the extensive collection of sediment flow data or appropriate predictive relationships. A single design discharge is selected when there are other significant flows that occur more frequently than those with a recurrence interval of 2 years (assuming the bankfull discharge is approximately equal to the 2 year discharge). In southern Ontario flushing flows and mobilizing flows are important. These flows are unique to each channel as a result of the variability in local sediment conditions (Villard and Ness, n.d.).

The rationale for the method used to select the design discharge is not specified in many of the design documents. Field data from the existing channel, specifically the field-identified bankfull flow, is most often used to guide the determination of design discharge in conjunction with other methods, such as modelling. Hydraulic modelling, specifically HEC-RAS (the most commonly used type of modelling), requires the input of a discharge and does not independently produce a discharge, however, flow conveyance for a designed channel can be given. It was not explicitly indicated in design documents or in conversations with practitioners why the design discharge is most often the bankfull discharge.

It is likely because of the three surrogates of channel forming discharge (the ideal discharge to base a channel design on); bankfull discharge is the only one that can be determined with relative ease and minimal extra expense in southern Ontario. The sediment data required to determine the effective discharge does not exist for southern Ontario. Most natural channel design projects are constructed in small, ungauged headwater channels. Because flow data are unavailable, determining a flow with the desired return interval is not easily done. Hence, the continued reliance on bankfull flows. This is an identified area for improvement. In order of improvement to occur, better data need to be available, either from a high quality, long-term, extensive monitoring network, including gauges in headwater channels and gauges located in areas uninfluenced by infrastructure or the development of regional relations for southern Ontario urban rivers.

5.2.3 Cross-sectional geometry and plan-form layout

The basics of NCD include plan-form, longitudinal profile, cross-section, riffles and pools, cascades for grade control, bioengineering, and bank treatments (Villard, 2010). Design documents most often include cross-sectional parameters versus channel plan-form. Of the basics listed by Villard (2010), gradient was the most commonly considered parameter. This is what Hey (2006) calls 'slope first' design. If the gradient is designed so the upstream and downstream tie-in points match the constructed channel and the gradient is gradually decreased over the length of the design, energy dissipation will occur in a more predictable fashion and there are unlikely to be any unanticipated areas of high energy that may cause erosion or other stability issues.

Few generalizations can be made regarding the geometry parameters used in the design of a channel and the type of channel or the project drivers. Additionally, there is limited information on how the parameters that are used are calculated, as there is generally more information on how design discharge is calculated. In discussions with practitioners, it was noted that the design discharge was used as the basis for determining stable or sustainable hydraulic or plan-form parameters. In other cases, it appears that the meander belt width drove the design of the other geometry parameters.

Other parameters that were considered in the design of the channel, which did not necessarily directly relate to the physical shape of the designed channel, nonetheless impacted the design of the shape of the channel. These commonly included boundary shear stress, roughness (Manning's n), Froude number, velocity, stream power, unit stream power, and the maximum grain size entrained during bankfull flows. These parameters helped ensure the channel would be dynamically stable or stable, depending on the objectives of the project, by ensuring the flows, particularly bankfull flows, would not significantly impact the designed channel by causing major changes in channel shape and layout.

5.3 The State of the Practice of Stream Restoration in Southern Ontario

Urbanization is spreading rapidly in southern Ontario and is impacting the hydro-geomorphic condition of channels, headwater swales and wet meadows. Because of this, restoration and other channel works projects are increasing in prevalence, and this type of work is increasingly being used to manage the impacts of proposed and ongoing development.

In southern Ontario, the practice is professionalized, as most practitioners hold advanced degrees in fluvial geomorphology, and is based on the consulting business model. Geomorphic consulting is a private industry where companies bid and compete for projects. Because of the competitive nature of the bidding process, practitioners have 'design secrets' that, for practical reasons, they were not willing to share. The proprietary nature of the industry makes the evaluation of design methodologies difficult through the review of Technical Design Briefs and other accessible design documentation.

NCD and river restoration is changing the landscape of southern Ontario, particularly in headwater areas. Low energy headwater channels may have undefined, or intermittently defined channels. Where channels are undefined, swale morphology is common, as evidenced by descriptions of existing conditions within the reviewed design documentation. The wet meadow is designed to mimic the geomorphic function of a swale. Based on the inventory and case study analysis, the use of wet meadow or wetland features is prevalent in many designs, particularly those that occur in developing, headwater channels and may be a unique aspect of design regionally as this is not seen in headwater channels in the standard restoration literature.

Headwater areas are typically in areas slated for development or outside the current built-up area. This is a function of geography. Urbanization initially began at the shores of Lake Ontario and is now expanding northward and into headwater areas. As development increases in the upstream and adjacent watershed areas, run off increases. To accommodate the increase in run-off, defined channels are created and typically include wet meadows or wetlands alongside the channel. Because of the current lack of development in the upstream watershed, designs in headwater constructed channels are built with anticipated adequate floodplain space to accommodate channel migration. Wet meadows and wetland cells are used to aid in water and sediment retention and detention. So part of the practice of NCD in southern Ontario is creating defined channels where none have previously existed. Imagining a functional morphology that does not exist in nature creates, rather then restores, fluvial landscapes. This type of project may be unique to the study area and the low gradient headwaters that are currently undergoing development.

Constraints within headwater areas are typically minimal and allow for the creation of a more dynamic channel (i.e. a softer design). That being said, due to the low energy of the system it is unlikely that smaller magnitude, more frequent, flows would cause any significant alterations in morphology, over the management lifespan. One case study indicated that channel relocation was completed to accommodate 'more efficient community design'. Moving a watercourse to allow streets to be laid out in a manner developers find more convenient for road and servicing layout seems like a rather expensive (financially and environmentally) and extreme option. Despite pre-existing conditions being described as less than natural (i.e. the channel had previously been straightened, had a trough-shaped cross-section and lacked plan-form and longitudinal diversity) one has to wonder that if the channel had not impact the layout of the development, would have it been slated for 'improvement' at all.

In lower reaches, the energy of the system is greater. These higher energy systems are located in urbanized areas, where development has likely been allowed and corridors are used as municipal infrastructure (such as sewers and water mains) pathways. Because of the sensitivity of these corridors (in terms of human needs and services) these channels cannot be dynamically stable. They must be stable to prevent risks to public and private property. As a result, the work undertaken in these areas is more geomorphic engineering, aesthetically pleasing design than true geomorphic design.

5.3.1 Evolution of the practice

Despite the proprietary nature of the channel design industry, the practice of river restoration has evolved over the last two decades. Based on my conversations with practitioners, it was clear that they prided themselves on providing their clients with scientifically based designs and continued to keep up with the latest peer-reviewed academic research in order to utilize the newest tools, where appropriate and expectable to the permitting conservation authority. This evolution in practice, away from hard, stable designs, towards softer more geomorphically functional designs (where constraints and local setting does not preclude this type of design), has also occurred without long-term systematic post-project monitoring. Without long-term monitoring to support the evolution of design practices it is difficult to ascertain whether this evolution has been beneficial to the landscape of the study area or whether the practice is improving the function (geomorphic and ecologic – two common objectives) of designed reaches.

Learning within the community of river restoration practitioners is more of a reflective practice in southern Ontario rather than a formal one. However, despite the evolution of the practice in the absence of formal long-term monitoring practitioners don't really know what is working in any documentable way.

5.4 Evaluation of Methodology and Data Sources

The selected study area provided a wealth of projects from which to draw case studies. The variety of conditions within the study area provided an understanding of the different types of constraints that designs may be required to accommodate and the different types of designs, undertaken in response to the differing conditions across the study area.

The methodology, review of accessible design documents and semi-structured interviews with practitioners, was the best way to gain a broad understanding of the industry and the state of the practice in southern Ontario. By obtaining data from multiple agencies/companies and by selecting case studies designed by a number of different companies, bias was avoided and an understanding of the practice across different designers was achieved. The review of Technical Design Briefs/available design documentation was the most practical way to review a large number of projects. Additionally, it was perhaps the only way to gather information on the design process, as any fieldwork would focus on implementation and performance over the life of the design. While this is valuable information, the goal of this project was to understand the design process and how geomorphology was incorporated into the design (refer to Section 5.2).

While Technical Design Briefs were the best available document through which to gain an understanding of the design process, these design documents only tell part of the story. Through a review of the available design documentation, I was able to understand *what* is being done in terms of design, but not *how*. The how, or the specific design methodologies and equations used are proprietary information and were therefore not available for review. The semi-structured interview component of this project's design methodology was integral to gaining a more in-depth understanding of the state of the practice in southern Ontario and the underlying attitudes of the practitioners, which aid in understanding why designs are approached in certain ways. Additionally, interviews were also used in the NRRSS study design. Their interview data indicated that public opinion was a stronger indicator of project success than geomorphic or ecologic performance and that quantitative post-project monitoring did not occur in a manner that could indicated the achievement or non-achievement of design objectives (Hasset, 2006).

Overall, the design methodology allowed for the broad understanding of the practice of river restoration and NCD even without access to the spreadsheets and equations practitioners utilize in the design process. Kondolf (1995) also stressed the importance of systematic post-project appraisals, stating that the field cannot advance without it. This, however, does not ring entirely true for southern Ontario where the field has evolved over the past two decades despite the lack of long-term systematic monitoring.

5.5 Comparing southern Ontario with NRRSS results

The NRRSS in the US summarizes basic project information, such as cost and length. At the outset of this project, it was hoped that an understanding of how much is actually spent on river restoration in southern Ontario could be determined. However, the reviewed design documents lacked some of the basic information, including length in some cases, which would have been helpful in establishing some basics for southern Ontario. Projects in Ontario, as those reviewed through the NRRSS were implemented for a variety of reasons and utilized multiple approaches (Palmer *et al.*, 2007). Long-term monitoring was an issue for both the NRRSS and project reviewed for this study. Understanding the current state of the practice will drive the practice forward. For whatever reason, practitioners typically do not publish in academically reviewed journals. What is published typically exists in 'grey' literature, which can be difficult to access for both the public and other practitioners, which further complicates the ability for practitioners to learn from one another. Palmer *et al.*, (2007) stated that this lack of incentive and requirement for collection and disseminating information on project outcomes weakened the business of restoration. In Ontario, despite the lack of published material and the lack of long-term quantitative monitoring, the practice has evolved to be more holistic. That is not to say that the practice in Ontario could not benefit from published data and information sharing between practitioners. Channel works projects reviewed for this thesis were termed realignment, restoration, natural channel design, alteration, enhancement, valley design, naturalization, or simply channel design (refer to Appendix D), whereas in the US the term 'restoration' is applied to projects that are clearly not restorations (e.g. infrastructure protection projects) (Palmer *et al.*, 2007).

The NRRSS reviewed a large number of project files and this thesis aimed to review a large number of projects, albeit on a smaller geographic scale. Written project records were difficult to obtain and file loss was a significant issue for the NRRSS. In Ontario, file management is a significant issue, especially at CAs. When attempting to access files at CAs, staff had a difficult time providing the complete file, including all design documents. As the CA is also the permitting authority for both permits under the *CA Act* and under the *Fisheries Act* (at least of the TRCA), it is important to maintain a well-organized, accessible filing system of completed and ongoing stream restoration projects. Additionally of the three companies specializing in channel design that I visited through the course of my research, only one appeared to have a well-organized, easily understandable filing system, where accessing desired project files was easy.

Findings from the NRRSS stated that in order for design of river restoration projects to improve, existing or improved restoration design manuals and certification programs are necessary. Lave (2009) echoes the need for a national certification program in the US. In Ontario, practitioners hold advanced degrees in geomorphology and senior practitioners are experienced. There is also an increasing tendency to use interdisciplinary teams and practitioners are increasingly becoming designated as professional geoscientists. Practitioners new to the industry are not required to have their designation. However, they are expected to work towards it within the first few years of employment. In the US, the restoration process is legislatively driven, which is not the case for Ontario. It has been suggested that the permitting process in the US should include the requirement of the proponent to justify the design and methods in the context of specific watershed, land use and the hydrogeomorphic setting of the river (Palmer *et al.,* 2007). For Ontario, this type of approach may be beneficial, particularly in the consideration of semi-alluvial conditions. Overall, this study has highlighted some differences as well as some similarities with the state of the practice in the US, but it has provided a better understanding of the actual design processes and methodologies utilized in Ontario.

5.6 Recommendations for future work

The next logical step for this study would be to determine how the different designs fare once they are put in the ground. Follow up monitoring studies, focusing on long-term functionality, would help assist practitioners in understanding whether their design methodologies and approaches are effective. An additional component to determining the long-term effectiveness of different design approaches and methodologies would be to understand how design drawings are actually manifested in the real world. Design implementation can be a very significant issue and understanding how designs are constructed and understanding what barriers the construction team faces when attempting to implement designs. If practitioners and contractors and the construction team agree on methods and tools that work for the function of the channel as well as for the implementation of the design, the long-term function of these constructed channels may improve. The implementation of these types of projects, and the success of the implementation was not an element of river restoration projects that was reviewed by the NRRSS.

The purpose of this thesis was to understand how NCD is undertaken within the southern Ontario context with regards to the application of geomorphic principles (design discharge, hydraulic and plan-form geometry, and sediment transport and continuity) in the design process. This thesis does not address the implementation of these designs or the long-term functionality of these designs in the real world. One avenue for future research would be to understand how these designs are implemented and how contractors approach the process.

Contractors do not have the advanced education in fluvial geomorphology that most practitioners possess, thus understanding how they see the designs, how they implement the designs, and what constraints they work with that the practitioners may not have been aware of in the design process. A second avenue for future research would be an investigation of how the case studies have fared since implementation. Monitoring records could be accessed to gain an understanding of short-term adjustment, as monitoring activities are typically only undertaken for a three-year period post-construction, and field investigations could be undertaken to understand how designs have adjusted in the longer term, in relation to the as-built drawings.

