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The Influence of Climate and Land Cover Change on Historical Brook Trout (Salvelinus Fontinalis) Populations in the Humber River, Rouge River, and Duffins Creek Watersheds

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by

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ABSTRACT

THE INFLUENCE OF CLIMATE AND LAND COVER CHANGE ON HISTORICAL BROOK TROUT *(SALVELINUS FONTINALIS)* POPULATIONS IN THE HUMBER RIVER, ROUGE RIVER, AND DUFFINS CREEK WATERSHEDS

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Environmental Applied Science and Management

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Long-term records of the abundance of organisms are needed to detect more progressive changes in their populations as a result of external stressors. Long-term changes in historical Brook Trout *(Salvelinus fontinalis)* population abundance were identified in the Humber River, Rouge River and Duffins Creek watersheds in Ontario through statistical analysis of twenty-six years of sampling records. Corresponding historical changes in air and stream water temperature, and in land cover were also examined. Changes detected in climate parameters, and in land cover were then related to Brook Trout population changes. Results revealed that Brook Trout abundance had decreased significantly. These changes were driven by populations in the Humber and Rouge River watersheds. Populations in the Duffins Creek watershed did not change significantly. Climate parameters did change but not significantly over time in the region. However, land cover changes were observed. In the short term, Brook Trout population changes were more likely due to changes in land cover than climate.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 THE PROBLEM

Aquatic organisms are continually exposed to external environmental stressors, potentially causing long-term changes to their populations at a local and regional scale. In southern Ontario, aquatic organisms have been subjected to a particularly large number of stressors over the past fifty years as a result of increases in anthropogenic activities, and changes in the local and regional climate. Many studies have investigated changes in aquatic populations as a result of external stressors in southern Ontario. However, a general lack of long-term monitoring data on aquatic organisms in southern Ontario makes it difficult to discern the long-term effects of these external stressors on aquatic populations.

A long-term historical dataset of southern Ontario Brook Trout *(Salvelinus fontinalis)* populations does exist, but no attempt has yet been made to interpret the full set of information. Many others have looked at the impact of external stressors on local Brook Trout populations in Ontario, particularly at the impact of increasing summer stream water temperatures (Meisner, 1990b; Stoneman & Jones, 2000; Picard, Bozek, & Momot, 2003). However, most of these studies were conducted at a much smaller temporal scale. This historical dataset may allow for the detection of Brook Trout population changes that have occurred over a longer period of time, and may provide opportunities to associate these population changes with more long-term progressive changes in the external environment, such as land use and climate change.

1.2 RESEARCH SIGNIFICANCE

Many of the conservation authorities in Southern Ontario have included Brook Trout as a target species for management in their Fisheries Management Plans (FMPs) because of its need for a specialized cold water habitat, and status as an indicator species. Some of these FMPs include the Duffins Creek FMP (Cook & Clayton, 2004), the Humber River FMP (OMNR & TRCA, 2005), and the Rouge River FMP (OMNR & TRCA, 2010). However, in order to implement effective management of Brook Trout populations in southern Ontario, it is important to be aware of the regional population changes that have occurred over time, and to understand the factors that are influencing these changes.

Furthermore, because of their sensitivity to changes in water temperature, it is expected that Brook Trout populations in southern Ontario are likely to become increasingly threatened as a result of continued land use intensification (Stanfield, Gibson, & Borwick, 2006), and climate change in the future (Magnuson J. J., 1991). The long-term Brook Trout data that are available are particularly useful for studying the impact of broad, long-term changes in the environment, such as climate change, on the populations of aquatic biota.

As implied by their status as an indicator species for high quality cold water habitats, Brook Trout are intolerant of degraded habitats that are generally associated with land use intensification. The threshold for the amount of land use intensification that Brook Trout can tolerate has been estimated to be anywhere from 33% (Stanfield, Gibson, & Borwick, 2006) to 55% urbanization (Steedman, 1988). In a species presence-absence model, the PIC (Percent Impervious Cover) was one of the most important factors that predicted the distribution of Brook Trout in southern Ontario, with water temperature being the most significant variable (Stanfield, Gibson, & Borwick, 2006). Likewise, another study has also concluded that Brook Trout populations are affected by land cover changes that alter the thermal regime of streams. Namely, land use cover types with more impervious surfaces, such as urban areas, do not allow water to percolate into groundwater aquifers, thereby decreasing the amount of cold groundwater inputs into nearby streams (Siitari, Taylor, Nelson, & Weaver, 2011). Sufficient groundwater discharge has in fact been found to be important at maintaining low water temperatures in Brook Trout streams (Meisner, 1990a; Siitari, Taylor, Nelson, & Weaver, 2011).

Many have also speculated on the future impact of climate change on stream water temperatures, and ultimately Brook Trout populations. Climate change is expected to shrink the range of suitable habitat for cold water fish species, including Brook Trout (Stefan, Fang, & Eaton, 2001). This decrease in suitable thermal habitat can crowd Brook Trout populations, potentially slowing down growth and recruitment rates (Dove-Thompson, Lewis, Gray, Chu, & Dunlop, 2011). In a study that forecasted reductions in Brook Trout habitat as a result of climate change, it was estimated that summer thermal habitat will shrink by 30% to 40% in two southern Ontario streams (Meisner, 1990b). This was determined by estimating the distance that Brook Trout's thermal barrier of 24°C would move upstream in response to increases in summer air temperature due to climate change (Meisner, 1990b). In a similar study that focused on populations at the southern boundary of the Brook Trout range, it was concluded that Brook Trout habitat will decrease and become increasingly fragmented as a result of climatic change (Meisner, 1990a). This conclusion was based on the concept that the southern boundary is determined by a groundwater isotherm of 15°C. Climate change projections were used to simulate increases in groundwater temperature at the southern boundary, and to estimate the resulting shifts in the 15°C groundwater isotherm and therefore Brook Trout range as well (Meisner, 1990a).

Knowledge of how Brook Trout populations have changed and responded to ambient air and stream water temperature in the past will indicate how Brook Trout populations will react to future changes in land use and climate.

1.3 RESEARCH OBJECTIVE

Using historical Brook Trout sampling records, this research attempts to identify long-term changes in Brook Trout population abundance over time in the Duffins Creek, Rouge River and Humber River watersheds in the Toronto and surrounding area in southern Ontario. This research also explores the relationship between these population abundance changes, and the corresponding historical changes in ambient air and stream water temperature, as well as past land use changes in the region. The objective of this research is to determine if ambient air and stream water temperature, or land use changes may have influenced the changes in Brook Trout population abundance over time.

1.4 RESEARCH APPROACH

This research consisted of a literature review of Brook Trout biology, ecology, its habitat requirements, and the factors that affected its habitat. A description of the general physiography and watershed features of the study areas was made, as well as the current status of Brook Trout in the Duffins, Humber and Rouge watersheds.

Historical Brook Trout records from the study areas were provided by the Toronto and Region Conservation Authority (TRCA), an agency that specializes in environmental protection and watershed management. The TRCA was interested in finding out how Brook Trout populations have changed over time in association with changes in air and stream water temperature, because of Brook Trout's sensitivity to increases in stream water temperature. The TRCA has over fifty years of Brook Trout records in their possession, with the earliest record collected in 1946 and the latest in 2010. This large dataset holds the potential to illustrate the history of Brook Trout populations in the region. However, no attempt has yet been made to quantitatively analyze the data in order to detect any trends or changes in historical Brook Trout populations in these regions over time. This historical Brook Trout dataset was analyzed to identify any changes in population abundance that have occurred over time. These population changes were related to corresponding historical changes in stream and air temperature in the study areas. In addition, historical land use changes were also examined in order to determine its relationship to Brook Trout populations in the same region over time.

CHAPTER 2: OTHER CONTRIBUTING STUDIES

2.1 Studies of the correlation between Brook Trout populations and temperature

Brook Trout is a sensitive, cold water fish species that is native to southern Ontario (Power, 1980). The presence of Brook Trout is widely used as a local indicator species for healthy cold water aquatic ecosystems in the region (Steedman, 1988) because it naturally inhabits areas that are "generally described as clean, pure, and aesthetically appealing" (Power, 1980). Brook Trout habitat is defined predominantly by temperature (Magnuson, 1991), with summer stream temperature being the single most important factor that determines Brook Trout distribution (Picard, Bozek, & Momot, 2003).

Many studies have examined the relationship between Brook Trout populations and stream water temperature. In the 1980s, Steedman (1988) adapted the already existing Index of Biotic Integrity (IBI), a multivariate measure of stream quality, to local conditions in southern Ontario. In the study, Brook Trout presence contributed significantly to high IBI scores, and was therefore determined to be a reliable indicator of high quality cold water habitats in southern Ontario (Steedman, 1988). In another study of Brook Trout distribution in southern Ontario, summer Brook Trout habitat was found to be restricted by a thermal barrier of 24ºC (Meisner, 1990b). This upper thermal barrier was further confirmed in Picard, Bozek and Mormot's (2003) analysis of Brook Trout presence against five thermal indices in a study in the Lake Superior watershed. The same study also confirmed that Brook Trout presence was a suitable indicator for cold water habitats when it was found that Brook Trout streams were cooler and more thermally stable than streams that contain no Brook Trout individuals (Picard, Bozek, & Momot, 2003). In a more recent investigation, water temperature was again found to be the most influential variable affecting Brook Trout populations in models that used landscape features to predict salmonid distribution and density in southern Ontario (Stanfield, Gibson, & Borwick, 2006).

Additionally, other studies have noted other ways in which water temperature influences Brook Trout individuals and populations. At warmer summer stream temperatures, Brook Trout survival (Xu, Letcher, & Nislow, 2010a), growth rate (Xu, Letcher, & Nislow, 2010b), and biomass (Stoneman & Jones, 2000) have all been observed to decrease. Brook Trout have also been observed to move to cooler areas as water temperatures increase during the summer season (Meisner, 1990b; Mucha & Mackereth, 2008).