Chapter 6: Conclusion

The inventory and analysis of selected case studies illustrate the range in types of projects undertaken in the study area and show how the process of NCD and river restoration is impacted by design objectives, project constraints, the semi-alluvial nature of streams and how the design of these types of projects is approached, as well as the influence of local/regional conditions on types of projects and overall approaches in the study area. In general, projects in the study area are associated with either headwater channel creation/enhancement or addressing the impacts of urbanization, such as erosion or infrastructure protection. Only projects undertaken in areas with available floodplain space can be considered true geomorphic design. However, typically only projects undertaken in headwaters have the available floodplain space, but these areas lack the energy necessary to do geomorphic work. NCD and river restoration is not greatly impacted by legislation or policy and is not driven by legislative requirements, overall design 'policy', or design manuals and requirements. Design constraints primarily impact the plan-form layout of the channel and the level of data collection that occurs prior to undertaking the design. Design objectives, which in theory are in place to guide the design, are often vague and lack quantitative baseline data from which to measure improvement or change in geomorphic or ecological conditions, depending on the type of objective. Streams in southern Ontario are generally semi-alluvial in nature and can be underlain by alluvium, glacial till, bedrock, or any combination of the above. Despite this impacting the nature of the function of the stream, the semi-alluvial nature of watercourses is not explicitly considered in the design process or approach. A lack of research into how semi-alluvial channels function impacts the ability of practitioners to take this unique feature of the study area into account during the design process. The extensive experience of practitioners in the study area has led to the development of methods for dealing with it, or at least a general understanding of what design approaches/methodologies might work under semi-alluvial conditions.

One goal of this study was to determine how geomorphic principles, sediment transport and continuity, cross-sectional and plan-form geometry, and design discharge, are incorporated into the design. Sediment transport and continuity through the system is not considered in any of the projects reviewed, although competence calculations are common. Ontario lacks a long-term, extensive water (especially in small urban watersheds) and sediment monitoring network. Without basic sediment load data, practitioners would be required to conduct their own sediment studies, which are generally beyond the scope of the project's timeline and budget. Gradient is the key parameter considered in the design.

In the projects reviewed, the design discharge, a major source of debate in the channel design literature, is usually a single value selected based on the identification of bankfull indicators in the existing channel (or nearby natural reach) in combination with modelling results usually applied to estimate designed channel capacity. The design discharge is equivalent to the bankfull discharge as the data required to determine the effective or 1.5-2 year recurrence interval discharge is not readily accessible for many sites in Ontario and there is no regional area-discharge curve for urbanized rivers (Ferencevic, 2008). Ontario's lack of monitoring network greatly impacts the extent to which geomorphic principles can be included in the design. If this type of data were available, practitioners would utilize it.

Who practices and their educational and experiential background significantly influence the state of the practice of natural channel design and river restoration in Ontario. Ontario practitioners hold advanced degrees in fluvial geomorphology and current senior practitioners who were interviewed have anywhere from three to more than ten years of experience. Practitioners pride themselves on providing their clients with scientifically based designs and maintain a current knowledge base of the applicable research in the academic field of fluvial geomorphology. Improvements that could be made to the practice of river restoration, including considering catchment scale issues, sediment transport, and utilizing different measures of channel forming discharge in the selection of the design discharge are not improvements that individual practitioners or companies could successfully strive for without the assistance of government agencies or research. Channel designs will significantly improve when practitioners have better databases from which to draw flow and sediment data on individual reaches and watersheds. This requires a significant investment from the government in an extensive monitoring network or research into establishing inexpensive methods or regional estimates of some of these issues.

In Ontario, the practice of stream restoration is professionalized and because of the physiographic diversity of the landscape, utilizes a variety of approaches and methods to design channels. Despite the proprietary nature of the industry, the practice has evolved over the last two decades and is now more holistic and attempts, where possible, to incorporate geomorphic function into the design.

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Appendix A: Inventory Dat

ID	Project Name	Data From	Dlanform parameters Con design	Included Sediment continuity/ transportation calculations	Included Grain Sizing	Monitoring Plan Included	Project Costing Included	Project Proponent/ Document Prepared For:
1	Berczy Village Burdenet Creek Channel Lowering	TRCA	w; avg bf d; terrace Cosburembankment slopes; Meander amplitude; radius	No	No	No	No	Burndenet Creek Landowners
2	Birkdale Ravine - Bank Restoration and Channel Stabilization for Bendale Branch of West Highland Creek at Ellesmere Road	GS	Geo So	No	No	Yes	No	City of Toronto
3	Black Creek Tributary Realignment	TRCA	's n; BF w; BF d; SNCwetted perimeter; Engirerpool gradient; riffle Cons; max pool depth; critical slope; Froude ber	No	Yes	No	No	York University
4	Block 32 (West) Don River Tributary Channel Realignment	TRCA	r radius; amplitude; Ce; stream gradient y; riffle velocity; pool width	No	Yes	No	No	TRCA
5	Carruthers Creek north of Bayly	TRCA	Phe size; pool widths; Geoy; stream gradient	No	Yes	No	No	Durham Region
6	Carruthers Creek Realignment and Design	TRCA	P Geolth	No	No	No	No	Runnymede Development Corporation
7	Curcio Property	TRCA	uosity; mean slope; f curvature; valley ; *width; width:depth* atio; cross-sectional ; Manning's n; mean ull discharge	No	No	No	No	Property Owners (The Curcios)
8	Duffins Creek Flood Protection Dyke Erosion Risk, Level of Service Assessment and Maintenance and Improvement Study	TRCA	Geo So	No	No	No	No	TRCA
9	East Branch of Fletchers Creek Headwater Stream Realignment and Enhancement (Phase I)	CVC	Ph; width:depth ratio; Geoth; stream power; tress; D50, D84	No	Yes	Yes	No	Gold Park Rowntree Developers Inc and Desuri Homes Ltd
10	East Branch of Fletchers Creek Headwater Stream *Realignment and Enhancement (Phase II)*	CVC	meander belt width; ; max depth; mean Ptio; velocity; stream Geo *substrate; valley* ; sinuosity ratio; belt s of curvature	No	Yes	No	No	Rosebay Estates Inc and Senwood Developments Inc
11	Erosion Protection for Silver Creek at Edenbridge Drive	GS	Geo Sol	No	No	Yes	No	City of Toronto
12	Etobicoke Creek - Courtney Park Drive	Parish	Pe; erosion potential; Geoream power; width; elocity	No	Yes	No	No	Not specified
13	Etobicoke Creek West Branch, Tributary 3	GS	h ratio; riffle-pool Geoidth; cross-sectional Solg velocity; Froude inuosity	No	Yes	Yes	No	City of Mississauga
14	Fletchers Creek, Phase 2: McLaughlin Road Tributary Channel Design	CVC	Aquar width; valley side es	No	Yes	No	No	Brampton 6-2 *Limited (c/o The* Kerbel Group Ltd)
15	Fletchers Creek, Phase 3: McLaughlin Road Tributary	Aquafor	Aquad design; side slope; corridor width	No				
16	Gore Road Tributary NCD at Pannahill Dr and Cottrelle Blvd	Aquafor	avg depth; area; Aquahear stress; Froude ; D50	No	Yes	Yes	No	Land Owner Group, Bram East Area 'G'
17	Highland Creek Rehabilitation Study	TRCA	Cur Coc	No	No	No	Yes	Not specified
18	Holy Trinity School	TRCA	ESG Intun-pool sequence	No	Yes	Yes	No	Not specified
19	Huttonville Creek, Springbrook West Tributary and Credit River Tributary	CVC	Aquangth; shear stress; itical threshold	No	No	No	No	Schaeffer and Associates
20	Little Etobicoke Creek	TRCA	M radius of curvature; avg meander length	No	Yes	No	No	City of Mississauga
21	Markham Centre	Parish	Pankfull depth; max Geoll width:depth ratio; gradient; sinuosity	No	Yes	Yes	No	Masongsong Associates Engineering Ltd

Appendix A: Inventory Database

ID	Project Name	Data From	Design Company	Watershed	Type of Project	Case Study	Length (m)	Designated as a NCD?	Technical Design Brief Reviewed	Design Drawings Reviewed	Other Documents Reviewed	Objectives / Purpose Stated	Constraints Stated	Approach to Design	Channel and Local Catchment History Included	Design Q Stated	Modelling Used?	Type of Modelling	Included Cross-Sectional & Planform Geometry Parameters	Cross-sectional and Planform parameters included in design	Included Sediment continuity/ transportation calculations	Included Grain Sizing	Monitoring Plan Included	Project Costing Included	Project Proponent/ Document Prepared For:
1	Berczy Village Burdenet Creek Channel Lowering	TRCA	Cosburn Patterson Mather	Rouge	SWM	NO	800	No	Yes	No	-	No	No	Rosgen natural channel design; Leopold and Wolman equations for channel geometry	No	Yes	Yes	QUALHYMO , HEC-2	Yes	average slope; avg bf w; avg bf d; terrace width; terrace slopes; embankment slopes; meander length; meander amplitude; meander radius	No	No	No	No	Burndenet Creek Landowners
2	Birkdale Ravine - Bank Restoration and Channel Stabilization for Bendale Branch of West Highland Creek at Ellesmere Road	GS	Geomorphic Solutions	Highland	Erosion/ Stabilization	NO		Draws on principles of fluvial geomorphology	Yes	Yes	-	Yes	Yes	Geomorphological and hydraulic analyses and results from field investigations; worst case scenario	Yes	Yes	Yes	HEC-RAS v. 3.1.2	Yes		No	No	Yes	No	City of Toronto
3	Black Creek Tributary Realignment	TRCA	SNC-Lavalin Engineers and Constructors	Humber	SWM	NO	150	No	No	No	Hoover Creek Fish Habitat Compensation Plan	No	No	No details provided	Yes	Yes	No	-	Yes	Avg slope; Manning's n; BF w; BF d; width:depth ratio; wetted perimeter; entrenchment ratio; interpool gradient; riffle gradient; riffle grade; max pool depth; velocity; critical depth; critical slope; Froude number	No	Yes	No	No	York University
4	Block 32 (West) Don River Tributary Channel Realignment	TRCA	Dillon	Don	Development	NO		No	No	No	OPA 400-Block 32 (West) and Vaughan Centre Fisheries Compensation Plan Overview	No	No	Rosgen	No	Yes	No	-	Yes	width; depth; meander radius; amplitude; upstream valley slope; stream gradient averages; sinuosity; riffle velocity; bandwidth; pool width	No	Yes	No	No	TRCA
5	Carruthers Creek north of Bayly	TRCA	Parish Geomorphic	Duffins & Carruthers	Bridge construction	NO	201	No	No	No	Permit No. C-01122 Inspection Report; Letters to TRCA from Durham Region (); Letter of Intent to Conduct works affecting fish habitat; Letter to TRCA from Dillon	Not explicit	No	HEC-2 for bridge and bridge works	No	Yes	Yes	Regional HEC-2	Yes	Riffle length; riffle stone size; pool widths; pool depth; sinuosity; stream gradient	No	Yes	No	No	Durham Region
6	Carruthers Creek Realignment and Design	TRCA	Parish Geomorphic	Duffins & Carruthers	Bridge construction	NO	204	No	No	No	Application to alter waterway, construct in a floodplain, place fill within a regulated area; Carruthers Creek Realignment and Design Addendum;	Not in available documentation	No	No details provided	No	Yes	No	-	Yes	Length	No	No	No	No	Runnymede Development Corporation
7	Curcio Property	TRCA				NO	26.4	No	No	No	Ontario Regulation 158, Permit No. C-98172; Letter to TRCA from Harrington & Hoyle (2); Harrington & Hoyle Report; Review of Earth Filled Dam and Pond; Letter to Property owners from TRCA; Fisheries Information	Yes	No	Rosgen	No	Yes	No	-	Yes	Length; belt width; sinuosity; mean slope; wavelength; radius of curvature; valley slope; max d; mean d; width; width:depth ratio; meander width ratio; cross-sectional area; wetted perimeter; Manning's n; mean velocity; bankfull discharge	No	No	No	No	Property Owners (The Curcios)
8	Duffins Creek Flood Protection Dyke Erosion Risk, Level of Service Assessment and Maintenance and Improvement Study	TRCA	Geomorphic Solutions	Duffins & Carruthers	Erosion	NO		No	Yes	No	-	Yes	No		No	No	unknown	-	No	-	No	No	No	No	TRCA
9	East Branch of Fletchers Creek Headwater Stream Realignment and Enhancement (Phase I)	CVC	Parish Geomorphic	Credit	Development	YES	475	Yes	Yes	No	Design Brief; Letter of Intent to implement compensation, mitigation and monitoring measure for the HADD of fish habitat	Yes	No	Reference reach; regime relationships; HEC-2; project prepared using multi-disciplinary team (engineers, landscape architects, biologist and stream geomorphologists)	No	Yes	Yes	HEC-2	Yes	Max depth; mean depth; width:depth ratio; velocity; critical depth; stream power; calculated shear stress; D50, D84	No	Yes	Yes	No	Gold Park Rowntree Developers Inc and Desuri Homes Ltd
10	East Branch of Fletchers Creek Headwater Stream Realignment and Enhancement (Phase II)	CVC	Parish Geomorphic	Credit	Development	NO	935	Yes	Yes	No	Stream Realignment Design Report	No	No	Regime relationships for pool and riffle lengths, inter-pool and inter-riffle lengths; meander belt width analysis; reference relationships for stable channels used to determine riffle gradients	No	Yes	Yes	HEC-2	Yes	Floodplain area; grade; meander belt width; pool-riffle sequencing; max depth; mean depth; width:depth ratio; velocity; stream power; shear stress; substrate; valley length; valley gradient; sinuosity ratio; belt width; avg radius of curvature	No	Yes	No	No	Rosebay Estates Inc and Senwood Developments Inc
11	Erosion Protection for Silver Creek at Edenbridge Drive	GS	Geomorphic Solutions	Humber	Erosion	NO	190	Hybrid - engineered armouring and natural channel design principles	Yes	Yes	-	Yes	Yes	HEC-RAS and hydrologic modelling; pools and cascading riffle features; create low flow channel within larger channel	Yes	No	No	-	No	-	No	No	Yes	No	City of Toronto
12	Etobicoke Creek - Courtney Park Drive	Parish	Parish Geomorphic	Etobicoke	Bridge construction	NO	200	No	No	Yes	Letter to AGRA Earth and Environmental, Re: Fluvial Geomorphology Component	Yes	No	No details provided	Yes	Yes	No	-	Yes	Boundary tractive force; erosion potential; stream power; unit stream power; width; depth; velocity	No	Yes	No	No	Not specified
13	Etobicoke Creek West Branch, Tributary 3	GS	Geomorphic Solutions	Etobicoke	SWM/ Stabilization	YES		Yes	Yes	Yes	-	Yes	Yes	soft', discharge provided by upstream SWM facility	Yes	Yes	Yes	by Skira and Associates	Yes	Avg bf d; width:depth ratio; riffle-pool sequences; gradient; width; cross-sectional area; Manning's n; avg velocity; Froude number; sinuosity	No	Yes	Yes	No	City of Mississauga
14	Fletchers Creek, Phase 2: McLaughlin Road Tributary Channel Design	CVC	Aquafor Beech	Credit	Development	YES	600	Yes - principles of fluvial geomorphology and flow hydraulics	Yes	Yes	-	Yes	Yes	Empirical relations; modelling; iterative	No	Yes	Yes	Not specified	Yes	Meander belt; corridor width; valley side slopes	No	Yes	No	No	Brampton 6-2 Limited (c/o The Kerbel Group Ltd)
15	Fletchers Creek, Phase 3: McLaughlin Road Tributary	Aquafor	Aquafor Beech	Credit	Development	NO	850	Yes - principles of fluvial geomorphology and flow hydraulics	Yes	Yes	-	No	Yes	Empirical relations; modelling; iterative	Yes	Yes	Yes	Not specified	Yes	Length; grade; wetland design; side slope; meander belt and corridor width	No				
16	Gore Road Tributary NCD at Pannahill Dr and Cottrelle Blvd	Aquafor	Aquafor Beech	Don	Crossings	YES		Yes, also guided by principles of fluvial geomorphology	Yes	Yes	-	No	Yes	Modelled 2-yr flow, field observations	Yes	Yes	Yes	Not specified	Yes	Width; max depth; avg depth; area; velocity; flow; max shear stress; Froude Number; D50	No	Yes	Yes	No	Land Owner Group, Bram East Area 'G'
17	Highland Creek Rehabilitation Study	TRCA	Cumming Cockburn	Highland	Long term Stability	NO	2000	Yes	No	No	Highland Creek Rehabilitation Study, Markham Branch	Yes	Yes	TASE modelling	Yes	No	Yes	TASE hydrodynamic model	No	-	No	No	No	Yes	Not specified
18	Holy Trinity School	TRCA	ESG International	Rouge	Building and parking lot expansion	NO	103m	No	No	No	Ontario Regulation 158, Permit No. C-01185, Inspection Report; Letter from MNR to ESG International Inc; HADD Authorization	Yes	No	TASE hydrodynamic modelling	No	No	No	-	Yes	Length; width; riffle-run-pool sequence	No	Yes	Yes	No	Not specified
19	Huttonville Creek, Springbrook West Tributary and Credit River Tributary	CVC	Aquafor Beech	Credit	?	NO	2410	Yes - principles of fluvial geomorphology and flow hydraulics	No	No	Fluvial Geomorphology Assessment	No	No	Iterative	No	Yes	No	-	Yes	Meander belt width; length; shear stress; mean velocity; critical threshold	No	No	No	No	Schaeffer and Associates
20	Little Etobicoke Creek	TRCA	MMM	Etobicoke	Erosion/ infrastructure	NO	1800	No	No	No	Letter to TRCA from City of Mississauga (2); Report on Rehabilitation of Little Etobicoke Creek Hydraulic Analysis; Environmental Study Report for the Proposed Flood and Erosion Control Program for Little Etobicoke Creek from Burnhamthorpe Road to South of Bloor Street; Letter to MNR from City of Mississauga	Yes	Yes	Previously developed design flows; engineering for stability, Leopold and Wolman equations for meander length, Rosgen design for vortex weirs; HEC-2 modelling for 1.5 and 2 yr flows	No	Yes	Yes	HEC-2	Yes	Avg meander amplitude; radius of curvature; velocity; length; slope; avg meander length	No	Yes	No	No	City of Mississauga
21	Markham Centre	Parish	Parish Geomorphic	Rouge	Bridge construction	NO	4062	No	Yes	Yes	Belt width Assessment; Letter to Masongsong Associated Engineering	Yes	Yes	No details provided	Yes	Yes	Yes	Completed by Masongsong Associates Engineering	Yes	bankfull width; avg bankfull depth; max bankfull depth; bankfull width:depth ratio; bankfull gradient; riffle gradient; sinuosity	No	Yes	Yes	No	Masongsong Associates Engineering Ltd