2.2 Gaps and opportunities for further investigation

Studies that have been completed on Brook Trout populations in Ontario have typically been conducted at much smaller temporal and/or geographical scales. Steedman (1988) collected fish data during only two summer seasons in 1984 and 1985 across ten watersheds in southern Ontario. Meisner (1990b) similarly looked at Brook Trout populations over only two years from 1987 to 1988 in two headwater streams in southern Ontario. Picard, Bozek and Mormot’s (2003) examination of Brook Trout populations in the Lake Superior watershed also only took place over two summers in 1993 and 1994. Ecological field studies are often constrained by limited human and financial resources, and/or inadequate timelines that are defined by funding agencies and academic institutions, making it difficult for long-term studies to be conducted.

Nonetheless, Stanfield, Gibson and Borwick (2006) have been able to conduct a longer term study that covered a larger geographic area, using fish sampling data that were collected over seven years from 1995 to 2002 in the Oak Ridges Moraine and Niagara Escarpment region of southern Ontario. However, the data were only used to determine the current distribution of Brook Trout, and did not include an examination of how the population had changed over time. An estimation of the reduction in the historic range of Brook Trout was made, but this estimation was not based on actual historical fish collection records (Stanfield, Gibson, & Borwick, 2006).

Additionally, a large number of population studies conducted in southern Ontario have focused on the distribution of Brook Trout in the region, and not their abundance. However, an examination of the abundance of Brook Trout is also warranted because a change in abundance will indicate whether a population is approaching absence at a given sampling site, thereby signifying a potential imminent change in distribution.

Stanfield, Gibson and Borwick (2006) did examine Brook Trout density (number of fish per 100 m^2), in addition to distribution, in southern Ontario. However, this study again only looked at the current density of Brook Trout without examining any changes in density that had occurred over time.

Existing historical fish survey records are valuable in detecting long-term population trends. More recently, the Toronto and Region Conservation Authority (TRCA) did identify changes in Brook Trout abundance through an analysis of fish survey records collected from 2001 to 2009 in the Toronto and surrounding area. It was found that Brook Trout abundance has decreased in approximately 60% of the fish collection sites where Brook Trout individuals were found since 2001 (Croft-White, 2011). Historical fish data were examined as well, but only a qualitative comparison of population trends was made between historical fish families and those from more recent surveys (Croft-White, 2011). Historical records of Brook Trout specifically were not statistically compared with Brook Trout records from 2001 to 2009.

Extensive historical records as far back as 1946 do exist for Brook Trout in southern Ontario, but no effort has yet been made to quantitatively analyze the full body of data that is available. This large dataset may potentially contain information about Brook Trout populations that will prove to be valuable for the management of the species, and warrants further investigation.

CHAPTER 3: BACKGROUND INFORMATION

3.1 BROOK TROUT BIOLOGY AND ECOLOGY

3.1.1 Distribution

Brook Trout are native to the northeastern region of North America, and is especially abundant in Newfoundland, Quebec, the Maritime Provinces and the Great Lakes basin in Ontario, as well as in Maine, Vermont, New Hampshire and New York in the United States (Power, 1980; Kerr & Grant, 2000).

3.1.2 Reproduction

Brook Trout spawn in the fall when day length begins to decrease, and temperatures drop to below 16^{o}C (Power, 1980; Kerr & Grant, 2000). In southern Ontario, conditions ripe for spawning usually occur in October to early December, with optimal spawning occurring at temperatures below 9^{o}C (Kerr & Grant, 2000; Casselman, 2002).

Sites that are selected for spawning by female Brook Trout are typically located on a gravel substrate, and near areas of groundwater upwelling or seepage (Kerr & Grant, 2000; Dove-Thompson, Lewis, Gray, Chu, & Dunlop, 2011). Areas of groundwater upwelling are ideal for incubating eggs because they provide an environment with a stable temperature and optimal dissolved oxygen concentrations (4.0-8.0mg/L) (Kerr & Grant, 2000), and enough flow to remove metabolic wastes from the eggs (Blanchfield & Ridgway, 2005). Presence of groundwater upwelling takes precedence over the type of substrate when selecting sites for spawning. Female Brook Trout compete for spawning sites with groundwater upwelling (Blanchfield & Ridgway, 2005), and are willing to spawn on a sandy or silty substrate, instead of gravel, if groundwater upwelling is present (Power, 1980; Kerr & Grant, 2000). In fact, inadequate groundwater flow contributes to egg mortality (Warren, Sebestyen, Josephson, Lepak, & Kraft, 2005), with eggs surviving only if flow exceeds 20mL/m^{2}min (Blanchfield & Ridgway, 2005).

3.1.3 Life history

In southern Ontario, Brook Trout eggs typically hatch in late February to early March, with fry emerging from the spawning site and swimming freely by March to April (Kerr & Grant, 2000). Brook Trout mortality is highest during the first few months after emergence (Power, 1980). It is a general rule that the reproductive success of fish depends more on larval mortality than egg production (Magnuson, 1991).

Factors that limit the survival of young-of-year Brook Trout include both the availability of overwintering areas (Kerr & Grant, 2000) and sites of thermal refugia during the summer. Young-of-year require shallow, low water velocity areas with abundant cover during the winter (Cunjak & Power, 1986), and areas with cool groundwater seepage to act as thermal refugia against rising temperatures in the summer (Biro, 1998).

Age of sexual maturation and life span varies widely depending on the condition of the surrounding environment. In more southern creeks and streams that have been heavily exploited, the life span is short, most fish spawn only once, and almost all egg production is provided by females of a single age class (Power, 1980). In this context, Brook Trout reach sexual maturation at age two or three, and rarely live for longer than five years (McFadden, 1961; Kerr & Grant, 2000).

3.1.4 Movement

Migration is also dependent on the habitat. Brook Trout that occupy lakes, estuaries and sea water migrate between feeding, overwintering and spawning areas; whereas, Brook Trout that dwell in streams and rivers hardly migrate at all (McFadden, 1961; Power, 1980). However, when environmental conditions are unfavourable, Brook Trout in streams do migrate to more suitable habitats. Brook Trout have been shown to move to cooler upstream reaches during the summer if downstream water temperatures increase to unfavourable levels (Meisner, 1990b; Biro, 1998). Additionally, in a study that tested the fragmenting effects of in-stream barriers on Brook Trout populations by using a computer model that simulated barriers that blocked upstream migration, local extinction of Brook Trout occurred (Letcher, Nislow, Coombs, O'Donnell, & Dubreuil, 2007). In-stream barriers are physical structures that block the upstream and/or downstream movement of fish. Local extinction can, however, be prevented if downstream immigrants are able to enter the blocked stream reach, or if local adaptations to increase juvenile survival, to decrease generation time, and to decrease body size, all characteristics of naturally isolated Brook Trout populations, have occurred (Letcher, Nislow, Coombs, O'Donnell, & Dubreuil, 2007).

3.1.5 Feeding

Brook Trout also display behavioural plasticity in terms of their diet. They are opportunistic feeders that consume whatever prey that is available and abundant around them at the time (Kerr & Grant, 2000). McLaughlin (2001) has observed that Brook Trout display diversification in their foraging behaviour, with some individuals feeding on insect prey in the upper portion of the water column while other individuals feed on crustacean prey in the lower portion of the water column. Brook Trout can, therefore, feed on both terrestrial and aquatic prey (Utz & Hartman, 2007).

3.1.6 Competition

Growth rate and recruitment decreases as Brook Trout density increases (Dove-Thompson, Lewis, Gray, Chu, & Dunlop, 2011). Furthermore, it has been found that higher summer temperatures can exacerbate this inverse relationship between population density and growth rate, possibly because of increased metabolic demands (Xu, Letcher, & Nislow, 2010b) or reduction of suitable thermal habitat at higher temperatures which leads to crowding of Brook Trout individuals and increased intraspecific competition (Dove-Thompson, Lewis, Gray, Chu, & Dunlop, 2011).

Regarding interspecific competition, Brook Trout are generally, but not always, more abundant when other fish species are absent (Stanfield, Gibson, & Borwick, 2006). Furthermore, when the biomass of other trout species is greater than $0.3 g/m^2$, Brook Trout will not be the dominant population within that particular stream reach (Stoneman & Jones, 2000).

However, water temperature has an influence on the competitive edge of Brook Trout against other fish species within a particular stream. When water temperature is less than $20^{o}C$, Brook Trout had a competitive edge that is equal to, if not greater than other fish in the stream. If the water temperature rises to over $22^{o}C$, that competitive advantage disappears (Kerr & Grant, 2000). Additionally, Brook Trout have been found to the dominant species over Rainbow Trout *(Orcorhynchus mykiss)* when in stream pools, in areas with cover, at cooler water temperatures, and at lower stream flow (Kerr & Grant, 2000).

3.2 BROOK TROUT HABITAT

3.2.1 Water temperature as the major limiting factor

Brook Trout are coldwater fish that are naturally found in habitats that are "generally described as clean, pure, and aesthetically appealing" (Power, 1980). The suitability of their habitat is defined predominantly by temperature (Magnuson, 1991), with summer stream temperature being the single most important factor that determines Brook Trout distribution (Picard, Bozek, & Momot, 2003).

The normal range of water temperature that Brook Trout can survive in is 0-20°C (Power, 1980), with their preferred temperature at 15-16°C (Kerr & Grant, 2000; Casselman, 2002), and their upper lethal thermal temperature at 24°C (Meisner, 1990a; Picard, Bozek, & Momot, 2003). The upper lethal temperature of Brook Trout is the same throughout its native range (Meisner, 1990a).

Summers with particularly high water temperatures have been shown to decrease Brook Trout survival (Xu, Letcher, & Nislow, 2010a), decrease their growth rate (Xu, Letcher, & Nislow, 2010b), and to lower overall trout biomass (Stoneman & Jones, 2000).