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ID	Project Name	Data From	Design Company	Watershed	Type of Project	Case Study	Length (m)	Designated as a NCD?	Technical Design Brief Reviewed	Design Drawings Reviewed	Other Documents Reviewed	Objectives / Purpose Stated	Constraints Stated	Approach to Design	Channel and Local Catchment History Included	Design Q Stated	Modelling Used?	Type of Modelling	Included Cross-Sectional & Planform Geometry Parameters	Cross-sectional and Planform parameters included in design	Included Sediment continuity/ transportation calculations	Included Grain Sizing	Monitoring Plan Included	Project Costing Included	Project Proponent/ Document Prepared For:
22	Miller Creek Realignment and Natural Channel Design	TRCA	Parish Geomorphic	Carruthers	Development	YES	1400	Yes	Yes	No	Miller Creek Realignment and Natural Channel Design Brief; Detailed Design Components: Natural Channel Design; Fisheries Act Authorization	Yes	Yes	Field investigations, geomorphologic and hydraulic analyses; post-development flows (i.e. 2-yr flows) modelled; iterative process; dimensions of XS determined by drawing upon a range of geomorphologic and hydraulic analyses (e.g. tractive forces)	No	Yes	Yes	Previously modelled 2-yr flow by Cosburn Patterson Mather Limited	Yes	Valley length; valley gradient; sinuosity; channel length; bankfull gradient; riffle gradient; max d; avg d; max boundary shear; max gain size entrained; avg roughness; max velocity; Froude number; stream power; unit stream power; avg w; radius of curvature; meander wavelength; amplitude	No	No	Yes	No	Town of Ajax
23	Milne Creek	TRCA	Totten Sims Hubicki and Harrington & Hoyle	Rouge	Erosion/ Flooding	NO	370	No	No	No	Hydraulic Report; Class Environmental Assessment - Milne Creek Restoration Project; Ontario Regulation 158, Permit No C-02345 Inspection Report; Letter of Intent to Implement Compensation, Mitigation, and Monitoring Measures for the HADD of fish habitat; Authorization for Works or Undertakings Affecting Fish Habitat	No	No	HEC-2 hydraulic modelling	Yes	Yes	Yes	HEC-2	Yes	Manning's n; length; width	No	No	Yes	Yes	Little Rouge River Restoration Project, Save the Rouge Valley System Inc.
24	Milne Creek Restoration Project	TRCA	Harrington & Hoyle	Rouge	Erosion Control	NO		No	See Above					HEC-2 hydraulic modelling							No				
25	Mimico Creek - West and East Branch	TRCA		Etobicoke & Mimico	?	NO		No	No	No	City of Mississauga Natural Areas Survey	No	No	No details provided	No	No	No	-	No	-	No	No	No	No	Unknown
26	Morningside and Neilson Tributaries Valley Design	TRCA	Schaeffers'	Rouge	Development	YES	2000	Yes	Yes	No	Valley Design Report	Yes	Yes	Iterative	Yes	Yes	Yes	Hydrologic modelling completed by Schaeffers	Yes	Pool-riffle sequencing; sinuosity; max depth; avg depth; max boundary shear stress; max grain size entrained; avg roughness; avg XS Q; stream power; unit stream power; cross-sectional area; Manning's n	No	Yes	No	No	Unknown
27	Morningside and Nelson Tributaries	TRCA	Schaeffers'		Development	NO		Yes	See Above					Iterative							No				
28	Morningside Heights Tributary	Parish	Parish Geomorphic	Rouge	Development	NO		No	No	Yes	-	No	No	No details provided	No	No	unknown	-	No	-	No	No	No	No	Unknown
29	Natural Corridor Designs for Unnamed Tributaries of Miller Creek within Picov Farm	GS			Habitat/ Ecosystem improvement	NO		No	Yes	Yes	-	Yes	Yes	No details provided	No	No	No	-	No	-	No	No	Yes	No	Picov Farm Inc
30	Naturalized Corridor for Tributary H2 of Humber River	GS		Humber	Development	YES		No	Yes	Yes	-	Yes	Yes	Geomorphological and hydraulic analyses and results from field investigations	Yes	Yes	No	-	Yes	Gradient; low flow channel width; total width; depth; cross-sectional area; Manning's n; Q conveyed; Q accommodated; Froude number; permissible velocity; max shear stress; max grain size entrained	No	Yes	Yes	No	Medallion Developments (Countryside) Limited
31	Neilson Tributary Improvements	TRCA	Schaeffers'	Rouge	Development	NO	370	Yes	No	No	HADD Authorization; Hydraulic and Riparian Storage Analysis for Morningside Heights Neilson Tributary Improvements	No	No	HEC-RAS	No	No	Yes	HEC-RAS	No	-	No	No	No	No	Unknown
32	Robinson Creek	Parish	Parish Geomorphic	Rouge	Erosion/ infrastructure	NO		No	No	Yes	-	No	No	Hydraulic modelling - HEC-2; tractive force calculation	No	No	unknown	-	No	-	No	No	No	No	Unknown
33	Robinson Creek Lowering, Wismer Commons	TRCA	Schaeffers'	Rouge		NO		No	No	No	Application for Authorization for Works or Undertakings Affecting Fish Habitat; Letter to TRCA planning ecologist from MMM;	Yes	No	No details provided	No	No	unknown	-	No	Does not explicitly provide dimensions	No	No	No	No	Unknown
34	Robinson Creek Naturalization	TRCA	Harrington & Hoyle	Rouge	?	NO	240	No	No	No	Hydraulic Report	No	No	No details provided	No	No	Yes	HEC-2, v.2.1	Yes	avg area; avg wetted perimeter; avg hydraulic radius; avg flow depth; max shear; D50	No	Yes	No	No	Harrington & Hoyle
35	Salt Creek Realignment	Aquafor	Aquafor Beech	Humber	Development	NO		Yes	No	Yes	Draft Salt Creek Relocation and SWM Pond 2 Outlet Channel; DFO Authorization; Drawings	No	Yes	No details provided	Yes	Yes	Yes	HEC-RAS	Yes	Grade; bankfull discharge; bankfull width; avg depth; max bankfull depth; side slopes; bankfull area; max step height; Manning's n; shear stress; stream power; Froude number; substrate entrained during bankfull flow; D50	No	Yes	No	Yes	Unknown
36	Salt Creek Relocation, Castlemore South	TRCA	Aquafor Beech	Humber	Development	NO	90	Yes	No	No	?	No	No	Reference reach, empirical equations (meander belt width); modelled 2-yr flow	No	No	No	-	No	-	No	No	No	No	Fanshore Investments Inc; EMC Group Ltd
37	Silver Creek - East-West Tributary	CVC	Aquafor Beech	Credit	Geomorphic Referenced River Engineering	NO		Integrated NCD and traditional river engineering	No	No	Stream Corridor Management Plan	Yes	Yes	Cross-sections sized according to geomorphic considerations	No	No	No	-	No	-	No	No	No	No	Town of Halton Hills
38	South Monora Creek	CVC	Parish Geomorphic	Credit	Development	NO	200	Yes	No	Yes	Letter to Jones Consulting, etc from Parish Geomorphic;	Yes	Yes	Geomorphological and hydraulic analyses (from and elements of design); GASWER model for 2-yr flow	No	Yes	Yes	GAWSER Model	Yes	Bankfull width; avg bankfull depth; radius of curvature; bankfull gradient; riffle gradient; avg riffle length; riffle-pool spacing; sinuosity; radius of curvature; meander wavelength	No	No	No	No	Jones Consulting Group Ltd; Triton Engineering Services Ltd; Gartner Lee Ltd
39	Spring Creek Tributary of East Etobicoke Creek	GS		Etobicoke	Development / Transition Channel	YES		Yes	Yes	Yes	-	Yes	Yes	Not specified	Yes	Yes	Yes	For radius of curvature, riffle length, pool length, riffle spacing	Yes	BF channel gradient; Manning's n; corridor width; BF width; max BF d; avg BF d; cross-sectional area; avg flow velocity; Froude number; Q conveyed; Q to accommodate; max shear stress; max grain size entrained; mean grain size entrained; radius of curvature	No	Yes	Yes	No	Schaeffers Consulting Engineers
40	Springbrook Creek - Proposed West Tributary Realignment, SV7 Channel Design	CVC	Aquafor Beech	Credit	Development	NO	1020	Yes	Yes	No	-	Yes	Yes	Iterative; principles of fluvial geomorphology and flow hydraulics; Fischenich, 2001 - used to determine permissible shear stress	No	Yes	No	-	Yes	Length; grade; width; depth; wetlands; shear stress	No	Yes	No	No	Schaeffer and Associates
41	Stanford Channel	CVC	Stantec/ Parish	Credit	Culvert	YES	440	Yes	Yes	Yes	Application for Authorization for Works or Undertakings Affecting Fish Habitat	Yes	No	Regime relationships, proprietary geomorphic design model	No	Yes	Yes	HEC	Yes	Area; hydraulic radius; wetted perimeter; max depth; mean depth; velocity; Manning's n; Froude number; stream power; unit stream power	No	Yes	No	No	Not specified
42	Stanford Channel - Alternation and Natural Channel Design	CVC	Stantec/ Parish	Credit	Culvert	NO		Yes	See Above					Regime relationships, proprietary geomorphic design model							No				
43	Upper Milne Creek Restoration Project	TRCA		Rouge	Erosion/ Flooding	YES	505	No	No	No	Application for Fill, Construction and Alteration of Waterways permit; Inspection Report, Permit No. C-04401; MNR Work Permit AUR-10-04/05; Letter to DFO from TRCA; Letter form Harrington and Hoyle; Letter to Harrington and Hoyle from TRCA	Yes	Yes	Stable reference sections were used to determine bankfull discharge; this value compared favourable to results for area-based calculations; Basis of design was Rosgen	No	No	Yes	HEC-2	Yes	Manning's n; slope; Shear force	No	Yes	No	No	Town of Markham