3.2.2 Importance of groundwater in maintaining optimal temperature

Groundwater discharge has been found to be the key variable that maintains low water temperatures in streams, more so than ambient air temperature (Meisner, 1990a). Sites of groundwater discharge are often 5-7.5ºC cooler than the surrounding ambient stream temperature (Picard, Bozek, & Momot, 2003). Brook Trout have been found to amass around groundwater discharge areas when stream temperatures rise above 20°C (Cunjak & Power, 1986), and to defend these cool microhabitats at the expense of feeding during the summer (Biro, 1998).

Precipitation infiltrates through soil and into underground aquifers. Cooler groundwater from these aquifers can then enter nearby streams through groundwater seepage sites (Siitari, Taylor, Nelson, & Weaver, 2011). The surrounding terrestrial ecosystem can, therefore, have an impact on the amount of groundwater that enters nearby streams.

Soil permeability influences the aquifer recharge rate, and therefore the amount of groundwater discharge into a stream as well (Siitari, Taylor, Nelson, & Weaver, 2011). In contrast to sandier soils, finer soils, such as clays and silts, decrease the ability of water to percolate through the ground, thereby reducing the amount of groundwater discharge into a stream as well (Siitari, Taylor, Nelson, & Weaver, 2011). Soil permeability has a large effect on the stream temperature of headwater streams (Gomi, Sidle, & Richardson, 2002), where Brook Trout are generally found in southern Ontario (Stanfield, Gibson, & Borwick, 2006). Headwater streams consist of the first-order, second-order, and ephemeral or temporary streams in the upper portion of a catchment from which water originates from in a river system, and its water temperature is largely influenced by groundwater discharge (Gomi, Sidle, & Richardson, 2002).

Futhermore, the type of surrounding land cover can affect the aquifer recharge rate as well. Grasslands allow the highest aquifer recharge rates, while industrial/commercial land types lead to the lowest aquifer recharge rates (Siitari, Taylor, Nelson, & Weaver, 2011). Therefore, in urbanized areas where a high proportion of the land is impermeable, precipitation is unable to infiltrate into the ground, thereby decreasing the aquifer recharge rate and reducing the amount of groundwater discharge into nearby streams as well. In southern Ontario, Brook Trout are found in areas with low impervious cover or high forest cover, with populations disappearing when the land cover of a given area reaches 33% urban or 65% agricultural (Stanfield, Gibson, & Borwick, 2006).

3.2.3 Other factors influencing water temperature

In the absence of sufficient groundwater discharge to maintain cool water temperatures in streams, other factors come into play to influence the thermal habitat of Brook Trout (Siitari, Taylor, Nelson, & Weaver, 2011). These factors include the local climate of the area, the amount of riparian cover along the stream banks, and in-stream barriers.

Ambient air temperature can affect stream temperatures by directly warming or cooling the surface waters. A linear correlation exists between ambient air temperature and stream temperature (Crisp & Howson, 1982; Mackey & Berrie, 1991) when air temperature is between 0ºC and 20ºC (Mohseni & Stefan, 1999), making it possible to predict stream water temperatures using only air temperature (Caissie, El-Jabi, & Satish, 2001). At air temperatures below 0ºC and above 20ºC, the regression slope flattens to produce an S-shaped curve because formation of ice cover prevents surface heat exchange at extreme low temperatures, and evaporative cooling maintains water temperatures at extreme high temperatures (Mohseni & Stefan, 1999). Streams that have a large area of surface water or are low in volume are particularly vulnerable to changes in water temperature through exposure to the surrounding ambient air temperature (Siitari, Taylor, Nelson, & Weaver, 2011). Most of the studies that derived a linear correlation between ambient air temperature and stream water temperature took place in areas that are predominantly forested (Crisp & Howson, 1982; Caissie, El-Jabi, & Satish, 2001), with one study that examined a stream with agriculture as the primary surrounding land use (Mackey & Berrie, 1991). Although agriculture, particularly livestock grazing, can increase stream temperature through the removal of riparian vegetation, and stream widening and shallowing, the impact of the land use is small when compared to the influence of weather conditions, such as the ambient air temperature (Borman & Larson, 2003; Webb, Hannah, Moore, Brown, & Nobilis, 2008). Likewise, stream water temperature regimes can change in urbanized areas as a result of the removal of riparian vegetation, wastewater input, and surface runoff, but in recent decades, increases in stream water temperature have instead been attributed to climatic drivers that cause global variations in temperature, such as the North Atlantic Oscillation (NAO) in Europe and the El Niño Southern Oscillation (ENSO) in the Americas (Webb, Hannah, Moore, Brown, & Nobilis, 2008).

The amount of forest cover or riparian vegetation along a stream corridor can also play a significant role in maintaining low water temperatures. Overhanging vegetation can regulate the microclimate around streams by shading and preventing surface water temperatures from rising due to direct insolation (Meisner, 1990a; Siitari, Taylor, Nelson, & Weaver, 2011). With shading, the maximum stream water temperature that was observed significantly decreased when compared to a stream reach without shade (Johnson, 2004). Minimum and mean stream water temperature was, however, unaffected (Johnson, 2004).