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ID	Project Name	Data From	Design Company	Watershed	Type of Project	Case Study	Length (m)	Designated as a NCD?	Technical Design Brief Reviewed	Design Drawings Reviewed	Other Documents Reviewed	Objectives / Purpose Stated	Constraints Stated	Approach to Design	Channel and Local Catchment History Included	Design Q Stated	Modelling Used?	Type of Modelling	Included Cross-Sectional & Planform Geometry Parameters	Cross-sectional and Planform parameters included in design	Included Sediment continuity/ transportation calculations	Included Grain Sizing	Monitoring Plan Included	Project Costing Included	Project Proponent/ Document Prepared For:
44	Upper Mimico Creek Natural Corridor Project & Upper Mimico Creek Aquatic Restoration Project	GS		Etobicoke	Create Dynamically Stable Channel	YES	1700	Yes	Yes	Yes	Upper Mimico Creek Aquatic Restoration Project: Best Options for Restoration; Technical Design Brief	Yes	Yes	Modeled values for radius of curvature, riffle length and pool length derived from relationships determined from C-type stream channels in southern Ontario by Annable (1996); Modeled values for riffle spacing based on Hey and Thorne, 1986 for vegetated channels with 5 to 50% tree and shrub cover along banks	Yes	Yes	Yes	Based on Williams, 1986 with 20% buffer	Yes	Radius of curvature; riffle length; pool length; bankfull width; riffle spacing; gradient; corridor width; max bankfull depth; average bankfull depth; cross-sectional area; width:depth ratio; Manning's n; avg velocity; discharge conveyed; Froude number; max shear stress; stream power; unit stream power; max grain size entrained; mean grain size entrained; permissible velocity	No	Yes	Yes	No	TRCA
45	Urfe Creek Natural Corridor Design	GS		Duffins & Carruthers	Infrastructure removal/ naturalization	NO	2148	Yes	Yes	Yes	Technical Design Brief	Yes	Yes	Geomorphological and hydraulic analyses and results from field investigations	Yes	Yes	Yes	for meander belt width assessment	Yes	Radius of curvature; riffle length; pool length; bankfull width; riffle spacing; gradient; corridor width; max bankfull depth; average bankfull depth; cross-sectional area; width:depth ratio; Manning's n; avg velocity; discharge conveyed; Froude number; m	No	Yes	Yes	No	Regional Municipality of Durham
46	Village Parkway Outfall Channel Restoration	Aquafor	Aquafor Beech	Rouge	Erosion Control	YES	35	'Intended to incorporate natural channel design principles into design', drew upon principles of fluvial geomorphology and flow hydraulics	Yes	Yes	-	No	Yes	MTO and DFO guidelines for plunge pools; analytical	No	Yes	No	-	Yes	Width; depth; area; flow capacity; flow velocity; length; plunge pool; riffles; avg grade	No	Yes	No	No	Town of Markham
47	West Highland Creek at Markham Rd	GS		Highland	Stabilize	YES		Hybrid	Yes	Yes	Technical Design Brief	Yes	Yes	Worst-case scenario to define areas of concern and a stable long profile	Yes	Yes	Yes	HEC-RAS v. 3.1.3	Yes	2-yr flow; flow depth; avg velocity; slope; shear stress	No	Yes	Yes	No	City of Toronto
48	West Humber River in Woodlands Golf and Country Club	Aquafor	Aquafor Beech	Humber	Development	YES		Yes	Yes	Yes	Design Brief	Yes	Yes	Reference reach, considers existing channel form	Yes	Yes	No	-	Yes	Grade; bankfull discharge; bankfull width; avg depth; max bankfull depth; side slopes; bankfull area; max step height; Manning's n; shear stress; stream power; Froude number; substrate entrained during bankfull flow; D50; radius of curvature	No	Yes	No	No	Giampaolo Investments
49	Highland Creek Valley Segment 4/4a	Pete	Parish Geomorphic	Highland	Erosion	NO		No - incorporates elements of NCD, but true NCD not feasible	Yes	No	Environmental Impact Assessment	Yes	Yes	HEC-RAS; historical planform; field investigation; stable width back-calculated based on flow competency for D50 and D84	No	Yes	Yes	HEC-RAS	Yes	avg bankfull width; max bankfull depth; bankfull gradient; riffle gradient; max shear stress; specific stream power; sinuosity; width:depth ratio	No	Yes	Yes	No	Not specified

Appendix B: Case Study Summary Tables

Table B.1: Case Study 1 – Realignment and Renaturalization of Tributary 3 of Etobicoke Creek, West Branch

Watershed	Etobicoke and Mimico Creeks	
Design Company	Geomorphic Solutions	
Estimated Year of Completion	2006	
Length	420 m	
Type	Associated with improvements to Everlast Stormwater Management Facility	
NCD?	NCD	
Cross-sectional & Plan-form Geometry	• Average bankfull depth • Width:depth ratio • Riffle-pool sequences • Gradient • Width	• Cross-sectional area • Manning's n • Average velocity • Froude number • Sinuosity
Objectives	• Restore design function to SWM facility • Improve functionality of stream corridor • Create dynamically stable corridor that replicated natural form and function • Allow conveyance of water, sediment and organic materials • Provide diverse habitat and naturalize corridor • Increase capacity of low flow channel • Improve floodplain diversity	
Constraints	• Upstream and downstream inverts • Replicate existing corridor function • Incorporate wet meadow and wetland features into design • Replication function of natural swale corridor	
Description – Prior to design	• Straight, limited variability and floodplain connectivity • Previously ditched to accommodate upstream and downstream inverts • Poor flow conveyance • Heavily vegetated	
Design Approach	'soft'	
Design Description	Hummocky pocket wet meadow/wetland features constructed on floodplain - will provide riparian diversity, sediment sinks and flow retention and detention functions; increase capacity of existing channel; increase channel sinuosity; plan-form will mimic hummocky features observed in the field	
Notes: This project is a good example of natural channel design in an urbanized context where both infrastructure needs are addressed in addition to improving the natural function of the stream.		

Table B.2: Case Study 2 - Upper Milne Creek Restoration Project

Watershed	Rouge River
Design Company	Harrington & Hoyle Ltd.
Estimated Year of Completion	2004
Length	505 m
Type	Erosion
NCD?	No
Cross-sectional & Plan-form Geometry	Manning's n Slope Shear force
Objectives	• Mitigate downstream flooding and erosion problems; create a healthier more productive aquatic system; stabilize bank slopes
Constraints	• Highly constrained by development
Description – Prior to design	• Unstable, undergoing adjustment • Some stable sections • Size of existing substrate doesn't represent appropriate substrate • Reach is sediment starved • Previously channelized • Bordered by commercial and light industrial • Narrow floodplain
Design Approach	Stable reference sections were used to determine bankfull discharge; this value compared favourable to results for area-based calculations; Basis of design was Rosgen
Design Description	Create plunge pools, vortex weirs, pool-riffle sequences, channel meanders, and riparian wetland cells with bioengineering to stabilize banks; stream may have to be sediment fed occasionally to maintain habitat quality

Table B.3: Case Study 3 - Village Parkway Outfall Channel Restoration

Watershed	Rouge River
Design Company	Aquafor Beech
Estimated Year of Completion	2008
Length	35 m
Type	Erosion Control
NCD?	'Intended to incorporate natural channel design principles into design', drew upon principles of fluvial geomorphology and flow hydraulics
Cross-sectional & Plan-form Geometry	• Width • Depth • Area • Flow capacity • Flow velocity • Length • Plunge pool • Riffles • Average grade
Objectives	• Replace failed bank protection • Provide for aquatic habitat • Stabilize channel
Constraints	• Outfall structure • Desire to use 'softer' engineering approaches/bioengineering techniques • Minimize loss of mature vegetation • Must convey flows emerging from outfall • Downstream tie-in point Constraints to plan-form alignment • Pedestrian walkway to north • Mature vegetation to south • Mature vegetation to north where pedestrian walkway is not immediately adjacent to channel
Description – Prior to design	• 35m channel connecting an outfall with Berczy Creek • Built in 1971, lined with gabions. Now corroded, emptied and destroyed
Design Approach	• MTO and DFO guidelines used in design of plunge pool • Analytical
Design Description	• Wider cross-section and energy dissipation mechanism (plunge pool) at outfall to dissipate flow energy and reduce stress on banks • Line plunge pool with stone to protect banks from scour and dissipate energy • Existing alignment maintained • Profile configuration of existing watercourse mimicked in design

Table B.4: Case Study 4 - West Highland Creek at Markham Road

Watershed	Highland Creek
Design Company	Geomorphic Solutions
Estimated Year of Completion	2006
Length	Not specified
Type	Stabilization
NCD?	Hybrid
Cross-sectional & Plan-form Geometry	2-yr flow; flow depth; average velocity; slope; shear stress
Objectives	• Initial goal to improve fish passage and local habitat by removing a weir immediately d/s of Markham Rd; stabilize section; restore channel form and function with enhanced stability to convey future storm flows with limited erosion
Constraints	• Markham Road bridge design determines local hydraulics; form and structure of bridge considered in selection and placement of bank treatments and grade control
Description – Prior to design	• Overall entrenched; detailed field work done prior to storm, post-storm survey completed approximately 2 weeks after storm; survey provided basis for channel design and detail to properly tie in any design but also the means assess channel changes in the future; 3 upstream cross section (incl. additional cross section immediately upstream of crossing) and 8 downstream cross section resurveyed; flashy flow regime due to increase in imperviousness of drainage area; increased peak flow discharge and erosion potential by runoff from storm events flow directly into channel - necessitates bed controls to limit down cutting
Design Approach	Worst-case scenario to define areas of concern and a stable long profile
Design Description	Design includes: river training to reduce future channel erosion, bed controls to provide backwater and local grade control, bank erosion protection, improved riparian cover; 'hard' bank protection necessary to limit future erosion; geomorphological and hydraulic analyses in combination with results from field investigation determine the appropriate channel form and elements in the design; design should be able to accommodate large events; long profile surveyed after storm event was used to define design profile; design will provide a deep pool

Table B.4: Case Study 4 - West Highland Creek at Markham Road

	for energy dissipation and elevation controls at three points along the channel to limit the potential of additional scour; vegetated buttresses proposed along the banks - constructed of material large enough to resist entrainment; re-vegetate with aggressive native pioneering shrub species; realignment and extension of armour stone proposed b/w bridge and storm sewer outfall; buttress and armor stone will be vegetated to provide improved riparian cover; formalize scour pool d/s of existing weir to confirm to pre-storm conditions; three grade structures will be installed; elevation set to existing grade to limit d/s impacts and limit fish passage issues; channel bed area b/w u/s and middle rock weir will be backfilled with stone; substrate hydraulically sized to limit potential for failure

Table B.5: Case Study 5 - Gore Road Tributary Natural Channel Design at Pannahill Drive and Cottrelle Boulevard Crossings

Watershed	Don River
Design Company	Aquafor Beech
Estimated Year of Completion	2008
Length	Not specified
Type	Crossings
NCD?	Yes, also guided by principles of fluvial geomorphology
Cross-sectional & Plan-form Geometry	• Width • Maximum and average depth • Area • Velocity • Flow • Maximum shear stress • Froude Number • D_{50}
Objectives	• Proposed construction of Pannahill Drive and Cottrelle Blvd crossings are opportunity to remove online ponds and replace them with watercourse features
Constraints	• Tie-in elevations
Description – Prior to design	**At Pannahill Drive** • Low flow energy • Vegetations is dominant influence on channel form and processes • Active meandering form not naturally sustainable • Bankfull channel poorly defined • Evidence of frequent floodplain access **At Cottrelle Blvd** • Situated in primarily wooded area • Area surrounding pond is vegetated with grasses • Mature trees present along periphery of pond • Private property fences in proximity to east side of pond • Floodplain contained evidence of historic meander cut-offs and abandoned channels which contain depressions of water
Design Approach	Modelled 2-yr flow, field observations
Design Description	• Intended to replicate elevation of low-level crossing with first riffle feature • Incorporates both pool and riffle bed morphology • Accounts for deeper online pool • Profile considered need to dissipate energy and promote flow conveyance

Table B.6: Case Study 6 - Stanford Channel Alteration and Natural Channel Design

Watershed	Credit River
Design Company	Parish Geomorphic
Estimated Year of Completion	2003
Length	440 m
Type	Culvert/crossing
NCD?	Yes
Cross-sectional & Plan-form Geometry	• Area • Hydraulic radius • Wetted perimeter • Maximum and mean depth • Velocity • Manning's n • Froude number • Stream power • Unit stream power
Objectives	• Provide fish habitat link from existing Wanless Rd culvert to channel constructed adjacent to Chinguacousy Rd in Fanshore Development lands • Lower watercourse to accommodate future upstream servicing • Restore form and function of channel • Provide diversity of aquatic habitat
Constraints	• Upstream and downstream tie-in elevations • Maintain a minimum 0.3 m freeboard from the top of the valley to the Regional Storm water surface elevation • Vegetation dominant
Description – Prior to design	• Low gradient, vegetation controlled, headwater swale with intermittent flow • Pools, flats, riffles and runs • Banks moderate to high instability in pastured area, otherwise generally stable • Low energy (rules of alluvial channel sinuosity, meander plan-form and thalwag definition do not apply)
Design Approach	• Design flow based on meander belt width report (Aquafor Beech, 2002), discussion with CVC, and field investigations • Regime relationships of pool and riffle, inter-pool and inter-riffle length • Proprietary geomorphic design model used to iteratively design hydraulic geometry of pool and riffle cross-sections • Riffle gradient determined as regime function of bankfull gradient • Limerinos • Strickler • Used criteria applicable to headwater swales in cohesive soils, relatively small drainage areas and medium drainage density

Table B.6: Case Study 6 - Stanford Channel Alteration and Natural Channel Design

	watersheds • Plan-form sinuosity based on proposed valley gradients needs for floodplain storage and conveyance
Design Description	• Steeper side slopes to transition the proposed channel within local topography, while providing required invert, belt width and freeboard during Regional Storm event • Low gradient, vegetation controlled, intermittent feature • Simple pool-riffle/run concept

Table B.7: Case Study 7 - West Humber River in Woodland Golf and Country Club

Watershed	Humber River	
Design Company	Aquafor Beech	
Estimated Year of Completion	2006	
Length	Not provided in design documents	
Type	Development	
NCD?	Yes	
Cross-sectional & Plan-form Geometry	• Grade • Bankfull width • Average and maximum bankfull depth • Side slopes • Bankfull area • Manning's n	• Shear stress • Stream power • Froude number • Substrate entrained during bankfull flow and D_{50} • Radius of curvature
Objectives	• Removal of online dam and reinstatement of channel in existing head pond • Mitigate effects from conditions created by dam in upstream channel and restore low-flow channel • Remove channel spanning structures that interfere with fish passage and natural channel processes • Maintain a base-level control point within study are to mimic existing controls to which the channel has been adjusting • Remove accumulation of fine sediment from within the head pond area • Remove any channel constrictions during crossing replacement	
Constraints	• Maintain large pool • Minimize impact to channel bed • Upstream and downstream tie-in points • Maintain grade control	
Description – Prior to design	• Overall good condition (RGA) • Affected by dam operations/backwater conditions • Well established riparian buffer from McVean to dam • Exposed bedrock in banks • Where backwater conditions are not impacting the channel, lateral bars and vegetation are adjacent to the low-flow channel • Mix of platey and rounded stone substrate	
Design Approach	Reference reach, considers existing channel form	
Design Description	• Two-tiered cross-sections • Reinstate channel in area occupied by head pond from dam • Intended to replicate a 20 m wide channel with similar depth to upstream sections • Within larger channel, slightly sinuous low flow channel • Includes 'pronounced' riffle features	

Table B.7: Case Study 7 - West Humber River in Woodland Golf and Country Club

	• Sequence of pool and riffle features • Radius of curvature over 2.5 for low flow channel, 3.8 for larger channel • Rounded stone substrate

Table B.8: Case Study 8 - East Branch of Fletcher's Creek Headwater Stream Realignment and Enhancement, Phase 1

Watershed	Credit River	
Design Company	Parish Geomorphic	
Estimated Year of Completion	2003	
Length	475 m	
Type	Development	
NCD?	Yes	
Cross-sectional & Plan-form Geometry	• Maximum and mean depth • Width:depth ratio • Velocity • Critical depth	• Stream power • Calculated shear stress • D_{50} and D_{84}
Objectives	• Facilitate floodplain storage modification and restore form and function;	
Constraints	• Maintain existing Regional Storm floodplain storage; capable of receiving increased flow volume and duration from future upstream development;	
Description – Prior to design	Intermittent warm water fishery; low gradient (~0.3%); poorly defined bed morphology; does not exhibit high level of stability and function; bottom of watercourse almost completely vegetated with terrestrial vegetation; flow likely ephemeral	
Design Approach	Reference reach; regime relationships; HEC-2; project prepared using multi-disciplinary team (engineers, landscape architects, biologist and stream geomorphologists)	
Design Description	Proposed design based on HEC-2 cross sections contained in Master Servicing and Stormwater Management Report; 34m meander belt width; 3 sub-reaches that would join with the existing channel above and below the study reach; and a separate wetland low flow channel in the centre of the study reach; implementation of upstream SWM will result in increase in flow volume and duration of low flows due to extended detention affects between rain events; blended design of cohesive channel cross-section with necessary stone treatment was determined; riffle gradients determined using reference relationships for stable channels; new channel cross section were iteratively tested and designed using a proprietary model; low flow features incorporated into riffles and pools respectively to reflect riffle symmetry and pool asymmetry; based on design of cross section, plan-form was laid out using bankfull width, channel sinuosity, channel length	

Table B.9: Case Study 9 - Miller Creek Realignment and Natural Channel Design

Watershed	Duffins and Carruthers	
Design Company	Parish Geomorphic	
Estimated Year of Completion	2000	
Length	1400 m – Two reaches - Reach 1 & 2: 600m - Reach 6: 800m	
Type	Development	
NCD?	Yes	
Cross-sectional & Plan-form Geometry	• Valley length • Valley gradient and riffle gradient • Sinuosity • Channel length • Bankfull gradient • Average and maximum depth • Maximum boundary shear • Maximum gain size entrained	• Average roughness • Maximum velocity • Froude number • Stream power and unit stream power • Average width • Radius of curvature • Meander wavelength • Meander amplitude
Objectives	• Remove fish barriers • Provide improved diversity of aquatic habitat • Restore the form and function of the channel	
Constraints	• Beaver dam in Reach 5, which affects the downstream function and sediment supply in Reach 1 & 2	
Description – Prior to design	• Previously been straightened • Trough-shaped cross-section and • Lacked diversity in plan-form and longitudinal profile • Banks showed evidence of erosion and slumping • Entrenched in some areas. • Beaver dam in Reach 5 has caused widening and sediment deposition upstream and • A drop structure in Reach 1 & 2 impedes fish passage and acts as a sediment trap, impeding the function of the stream	
Design Approach	Data from detailed field investigation used in general geomorphologic and hydraulic analyses to assess existing channel form and function and ID processes that currently operate within channel; post-development flows (i.e. 2-yr flows) that will be conveyed through Reaches 6 and 1-2 were modelled by CPM in support of the EMDP; iterative process; dimensions of XS determined by drawing upon a range of geomorphologic and hydraulic analyses (e.g. tractive forces); aim of analysis was to ensure that the erosion potential of the bankfull flows was optimized, allowing for sediment transport but preventing excessive erosion	

Table B.9: Case Study 9 - Miller Creek Realignment and Natural Channel Design

Design Description	Movement and realignment of 2 reaches (6 and 1-2); increase sinuosity; removal of drop structure means energy gradient will be nearly constant through the reach, ensuring that excessive erosion caused by local increases in flow energy are less likely to occur; designed stream corridor has a linear orientation; design of Reach 6 and 1-2 is somewhat restricted in natural expression; all natural meandering tendencies must be contained within a linear corridor; data collection during detailed field investigation used to estimate the magnitude of the bankfull flow events in Reaches 6 and 1-2; estimated bankfull flow that is conveyed through Reach 6 is comparable to the modeled 2-yr flow while in Reach 1-2 it is less; sinuosity reduced for channel design to ensure that the energy gradient of the bankfull flows is sufficient to enable sediment conveyance through the channel; energy gradient reduced for study reaches since the sinuosity of proposed channel is larger than the existing sinuosity while the change in elevation at reach boundaries remains constant; cross-sections are rounded and adjusted slightly to obtain a more natural conditions; final cross-sectional dimensions of riffle accommodates, or nearly accommodates the bankfull discharge while approaching or exceeding average critical flow conditions (i.e. Froude No. >=1)

Table B.10: Case Study 10 - Morningside and Neilson Tributaries Valley Design

Watershed	Rouge River
Design Company	Schaeffers Consulting Engineering
Estimated Year of Completion	2001
Length	Morningside Tributary: 2213.5 m Neilson Tributary: 501.5 m
Type	Development (290 ha upstream development)
NCD?	Yes
Cross-sectional & Plan-form Geometry	• Pool-riffle sequencing • Sinuosity • Maximum depth • Average depth • Maximum boundary shear stress • Maximum grain size entrained • Average roughness • Average discharge • Stream power • Unit stream power • Cross-sectional area • Manning's n
Objectives	• Improve upon existing conditions
Constraints	• Upstream and downstream invert elevations • Hydro towers within valley should be avoided • Must properly design confluence of Neilson and Morningside Tributaries
Description – Prior to design	Morningside Tributary • Upstream of diversion structure: Well defined with active bank undercutting and bank slumping • Downstream of diversion structure: grassy swale morphology, some head-cutting at confluence of Morningside and Neilson • Further downstream: better defined, bed morphology not well developed Neilson Tributary • Intermittent, shallow grassed ditch • Poorly defined bed morphology • Areas of excessive erosion and deposition (associated with channel adjustment processes in response to previous straightening • Capacity insufficient to convey bankfull flows
Design Approach	Iterative, used field investigations wherever possible, hydraulic and geomorphic analyses to minimize flow energy
Design Description	• Each reach will have two pool-riffles and one transition feature • Hydraulic jump dissipates into pool • D50 and D84 entrained during bankfull flow • Riffles immobile during bankfull flow • Adjust cross-sectional shape and long profile, minor plan-form adjustments

Table B.11: Case Study 11 - Naturalized Corridor for Tributary H2 of Humber River

<table>
<tr><td>Watershed</td><td colspan="2">Humber River</td></tr>
<tr><td>Design Company</td><td colspan="2">Geomorphic Solutions</td></tr>
<tr><td>Estimated Year of Completion</td><td colspan="2">2006</td></tr>
<tr><td>Length</td><td colspan="2">Not indicated in project file</td></tr>
<tr><td>Type</td><td colspan="2">Development</td></tr>
<tr><td>NCD?</td><td colspan="2">No</td></tr>
<tr><td>Cross-sectional & Plan-form Geometry</td><td>• Gradient
• Low flow channel width
• Total width
• Depth
• Cross-sectional area
• Manning's n</td><td>• Q conveyed and discharge accommodated
• Froude number
• Permissible velocity
• Maximum shear stress
• Maximum grain size entrained</td></tr>
<tr><td>Objectives</td><td colspan="2">• Provide diverse habitat
• Naturalize corridor
• Restore channel form and function
• Convey post-development flows within confines of proposed development</td></tr>
<tr><td>Constraints</td><td colspan="2">• Channel crossing confine path and alignment of channel
• Upstream and downstream tie-in points</td></tr>
<tr><td>Description – Prior to design</td><td colspan="2">• Swale with intermittently defined channel; previously modified by agriculture; resulted in loss of variability in corridor morphology and vegetation and associated loss of channel/corridor function</td></tr>
<tr><td>Design Approach</td><td colspan="2">• Geomorphological and hydraulic analyses in combination with results from field investigation determine appropriate channel form and elements in design
• Design discharge determined from hydrologic assessments based on geomorphic function
• Hydraulics for cross-section dimensions based on well-vegetated channels
• Channel materials laterally extended beyond banks for several meters</td></tr>
<tr><td>Design Description</td><td colspan="2">Increased diversity in form with respect to low flow drainage pattern and overall floodplain; hummocky pocket wetland/wet meadow features will be constructed on floodplain - will provide additional riparian diversity and sediment and flow retention and detention functions; vary geometry and placement of wetland features will enhance habitat across floodplain corridor; proposed design ensures that the capacity for the defined channel sections of the corridor is sufficient to convey proposed bankfull/effective discharge before spilling onto floodplain; propose a defined low flow channel and undefined channel (wet meadow)</td></tr>
</table>

Table B.11: Case Study 11 - Naturalized Corridor for Tributary H2 of Humber River

	sections; avoids erosion via entrenchment by assuring that the width of the floodplain at an elevation equivalent to the average bankfull depth above the channel bank is approx 4x the bankfull width; backwater provided by wet meadow feature will enhance spilling on to floodplain; channel materials will be stable at bankfull conditions

Table B.12: Case Study 12 - Spring Creek, Tributary of East Etobicoke Creek

Watershed	Etobicoke and Mimico Creek
Design Company	Geomorphic Solutions
Estimated Year of Completion	2010
Length	Unknown
Type	Development
NCD?	Yes
Cross-sectional & Plan-form Geometry	• Bankfull channel gradient • Manning's n • Corridor width and bankfull width • Maximum and average bankfull depth • Cross-sectional area • Average flow velocity • Froude number • Discharge conveyed and to accommodate • Maximum shear stress • Maximum and mean grain size entrained • Radius of curvature
Objectives	• Restore form and function • Convey post-development flows
Constraints	• Transition channel; tied into inverts; must accommodate increase in discharge d/s; valley width is sufficient
Description – Prior to design	• 3 reaches; no evidence of recovery; no evidence of previous channel scars, oxbows or other features indicating historic alignment
Design Approach	Field observations, hydraulics and valley gradient (determine cross-sections), vary geometry of pools, riffles and substrate, riffle and pool length from Annable C-type channel (Annable, 1996), modelled value for riffle spacing (Hey and Thorne, 1986), Meander belt modelled in three ways: 1) TRCA model, based on regression equations using stream power and drainage area, 2) Williams, 1986, simple power function, 3) relations based on cross-sectional geometry
Design Description	Based primarily on field estimates and observations (considered modeled value); flood modelling results were inappropriate; transition channel, Countryside Dr lowered in future, as a result a temporary, relatively high gradient channel must be constructed to tie in with proposed valley corridor; u/s and d/s inverts; flow Q increase in d/s direction; wetland features to replicate conditions found along natural channel systems; hydraulic analyses ensure that flow energy is minimized and