In-stream barriers, structures that block the passageway of fish, can also alter the thermal regime of streams, negatively impacting Brook Trout populations (Ward & Stanford, 1983). Moreover, since Brook Trout individuals are known to move to areas of cooler waters when stream temperatures reach unfavourable levels (Meisner, 1990b), in-stream barriers can prevent this migration to more suitable thermal habitats (Siitari, Taylor, Nelson, & Weaver, 2011). On the other hand, in-stream barriers also have a positive effect on Brook Trout by isolating them from other competitive species such as Rainbow Trout (Stanfield, Gibson, & Borwick, 2006). In fact, in-stream barriers have actually been maintained, as a part of fisheries management actions, in order to protect Brook Trout populations from harmful competitors (Cook & Clayton, 2004; OMNR & TRCA, 2010).

3.2.4 Other habitat features

In streams with ideal water temperatures of below 20°C, other habitat features become more important in distinguishing healthy and unhealthy Brook Trout populations (Picard, Bozek, & Momot, 2003). Stoneman and Jones (2000) has found that Brook Trout biomass is greatest when the percentage of pool habitat within a given stream reach is high (>20%), when the size of the stream bed substrate is small (pebbles <26.mm in diameter), and when there is ample riparian cover present (>15.6%). Moreover in another study, it was found that Brook Trout that are greater than one year old require more cover (35%) than younger individuals (Johnson, 2008).

Brook Trout prefer moderate to slow flowing water (Kerr & Grant, 2000), although it has been found that extreme low flow during the summer can decrease the survival of larger fish in smaller tributaries at the headwaters (Xu, Letcher, & Nislow, 2010a).

Brook Trout also have a wide pH tolerance (Power, 1980), but habitats with pH levels greater than six are ideal (Dove-Thompson, Lewis, Gray, Chu, & Dunlop, 2011). Populations are extirpated from lakes with a pH level of less than five (Beggs & Gunn, 1986). Dissolved oxygen levels that are greater than 7.0mg/L at 15°C are optimal, with the lowest tolerable dissolved oxygen levels at 0.9mg/L at 10°C or 1.8mg/L at 20°C (Kerr & Grant, 2000).

CHAPTER 4: STUDY AREAS

The study areas for this research were defined by the locations of historical Brook Trout sampling records that were available and appropriate for analysis. These records were collected in areas located within tributaries of the Humber River, Duffins Creek, and Rouge River watersheds. The majority of records are situated in the headwaters region of the watersheds, with the exception of the Duffins watersheds where many Brook Trout records exist within the mid-reaches as well (Figure 1). In the Humber River watershed, Brook Trout records extend from the headwater reaches, and south into Caledon, King, and the northern portion of Vaughan. Brook Trout records in the Rouge River watershed are generally present for Richmond Hill and Stouffville, with a few records extending south into the northern edge of Markham. Brook Trout records are present throughout the Duffins Creek watershed with records extending as far south as Highway 401.