Table B.12: Case Study 12 - Spring Creek, Tributary of East Etobicoke Creek

	erosion is inhibited while allowing for transport and sediment delivered to the channel; bf Q events - near critical flows over riffles, subcritical in pools (where possible); overall corridor mimics form and function of natural headwater systems while accommodating constraints and considerations imposed by proposed development; increase sinuosity from 1.0 to 1.2; modeled radius of curvature value used to guide initial channel plan-form layout

Table B.13: Case Study 13 - Proposed McLaughlin Road Tributary, Phase 2 Channel Design

Watershed	Credit River
Design Company	Aquafor Beech
Estimated Year of Completion	2004
Length	600m
Type	Development
NCD?	Yes
Cross-sectional & Plan-form Geometry	• Meander belt • Corridor width • Valley side slopes
Objectives	None stated
Constraints	• Design flow (merging 2 watercourse into one), no reference/analogues available, upstream and downstream tie in points; capacity of design channel needs to reflect anticipated flows from resulting combination of 2 drainage courses
Description – Prior to design	• Currently 2 reaches, merging into one;
Design Approach	Principles of fluvial geomorphology and flow hydraulics
Design Description	Riffle-pool morphology; wetland pockets line main channel; on-line pools; meandering; backwater conditions behind riffles;

Table B.14: Case Study 14 - Upper Mimico Creek Natural Corridor Project & Upper Mimico Creek Aquatic Restoration Project

Watershed	Etobicoke and Mimico Creeks
Design Company	Geomorphic Solutions
Estimated Year of Completion	2006
Length	1700km
Type	Environmentally driven
NCD?	Yes
Cross-sectional & Plan-form Geometry	Manning's n; slope; Shear force
Objectives	• Employ natural channel design principles to: reestablish a more naturalized channel form within the valley; provide variability with respect to topography and vegetation on the floodplain to improve terrestrial and aquatic habitat; enhance water and sediment retention and detention functions
Constraints	• Several instream barriers (73 in total system, 3 gabion grade control structures in study area) fragment aquatic system and prevent fish from accessing habitat; impacted by stormwater runoff; channel lined with flexible concrete
Description – Prior to design	• 9 reaches; Reaches 1-4 located d/s of Intermodal Drive, below identified restoration site; Reach 2 potential reference reach, least altered; Reaches 5-8 actual restoration site, reach breaks at 3 grade control structures, at u/s limit of flexible concrete mattress lining; Reach 9 u/s ref reach; Reach 9 selected as surrogate reach for design purposes
Design Approach	Modeled values for radius of curvature, riffle length and pool length derived from relationships determined from C-type stream channels in southern Ontario by Annable (1996); Modeled values for riffle spacing based on Hey and Thorne, 1986 for vegetated channels with 5 to 50% tree and shrub cover along banks
Design Description	Sinuous plan-form, variably spaced riffles and pools, existing fish barriers and flexible concrete mattress, existing corridor alignment was maintained and the modelled radius of curvature was used to guide the initial plan-form layout.

Appendix C: Semi-Structured Interview for Restoration Practitioners

1. What does 'natural channel design' mean to you?

2. Describe the types of projects you typically undertake
   a. Would you classify these projects as 'natural channel design'? Why or why not?

3. Describe the different approaches and calculations you've used in your design process

4. How has your design approach evolved?
   a. What do you think triggered this evolution

5. Describe typical constraints you face in the design process
   a. How do you overcome/deal with these constraints

6. How do you account for sediment movement and sediment continuity in your designs?
   a. What constraints are faced when attempting to include these concepts in your design?

7. How do you determine design discharge?

8. What hydraulic and plan-form geometry parameters do you include in the design process?
   a. How do you determine when you will or won't use a specific parameter?

9. How do you navigate the permitting process?
   a. Relevant regulations/legislations?
   b. How do the relevant regulations/legislations impact your design process? If not, why?

10. Do you do work on semi-alluvial rivers? (cohesive or bedrock)
    a. How does this impact your approach/design?
    b. What specific things change when designing a channel that is semi-alluvial?

11. Are there any particular design manuals/guidebooks/handbooks that you refer to in the design process?
    a. Why or why not?

12. What aspects of a design make a channel geomorphically functional?

13. Does geomorphology take precedence over other design objectives?
    a. How and why is geomorphology considered in the design process?

14. Implementation

Appendix D: Case Study Data Sources

Case Study 1: Etobicoke Creek West Branch, Tributary 3

Realignment and Renaturalization of Tributary 3 of Etobicoke Creek West Branch
Highway 410 /Derry Road East, City of Mississauga
Technical Design Brief
Prepared for: The Corporation of the City of Mississauga
Prepared by: Geomorphic Solutions
Date: October 2005
Project No.: 03217.400

Case Study 2: Upper Milne Creek Restoration Project

Upper Milne Creek Restoration Project
Application for Fill, Construction and Alteration to Waterways permit
Prepared for: Corporation of the Town of Markham
Prepared by: Harrington and Hoyle Ltd
Date: March 2004

Case Study 3: Village Parkway Outfall Channel Restoration

Village Parkway Outfall Channel Restoration
Prepared For: Town of Markham
Prepared by: Aquafor Beech
Date: June 27, 2007
Reference: 64717

Case Study 4: West Highland Creek at Markham Road

West Highland Creek at Markham Road: Channel and Aquatic Habitat Restoration
Technical Design Brief
Prepared for: City of Toronto
Prepared by: Geomorphic Solutions
Date: July 2006
Project No.: 05306.451

Case Study 5: Gore Road Tributary Natural Channel Design at Pannahill Drive and Cottrelle Blvd

Gore Road Tributary Natural Channel Design at Pannahill Drive and Cottrelle Blvd Crossings
Prepared for: Land Owner Group, Bram East Area 'G'
Prepared by: Aquafor Beech
Date: May 11, 2007

Case Study 6: Stanford Channel

Stanford Channel
Alteration and Natural Channel Design Brief
Prepared by: Stantec Consulting
Date: April 2003
File: 21T-02012

Case Study 7: West Humber River in Woodlands Golf and Country Club

Design Brief: West Humber Creek Restoration and Channel Design
Woodlands Golf and Country Club, Brampton
Prepared for: Giampaolo Investments
Prepared by: Aquafor Beech
Date: September 9, 2005

Case Study 8: East Branch of Fletcher's Creek Headwater Stream Realignment and Enhancement, Phase 1

East Branch of Fletchers Creek Headwater Stream Realignment and Enhancement (Phase I)
East ½ of Lot 14, Concession 2, City of Brampton
Prepared by: Parish Geomorphic
Date: November 2002

Case Study 9: Miller Creek Realignment and Natural Channel Design

Miller Creek Realignment and Natural Channel Design Brief
Development Area A6, Neighbourhood 2 Lands
Prepared for: Town of Ajax
Prepared by: Cosburn Patterson Mather Limited
Date: February 2000

Case Study 10: Morningside and Neilson Tributaries Valley Design

Valley Design Report, Morningside & Neilson Tributaries
Prepared for: Morningside Heights, City of Toronto (Scarborough)
Prepared by: Schaeffer Consulting Engineers
Date: February 2001

Case Study 11: Naturalized Corridor for Tributary H2 of Humber River

Naturalized Corridor for Tributary H2 of Humber River
Technical Design Brief
Bramalea/Countryside, City of Brampton
Prepared for: Medallion Developments (Countryside) Limited
Prepared by: Geomorphic Solutions
Date: August 2005
Project No.: 05076.451

Case Study 12: Spring Creek Tributary of East Etobicoke Creek

Spring Creek Tributary of East Etobicoke Creek
Rosedale Village, City of Brampton
Technical Channel Design Brief
Prepared for: Schaeffers Consulting Engineers
Prepared by: Geomorphic Solutions
Date: February 2007
Project No.: 06432.450

Case Study 13: McLaughlin Road Tributary Channel Design, Phase 2

Fletchers Creek – Proposed McLaughlin Road Tributary
Phase 2 Channel Design
Design Brief
Prepared for: Brampton 6-2 Limited (c/o The Kerbel Group Ltd)
Prepared by: Aquafor
Date: March 2003, Revised June 2004
Aquafor reference: 64082

Case Study 14: Upper Mimico Creek Natural Corridor Project and Upper Mimico Creek Aquatic Restoration Project

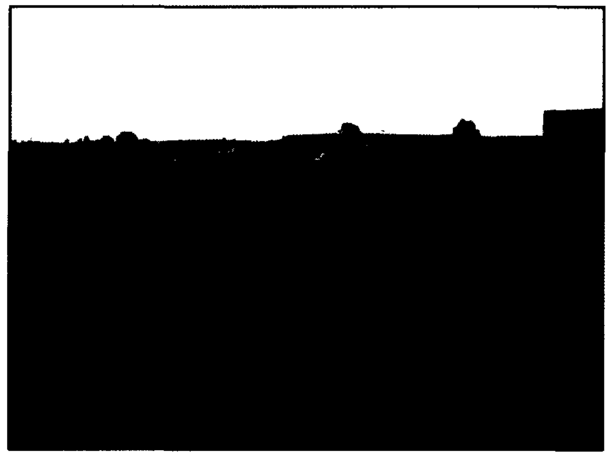
Upper Mimico Creek Natural Corridor Project
Technical Design Brief
Prepared for: TRCA
Prepared by: Geomorphic Solutions
Date: October 2006
File No.: 05460.450

Upper Mimico Creek Aquatic Restoration Project: Best Options for Restoration
Prepared for: TRCA
Prepared by: Geomorphic Solutions
Date: February 2006
Project No.: 05460.450

Appendix E: Pre-Construction, Construction and Monitoring Photos for Selected Case Studies

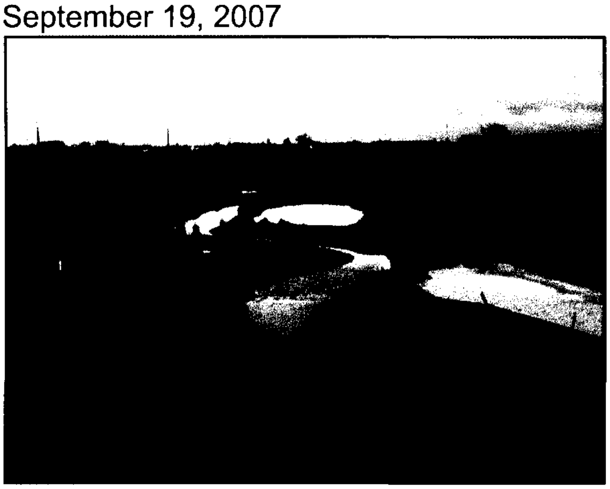
Case Study 1: Tributary 3 Etobicoke Creek, West Branch – Monitoring Photos

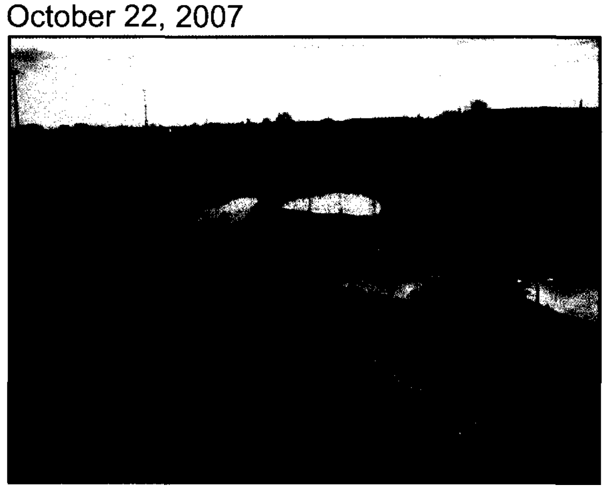

July 15, 2004


August 20, 2007


September 19, 2007


October 22, 2007


December 15, 2007


April 30, 2008

Appendix E: Pre-Construction, Construction and Monitoring Photos for Selected Case Studies

Case Study 1: Tributary 3 Etobicoke Creek, West Branch – Monitoring Photos


July 15, 2004


August 20, 2007


September 19, 2007


October 22, 2007


December 15, 2007


April 30, 2008

June 18, 2008

July 23, 2008

October 15, 2008

March 6, 2009

March 12, 2010

June 24, 2010

Case Study 4: West Highland Creek at Markham Road

August 12, 2005: View of Crossing, Pre-Storm

August 26, 2005: Storm Damage

August 26, 2005: Storm Damage

September 1, 2005:View of Crossing, Storm Impact

May 14, 2007: View of Crossing

May 14, 2007: View of Crossing


February 14, 2008


February 20, 2008


February 25, 2008


May 14, 2008


May 14, 2008


June 5, 2008


June 5, 2008


November 6, 2009


November 6, 2009


November 6, 2009

Case Study 11: Naturalized Corridor for Tributary H2 of Humber River

August 24, 2006

August 24, 2006

August 24, 2006

August 24, 2006

August 24, 2006

May 30, 2007

May 30, 2007

May 30, 2007

May 30, 2007

May 30, 2007

May 30, 2007

May 30, 2007

Case Study 14: Upper Mimico Creek Natural Corridor Project & Upper Mimico Creek Aquatic Restoration Project

Pre-Construction

August 30, 2007

August 30, 2007

August 30, 2007

August 30, 2007

August 30, 2007

August 30, 2007


August 30, 2007


August 30, 2007

Construction


December 24, 2009


December 24, 2009


December 24, 2009


December 24, 2009

December 24, 2009

December 24, 2009

December 24, 2009

December 24, 2009

Appendix F: Semi-Structured Interview Notes

Interviewees	Mariette Pushkar, Roger Phillips, Robert Amos
Date	April 13, 2011
Location	Mississauga Office