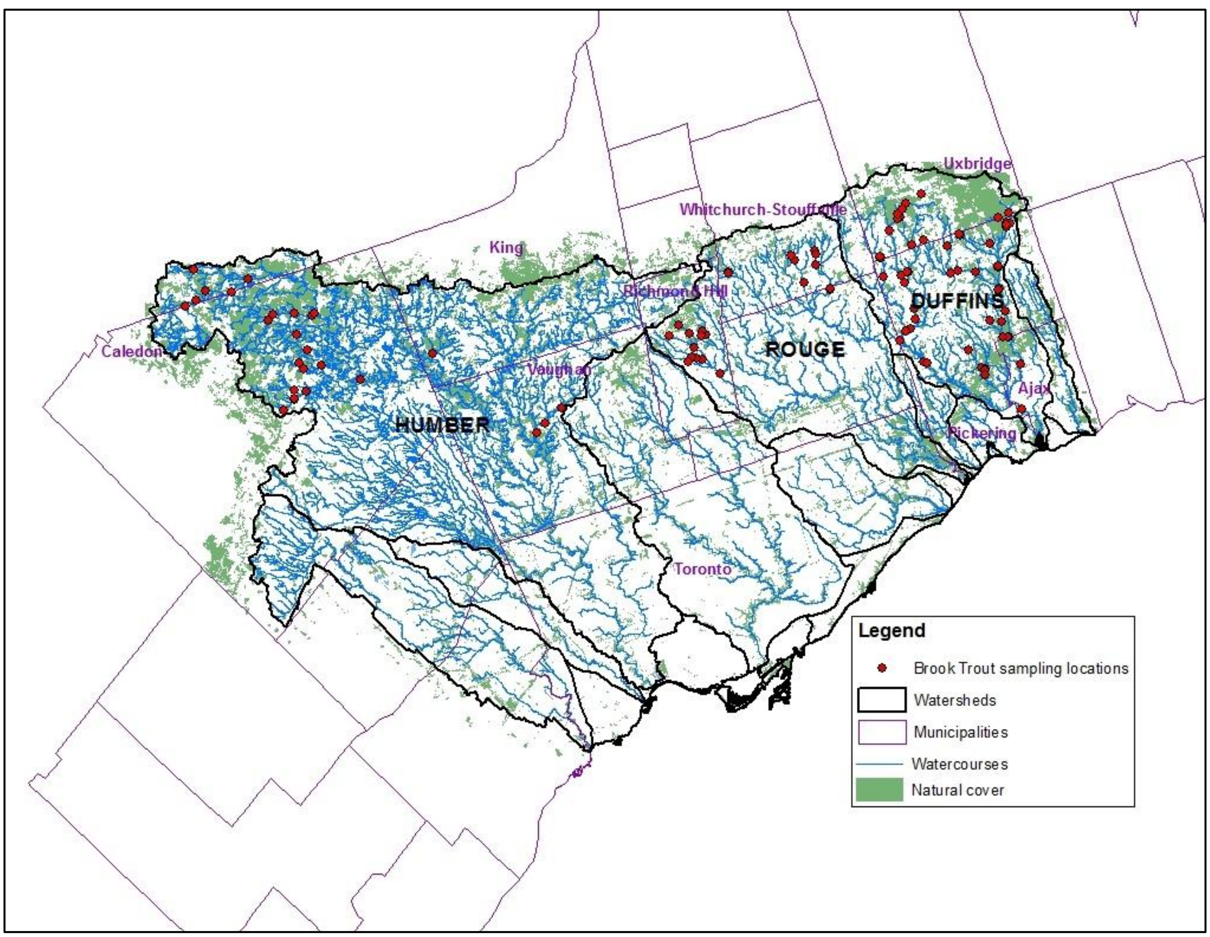

Figure 1: Map of Brook Trout sampling locations in the Humber River, Rouge River, and Duffins Creek watersheds. Source: Map created by compiling ESRI shapefiles provided by TRCA using ArcMap 10.

4.1 GENERAL PHYSIOGRAPHY

The headwaters of the Duffins Creek and Rouge River watersheds originate in the Oak Ridges Moraine (Chapman & Putnam, 1984), while the headwaters of the Humber River watershed is sourced mainly from the Oak Ridges Moraine, with a small percentage of the watershed originating from the Niagara Escarpment (Humber Watershed Task Force, 1997) (Figure 2). The Oak Ridges Moraine is a ridge of drift extending east-west from the Niagara Escarpment to the east, to the Trent River to the west (Chapman & Putnam, 1984). The soil surface of the moraine is made up of coarse sand or gravel substrate (Chapman & Putnam, 1984), which increases the degree of water infiltration into the soil and groundwater discharge to headwater tributaries. These characteristics minimize the amount of surface water run-off that enters into the streams, and keeps water temperatures cool (OMNR & TRCA, 2005). The Niagara Escarpment bisects the western end of the Oak Ridges Moraine, and extends north-south from the Niagara River to the south, to the Bruce Peninsula to the north (Chapman & Putnam, 1984).

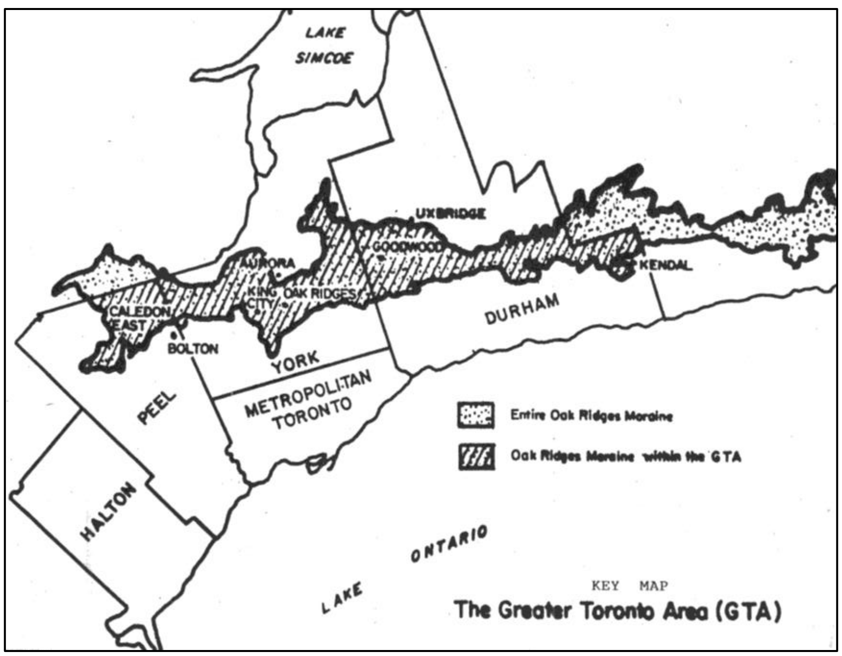

Figure 2: Map of the Oak Ridges Moraine. Source: OMNR. (1994). *Land use patterns on the Oak Ridges Moraine area within the Greater Toronto Area.* Toronto: Ontario Ministry of Natural Resources.