1. **What does 'natural channel design' mean to you?**

- Aquafor interview participants had trouble with the terminology
- Used primarily to market services to non-practitioners (engineers and ecologists)
- The terminology seems to be about getting environmental approvals, as NCD may be required by permitting agencies
- There is no consistent definition
- Preference for 'environmentally sensitive river engineering' or 'modified NCD' as used by TRCA in 2009 document
- NCD terminology is left over from the 90's and Rosgen
- NCD is supposed to mean dynamically stable
- Regulatory agencies can modify original design. May not be as NCD as originally intended
- Consistently use aspects of NCD: bankfull flow, sediment sizing and reference reaches
- Best practices of NCD are what is expected, not necessarily true NCD
- Difference between what practitioners and what clients think NCD is – expectations for outcomes of design process
- In regulatory agencies engineers and biologists expectations don't line up in terms of what they expect from design (stability vs. mobility)
- Engineering requirements win out
- Municipalities may over ride design
- Important to consider floodlines and that they cannot be increased, have to be careful
- In headwater systems
    - Ecology matters more than geomorphology
    - Vegetation dominated
    - Requirements of engineering and ecology stick with simple fundamentals
    - No coherent vision in the industry on design approach in these areas
    - Floodlines - channel lowering, vertical and horizontal alteration

2. **Describe the types of projects you typically undertake**
    a. **Would you classify these projects as 'natural channel design'? Why or why not?**

- Headwaters
- Higher order
- Step-pool
- Bank protection
- Scale is significantly different in big systems as opposed to small shiftings
- Whole sale design in lower order streams

3. **Describe the different approaches and calculations you've used in your design process**

- Hydrology on ungauged streams, need to rely on models, however little gauging on small streams
- Doing the best they can
- Models may be older, CA's update them about every 10 years
- Inputs to the design could improve
- Question about whether the provided flows are correct
- Determine bankfull flow based on field indicators
- Use of a few different approaches – determine where they converge
- Sometimes parameters are provided by the client, e.g. Q2, Q5
- Hydraulics
    - o Start with spreadsheets
    - o Based on standard 1-D models
    - o Manning's n
    - o Down the road in the design process 3-D modelling like HEC-RAS is used to refine the design, uses an iterative approach, is not a standard approach
        - ▪ Used as an end check or used midway through as part of iterative design process
    - o Preference to include in design documentation (HEC-RAS)
    - o HEC-RAS used as a check – recommended by Newbury
    - o HEC-RAS not as great for smaller streams
    - o Main capacity, different shear stresses
    - o Good for velocities for fish passage when 1-D is not appropriate
- Utilize multiple approaches
- HEC-RAS better for shorter sections, calibrations and data input for longer sections can get expensive
- Industry competition can prevent improvement. HEC-RAS is not included in the proposal as it's expensive and if included you will be out-bid and not get the project

4. How has your design approach evolved?

a. What do you think triggered this evolution

- Red side dace – current issue in evolving practice
- Learned from putting project in the ground
- Conferences and literature
- Always trying to enhance
- Every project is a bit different – but can still build on learning from previous projects
- Follow-up monitoring is very helpful
- Learning from successes – what helps or hinders and design from functioning as intended
- Design approach can be watershed dependant, e.g. decrease mobility of stream to save trees/riparian vegetation

5. Describe typical constraints you face in the design process

a. How do you overcome/deal with these constraints

- Saving slopes
- Saving trees
- Trend in TRCA to protect vegetation

- Biggest constraint: channel stability in the vicinity of infrastructure, which is typically the reason for the project
- Stable stability
- Tie-ins
- Vertical, horizontal
- Budget, capital funding
- Time – construction window, permitting
- Client perception
- Timing for regulatory process
- MNR is understaffed, process not set for permitting through the Endangered Species Act
- Review through the CA's, depends on who the reviewer is
- Staff turn over at CA's over lifetime of project, impacts the design, new reviewer may want/not want something the other reviewer had previously okay-ed, may also impact how long the review process takes
- Question of who is the designer and who is the reviewer. CA's and other regulatory agencies and clients can and do make changes to the design throughout the process
- Firm can recommend a certain design, client, CA, regulatory input can alter the design
- What is the education and qualifications of review staff? They may be miss informed or uninformed
- Not a broad enough focus during the review process
- Designers need to pick up numerous objectives and constraints
- 'Who's design is it' – firm still has to stamp design in the end
- Practitioners have to stamp drawings – issue, reluctant to stamp because of the changes made by non-practitioners
- Practitioners have to stand up for the design because they have to stamp it
- Keeping the client happy
- Take recommendations, assess viability, how can recommendations be incorporated without compromising the design or how can you show that they won't work
- Need to get more senior/experienced reviewers involved
- Land development over time can also alter design

6. **How do you account for sediment movement and sediment continuity in your designs?**
    a. **What constraints are faced when attempting to include these concepts in your design?**

- No upstream supply
- Supply limited
- Need to introduce sediment
    - Into banks, as future source
- Don't really look at sediment transport
- More important to maintain velocities and stresses
- As a tool for appropriate spans of bridge crossings
- Idea of stable particle size and bankfull discharge
- Larger particles remain stable, finer materials winnowed out
- Use keystones as structural features

- Sediment transport is an important issue and it is not considered enough, important for longevity and sustainability of project
- Want fairly stable channel
- Don't use a single stone size, use a gradation
- Consider providing local supply
- Local availability of sediment can differ in design reach
- Smaller stuff may be winnowed out
- Larger stones
    - Not natural
    - Stream may out flank stones
- Consider the 'life expectancy' of a project – particularly for more engineered projects
- If more engineered pull out the 'natural'
    - Can't be dynamically stable
    - Requires maintenance
- The term NCD should mean ecologically sensitive and self sustaining geomorphically to varying degrees

7. How do you determine design discharge?
- Field indicators
- Hydrologic and hydraulic models
- Rating curves and spatial relations
- Sometimes not able to find reference reach nearby, need to look further for it

8. What hydraulic and plan-form geometry parameters do you include in the design process?
   a. How do you determine when you will or won't use a specific parameter?
- Hydraulic
    - Discharge
    - Velocity
    - Shear stresses
    - Froude number
    - Stream power
    - Energy curves
- Above used to feed into plan-form type
- Also consider fish passage and permissible velocities
- Plan-form
    - Use existing conditions
    - Fit with in constraints and other parameters
    - Can be highly constrained
    - Geomorphology may be secondary to length, chainage requirements based on constraints
    - Radius of curvature, width
    - Meander belt width
- Experiences intuition and artistic license while still being quantitative
- Slope at the reach scale
- Channel length
- Width to depth ratios

- Fish habitat considerations – depths, low flow, pool depth, life stage requirements
- Variable meandering, riffle:pool, more complicated for construction
- Aesthetic/artistic aspect
- Variability = more natural
- Sine wave design still occurring ('coffee cup' design)
- Ultimate channel form
  - Based on existing conditions
  - Future conditions
  - Boundary conditions

9. How do you navigate the permitting process?
   a. Relevant regulations/legislations?
   b. How do the relevant regulations/legislations impact your design process? If not, why?

- MNR – Endangered Species Act
- Start with CA, involved DFO if there's a HADD
- Every CA has different levels of DFO/HADD authorization/involvement
- Working agreement between CA and DFO
  - TRCA has a lot of control
- MNR has to provide approval first
  - CA/DFO won't give permits until MNR gives theirs
- Biologists/ecologists trying to keep up with approvals process, they know where there are Red Side Dace
- Important to get CA on board from onset of project
  - Have a number of meetings over the design process
  - Feedback provided throughout the process
  - To prevent big surprises to the CA at submission type and vise versa
  - Enables CA to make recommendations early
  - Decrease the number of submissions (from 3 to 2)

10. Do you do work on semi-alluvial rivers?
   a. How does this impact your approach/design?
   b. What specific things change when designing a channel that is semi-alluvial?

- Definition of semi-alluvial (I said underlain by glacial till)
- Semi-alluvial with bedrock a bigger issue
- Defining or more/less resistant to erosion (glacial semi-alluvial)
- Bedrock is also variable
- Equilibrium vs. disequilibrium
- Semi-alluvial, currently incising, this is a watershed issue, can't be addressed/mitigated adequately at the reach scale
- Semi-alluvial nature of streams not really addressed
- Disconnect between scale of projects and scale of problems
- The economics of it – CA's required to protect private property
- Need to get people to be proactive instead of reactive
- **<u>Watershed issues</u>**

11. Are there any particular design manuals/guidebooks/handbooks that you refer to in the design process?

a. Why or why not?

- Newbury
- Other guidelines specifically for culverts
- USACE
- Annable relations (Rob was a student of Annable's)
- Suite of different approaches
- Grey literature
- NOT COOKIE CUTTER/BOILER PLATE – this type of approach is NOT appropriate
- Experience + resources, multiple approaches
- Use reference reach, but not cookie cutter
- Rosgen good for communication, but not for detailed channel design
    - Biologists/ecologists find Rosgen more useful then geomorphologists
    - Oversimplified
    - Could give impression that it (design process) can be simplified
    - Rosgen can miss elements
- CA manuals have standards including minimum widths for stream crossings

12. What aspects of a design make a channel geomorphically functional?

- Function
- Driven by ecologic or engineering objectives
- Geomorphology is a tool
- With geomorphology change and instability are good things, not so in an urban setting
- How do we place ecologic value into function?
- Geomorphology is at the bottom of objectives
- Geomorphology ties it all together
- To make channel functional:
    - Floodplain access
        - 1-2 yr RI should overflow – appropriate for urban areas
        - Flood frequency issues
        - Some urban channels contain the 5 yr RI
- Entrenched systems
- Localized vs. new reach – floodplain access is implicit when designing a new channel (think headwater)
- Channel design is a big, complex issue/process
- Everything must tie in together

13. Does geomorphology take precedence over other design objectives?

a. How and why is geomorphology considered in the design process?

- Lots of work because geomorphology is the science that ties it all together (ecology, environment, infrastructure and public safety)
- Expected that geomorphologists will be involved in the design process
- Other interests see the value in geomorphology to bridge the gap
- Awareness of importance of geomorphology has improved
- Geomorphology is the underlying aspect of all designs
- Importance of geomorphology is recognized
- Who is a geomorphologist?
    - Growing requirement to get P.Geosci
    - But P.Geosci is slanted to geology, hydrogeology and geophysics

  - o Doesn't adequately recognize geomorphology
  - o Disconnect to relevance to southern Ontario
- Other than P.Geosci can be a 'geomorphologist' with a masters in geomorphology + 5 yrs of experience
- Or some practitioners make a name for themselves in the industry, then are recognized as qualified (question as to whether this is good for the practice?)

14. Implementation

- Implementation is a BIG challenge
- Less than 6, maybe only one trusted construction company
- Construction companies modify what they see on the design drawings
- Need to be specialists
- In different world than designers
- Sediment erosion control issues during construction
- Field supervision of construction process is important, need staff onsite regularly
- Could also use an open-minded landscape contractor + full time supervision
- But specialist contractors don't like to be micro-managed
- There's a disconnect between the design drawings and what's actually in the ground
- Construction staging – its just a plan, need to show that the plan is reasonable, with the knowledge that it will have to be adjusted
- 9 steps (MNR – Natural Channel Systems)
  - o There is a big focus on the first 3 steps
  - o Not as much focus on final 4 steps (at least not in a structured way)
  - o CAs starting to focus more
- Communication between practitioners important to improve practice, doesn't always happen.

Interviewees	**John Parish**
Date	**May 16, 2011**
Location	**Mississauga Office**

1. What does 'natural channel design' mean to you?

- Very natural
- Incorporates hydrology, hydraulics, geomorphology, sediment regime
- Design and build without reinforcement
- Functional design = with reinforcement
- A NCD design, after 5 years you don't know its been done/can't tell its been rehabilitated

2. Describe the types of projects you typically undertake

a. Would you classify these projects as 'natural channel design'? Why or why not?

- Move/realignment or stabilize with respect to infrastructure
- Relocations – determine what's going to be more beneficial/detrimental
- Dam removals – very natural, back to how it was
- Create channel for urbanization – have to make a management choose, make the channel longer, more diverse move from ephemeral to more permanently flowing
- Lots of projects related to infrastructure

- From 20m to 1km
- Removal of old grade control structures
- Agricultural drains
    - o Work within drainage act
    - o Change geometry and cross-section, to move water and sediment faster as agricultural drains have a tendency clog with sediment
    - o Less future maintenance
- Some realignment associated with road crossings – tend to be more NCD
    - o E.g. 407 extension

3. **Describe the different approaches and calculations you've used in your design process**

- Don't follow a manual
- Have master spreadsheet, which is based on a variety of sources
- Rely on Williams for meander geometry
- Have own database of Regional Curves
- Approaches vary based on design/project
- Challenge to decide where to start
    - o Usually with profile and grade, then design discharge
    - o Then cross-sectional form and shape (in spreadsheet)
    - o Previously relied on Pierre Julian (book on open channel hydraulics)
    - o Craig Fischnieck (USACE)
- Do different tests
- Different spreadsheet for stone sizing – driven by tractive stress, shear stress, critical velocity
- Iterative process – based on objectives/constraints e.g. fish habitat
- Lots of stuff available on the internet
- End up with equations and approaches you know work for this landscape

4. **How has your design approach evolved?**
    a. **What do you think triggered this evolution**

- Evolution into more empirical/science based approaches
- Getting away from Rosgen
- 10yrs ago more structure, fairly hardened
- Lack of confidence in science therefore more stone, bioengineering
- More practice = softer, more natural
- Helped with monitoring
- Now have more confidence
    - o Still have issues with stone sizing in riffles
    - o Frustrating
    - o Importing larger stones than what would naturally be found
- Better at coming up with approaches in different settings
    - o i.e. cohesive, bedrock

5. **Describe typical constraints you face in the design process**
    a. **How do you overcome/deal with these constraints**

- There are no typical constraints
- Varies from project to project
- Property – staying within
- Urban settings – infrastructure

- Cost
- Frustration with monitoring
  - Municipalities not big on investing in monitoring for learning\
  - Municipalities have set capital works budgets – therefore may have to shorten the length of channel realigned in that year
- Or some municipalities want the design over the top – bigger, harder i.e. the City of Toronto
- Timing, permitting
  - More of an implementation issue
- Not enough good info on flows
  - Don't have time to understand the flows
  - Models developed by CAs based on floodlines, therefore have confidence around regional flood and 50-yr flood but confidence in more frequent flows is not as good
- Don't have as long/enough field data
- Downstream connections
  - Don't compromise downstream erosion sites
- Geotechnical and hydrogeological
  - Bank conditions, soil mechanics
  - Surface – groundwater interactions
- Old trees (natural heritage)
- Natural and cultural heritage feature
- Different constraints based on areas (urban vs. rural)

6. How do you account for sediment movement and sediment continuity in your designs?

a. What constraints are faced when attempting to include these concepts in your design?

- You don't
- Very difficult
- Don't have a good set of data
- Upstream and downstream conditions, bar deposits
- What has been moved, what can be moved
- Don't do a lot of modeling – do it for check and balance
- Try to not make it unusual for the site
- In urban areas sediment regime is changing – it's a moving target
- Sediment transport very dynamic in urban areas
- Dominant discharge/effective discharge can be 2-3x design or bankfull discharge
- Bedrock channels – more effected by larger flows – can't design that big
- Don't do it, but be aware
- Not enough data

7. How do you determine design discharge?

- Rely on what is seen in the field
- Typically Qbf
- Based on 'full bank sections'
- Manning's or more
- Figure out capacity
- Is it aggrading?
- What to do to balance sediment in – sediment out

- If using a hydraulic model – take a look
- Balance between art and science
- Sometimes told by client what discharge to use – this typically leads to a more functional channel
- Combination of field data and hydraulic and hydrologic models
- Try to incorporate variability
- More diverse, variable channel
    - Key factor
    - Used in analysis
    - Not married to maintaining same discharge all through design

8. What hydraulic and plan-form geometry parameters do you include in the design process?

  a. How do you determine when you will or won't use a specific parameter?

- Varies
- Depends on every project
- Dictated by science?
- Constrained by for example, right of way
- Roles of thumb – you know what tends to work
- If you can't do a true NCD
    - Have to give up some hydraulic and meander geometry
    - Still figure out where the 'natural' would be
- Don't have a scientific answer
- Have to know the state of the science, that state of the practice and the state of the art
- Have to know the setting
- Have to know the hydraulics
- Do it all, then adjust
- Chase things around
- Iterative process
- Diversity of form
- Meander geometry – start with sin wave, then modify

9. How do you navigate the permitting process?

  a. Relevant regulations/legislations?

  b. How do the relevant regulations/legislations impact your design process? If not, why?

- Shouldn't impact the design process
- Fisheries Act – HADD
- CA – more to do with hydraulic, floodlines, floodplain, natural heritage
- MNR, MOE, ESA
- An ESA will change the design
- PTTW for dewatering to work in the dry – then pumping water out of creek bed
- Agencies know you're trying to make the creek better so they are typically on board because they want to see improvement
- Key to meet with agencies, especially CAs, early that way you know the red flags early
- Agencies might add to constraints or objectives
- Get dialogue started early with CA

  - o Best way to go through permitting process
  - o Know confrontation early
- Permitting is the most straight forward part of the design process

10. Do you do work on semi-alluvial rivers? (cohesive or bedrock)

a. How does this impact your approach/design?

b. What specific things change when designing a channel that is semi-alluvial?

- Everything in southern Ontario (mostly) is semi-alluvial
- 60% of all designs implemented in glaciated landscapes
- 10-15% in bedrock
- 10% in till
- ~5% in sand bed
- Lots of equations from US mid-west for fully alluvial channels
- Comfortable with analyses we know work in this landscape – some from own database
- Secondary classification when you design
- Look upstream – smaller drainage area, tend to vegetation dominated
- In big rivers don't worry as much re: hydraulics, or issues related to semi-alluvial rivers
  - o Big rivers are typically regulated so they behave differently
- Also need to know SCALE, upstream drainage area

11. Are there any particular design manuals/guidebooks/handbooks that you refer to in the design process?

a. Why or why not?

- Incorporated into #3

12. What aspects of a design make a channel geomorphically functional?

- Connect to floodplain
- Spatial connection
- Is it in balance – flows and cross-sectional area
- Dynamics incorporated into design
- Movement of water and sediment
- How is it migrating?
- Sediment in, out, storage
- Creating different zones
- Functions we're trying to incorporate
- As a practitioner you want to go beyond geomorphic function and include as many natural functions as possible (e.g. aeration, fish passage)
- Work with multi-disciplinary team
- Geomorphologist is typically the lead on design process, because of stamp from P.Geo
- Emphasize fisheries over geomorphology in terms of function because of Fisheries Act

13. Does geomorphology take precedence over other design objectives?

a. How and why is geomorphology considered in the design process?

- If you build it they will come
- Depends, every design is different

- Depends on site, setting and objectives of project
- Doesn't take precedence with Red Side Dace
- Have to get geomorphology right first
- Dynamically stable – from geomorphology
- *Objectives and setting

14. Implementation

- Sometimes geomorphologist not on site during construction
- Stone sizing gradation not available
- Good contractors can do it quickly
- Contractors better at visualizing how they want to access the site
- Strict erosion and sediment control guidelines
- Some contractors now working in the wet – easier wrt to erosion and sedimentation mgmt
- Construction in winter – frost, settlement, can't grade as finely
- Big machines don't have the precision that may be indicated on the design drawings
- Need to understand design tolerances
- Unforeseen stuff comes up during construction
    - Sand seams
    - Spring
    - Sewer
- Don't know what you'll find when you start digging (issues with amalgamation and knowing where all infrastructure is) therefore need good contractor
- Practitioner often assists in tender process to aid in the selection of appropriate construction company (only about a half dozen who do this type of work)

Interviewees	**Kevin Tabata**
Date	**May 16, 2011**
Location	**Mississauga Office**

1. What does 'natural channel design' mean to you?

- Full range of natural processes are permitted
- Then natural form will develop
- Processes are more important than form
- Where the science comes in
- We're good at adopting new things
- Still read academic literature regularly
- Try to incorporate new/interesting/useful things
- Build simple models to test new things
- Have to use judgment as to what might be useful
- Try no to make field work too onerous
- 2D hydraulic flow modelling is very data intensive
- Would love to be able to explore new research i.e. modelling but hands tied – too expensive/time intensive
- Processes
- Won't use work erosion in design – tends to get flagged by regulatory agencies

2. Describe the types of projects you typically undertake

a. Would you classify these projects as 'natural channel design'? Why or why not?

- Full NCD usually involved with development projects – sometimes municipalities, CAs
- Focused on smaller watercourses
- NCD unusual on large watercourses where bankfull width = 4m
- Larger rivers = more complex design process – HAVE to consider 2D and 3D flows
    - Turbulence is also important but difficult to incorporate
- Work with engineers
    - Channel design under bridge structures where there is limited light, therefore no vegetation which = beefier rocks to stabilize
- Don't construct concrete channels – that's more of an engineering thing
- Roadside ditches – improved design over old ways
- In not fully alluvial area within a narrow corridor, need to address erosion issues
- If full meander belt with not available therefore requires more bioengineering
- NCD principles are used for bank stabilization/protection
    - Even with small projects
    - It's the only way to apply appropriate movement
- Try things incrementally
    - New ideas might get rejected by regulatory agencies
- Have to be able to speak the same language as client/regulatory agencies

3. Describe the different approaches and calculations you've used in your design process

- Most are from academic literature
- Literature is reviews, articles that are more commonly used, confirm similar assumptions, note limitations of model
- Refining of academic literature (e.g. articles keep building on previous shear stress work)
- Paul developed a spreadsheet
- Looking at design Q = Qbf
- Find reference reach
    - Survey
    - Determine Qbf and dimensions based on Manning's
- Manning's provides decent results
- Step 1: Determine existing bankfull parameters for reference reach
- Step 2: channel design
    - Plug into spreadsheet
    - Specify slope, estimated Manning's and bf dimensions
    - Slope and Manning's = not much flexibility
    - Adjust sinuosity when dealing with invert to invert
- Depends on conditions and constraints
- Can change cross-sectional dimensions (i.e. w:d ratio)
- Once variables are defined, goes through a number of calculations for discharge, velocity, shear stress, competence
- Shear stress, slope-depth
- Assuming steady uniform flow
    - Impossible to model otherwise
- Manning's helps determine velocity

- Competence determined by Komar, 1964(?)
- Shields equation – used quite a bit
- Once you learn them, know they function reasonably well, just let the worksheet do its job
- Equations can be tied into other worksheets (e.g. erosion threshold – developed in house by Jeff)
- Use if warranted
- In NCD don't typically need sediment transport model

4. How has your design approach evolved?

a. What do you think triggered this evolution

- Not changed a lot
- Wasn't until recently that everyone began using NCD principles and a more natural approach
- Within the last decade things have turned in the right direction
- Now more holistic, look at
  - Floodplain
  - Water quality
  - Riparian conditions
  - Hydrologics and hydraulics
- Geomorphic Solutions uses a more natural approach
- Now more tools, more accurate assessments
- Peer reviews of designs
  - Still see a lot of engineering
  - If just a single geomorphologist within an engineering firm they may be pressured to do more engineering based designs
- Now geomorphologists aren't an after thought – this has been pushed by the regulatory agencies and as it is necessary for them to get permits a geomorphologist is involved in the design process\

5. Describe typical constraints you face in the design process

a. How do you overcome/deal with these constraints

- If we're brought into the process in a later stage of the process then we get less say and therefore we may not be able to propose a full NCD
- Introduce new design elements to CA/regulatory agencies slowly
- Expectations of regulatory agencies
- Some CA's are easier to work with because they have lower staff turn over
- CAs with higher staff turnover, end up doing indirect training to get them to think how we're thinking
- High turnover = more explanation is necessary
- Have to explain in great detail what design is trying to achieve = more time, money and effort required

6. How do you account for sediment movement and sediment continuity in your designs?

a. What constraints are faced when attempting to include these concepts in your design?

- Yes included
- For NCD size of bed materials to become entrained at Qbf~Qe~Qcf
- Sediment through-put

- Monitoring shows that it's working
- Don't just look at instream sediment – also look at wetland pockets which act as both a sink and a source of sediment

7. **How do you determine design discharge?**
- Qbf = design Q
- Need experience especially in urban channels to ID Qbf
- Use:
    - Undercutting
    - Bar height
    - Change in vegetation
- Topographic survey
    - Do a survey of the long profile of reference reach
- Reference reach = upstream or downstream, as similar as possible
- We don't have regional relationships for Ontario
- Topographic survey
    - Long profile survey = 20x width
    - Start at riffle, end at riffle
    - Bed profile or bankfull profile
    - Cross-sectional survey
        - Depending on uniformity do ~10 cross sections, going beyond the top of channel bank
    - Determine average depth, bankfull with, max depth (useful for range of pool depths), estimated Manning's n based on bankfull conditions
- Also have to look at bigger picture, especially for appropriate meander belt with and amplitude
- Use some of Annables equations
    - Guidelines
    - NEED to understand what limitations there are
- TRCA-Parish Meander Manual – very conservative and not very useful
- Models
    - Williams – empirical relations provide more reasonable numbers therefore don't base meander belt width on single model – see if you have any sort of convergence

8. **What hydraulic and plan-form geometry parameters do you include in the design process?**
    a. **How do you determine when you will or won't use a specific parameter?**
- Riffle-pool spacing
- Radius of curvature
- Wavelength

9. **How do you navigate the permitting process?**
    a. **Relevant regulations/legislations?**
    b. **How do the relevant regulations/legislations impact your design process? If not, why?**
- CA Act
- DFO –implicitly considered, it depends on the level of agreement with the CA and the level of delegation
- This streamlines the process, don't have to approach multiple agencies
- Dealing more with MNR recently re: ESA

   - MNR staff thrown into permitting process
   - Didn't have all procedures in places
   - Slows things down
   - EBR posing period (4 weeks)
   - Has to be signed off by the Minister
- True NCD doesn't influence decision making
   - On same level, trying to provide a benefit
- Issue with process (timing), especially with MNR
- MOE rarely involved
   - More in implementation stage because they control what enters the watercourse
   - PTTW can be lengthy process, depends on category
   - Needed if doing a pump-around, but trying to move away from that
- Now build more diversion channels, temporary flume
- May need to involve a hydrogeologist
- With larger watercourses involve Transport Canada under the Navigable waters (submit design to them, they provide comments)

10. Do you do work on semi-alluvial rivers? (cohesive or bedrock)

a. How does this impact your approach/design?

b. What specific things change when designing a channel that is semi-alluvial?

- Doesn't impact because its all we work with, all our models are built around it
- Same basic concepts because fully alluvial and semi-alluvial

11. Are there any particular design manuals/guidebooks/handbooks that you refer to in the design process?

a. Why or why not?

- Asked as part of Question #3

12. What aspects of a design make a channel geomorphically functional?

- Science based approach
- Open channel, natural system
- Everything
- Provided constraints
- Able to migrate
- Erosion and deposition permitted
- Sediment transport
- Appropriate width:depth ratio
- Take as much into consideration as we can to make sure it functions geomorphically

13. Does geomorphology take precedence over other design objectives?

a. How and why is geomorphology considered in the design process?

- Skipped this question, addressed during previous question

14. Implementation

- Bound to implement what's been designed
- A little bit of flexibility
- May have to do a field fit

- It's an evolving system
- Time between design and implementation
- E.g. downstream invert may now be lower, therefore have to adjust at least part of the design
- Trying to replicate natural system
- Need inspectors that really understand the design
- Erosion and sediment control a big thing right now
- Need in-house inspectors/supervision with proper training
- Inexperienced contractors need to be supervised closely – require more of a plan from us
- Sometimes contractors don't know how to read drawings
- Necessary to be assertive when supervising