Further downstream from the headwaters, the watersheds are generally made up of Peel Plain in the Humber River watershed (Humber Watershed Task Force, 1997) and the Rouge River watershed (Rouge Watershed Task Force, 2007), and Halton Till Plain in the Duffins watershed (Cook & Clayton, 2004). These middle portions of the watersheds consist of mainly clay and silt soils, which increase the degree of surface water runoff into the streams, leading to unstable stream water temperature and flow (OMNR & TRCA, 2005).

4.2 HUMBER RIVER WATERSHED

4.2.1 Watershed features

The Humber River Watershed encompasses a total drainage area of 908 km^2, with the main branch of the river running 100 km from the Niagara Escarpment to the Lake Ontario shore to the south (Humber Watershed Task Force, 1997). It is comprised of five subwatersheds: the Upper Main Humber River subwatershed, the West Humber River subwatershed, the East Humber River subwatershed, the Lower Main Humber River subwatershed, and the Black Creek subwatershed (OMNR & TRCA, 2005).

4.2.2 Land use

Types and degrees of land use vary widely throughout the Humber River watershed. Overall, Approximately 26% of the watershed is developed, 40% of the watershed is comprised of rural lands, and 32% of the watershed is still under natural cover (TRCA, 2011). Development has historically been concentrated in areas south of Highway 7 (OMNR & TRCA, 2005).

At the headwaters, the Niagara Escarpment is designated as a United Nations Education, Scientific and Cultural Organization (UNESCO) World Biosphere Reserve, and the Oak Ridges Moraine is predominantly rural and agricultural (Humber Watershed Task Force, 1997). On the South Slope of the Oak Ridges Moraine, agriculture again dominates in the municipalities of Caledon, King and Vaughan (Humber Watershed Task Force, 1997).

4.2.3 Habitat quality

The quality of the aquatic habitats also varies widely across the entire watershed. Generally, the more rural upper potions of the watershed, the Upper Main, East and West Humber River subwatersheds, hold the highest quality aquatic habitats (OMNR & TRCA, 2005). The Upper Main Humber River subwatershed has the most overhanging riparian vegetation over its watercourses in the entire watershed, which helps to keep water temperatures cool. The West Humber River subwatershed, however, has the least amount of riparian vegetation along its banks (28%) and is therefore more susceptible to water temperature increases due to insolation (OMNR & TRCA, 2005). The main contributors to water quality degradation in these subwatersheds are suspended solids, bacteria and nutrients (OMNR & TRCA, 2005).

The aquatic habitats in the more urbanized Lower Main Humber River and Black Creek subwatersheds are more degraded. Water quality impairment within these subwatersheds are due to contaminant loading from stormsewers, combined sewage overflow and chemical spills, to name a few (OMNR & TRCA, 2005).

An analysis of the current water quality (samples taken from 2005 to 2009) of watersheds within and around the Toronto region was made in 2010. The study included an examination of several water quality parameters including the degree and frequency of nutrient loading, heavy metals and bacterial presence, and assigned each watershed with a rating, ranging from “A” to “F”, for its water quality (TRCA, 2010). The Humber River watershed received the second highest rating (“B”) for its water quality, with the overall water quality rating for all of the watersheds in the study combined at “C” (TRCA, 2010).

4.2.4 Brook Trout

In 2001, fish stations all across the Humber River watershed were sampled and a total of 43 fish species were found, including Brook Trout. Brook Trout were found in 26% of the fish stations sampled, but their presence was confined to only the higher quality coldwater habitats of the Upper Main and East Humber River subwatersheds (OMNR & TRCA, 2005). Development in the upper regions of the watershed, on the Niagara Escarpment and Oak Ridges Moraine, is limited, and groundwater recharge of streams is high, creating suitable coldwater habitat for Brook Trout (Humber Watershed Task Force, 1997). It was recognized that the presence of

Brook Trout was an indicator of streams that were not highly urbanized and had adequate riparian vegetation (OMNR & TRCA, 2005).

Brook Trout harvesting does occur, but only recreationally by individual anglers. The OMNR has strict regulations in place to control catch limits to manage Brook Trout populations (OMNR & TRCA, 2005). Brook Trout stocking has occurred in the Humber River watershed to enrich already present populations. A total of 306,960 individuals have been stocked every year between 1923 and 1972 in parts of the Town of Caledon, and in the Townships of Mono and Adjala-Tosorontio (OMNR & TRCA, 2005). Stocking of Brook Trout has not occurred since 1972 (OMNR & TRCA, 2005). However, mitochondrial DNA analyses have shown that there is no longer any Brook Trout hatchery fish present at the stocked sites (McLaughlin, 2001).

4.3 Duffins Creek Watershed

4.3.1 Watershed features

The Duffins Creek watershed covers an area of 283 km^2 (Duffins Creek and Carruthers Creek Watershed Task Force, 2003), with a total of 373 km of watercourses running through the area (Cook & Clayton, 2004). It is comprised of two larger subwatersheds, the West Duffins Creek and East Duffins Creek, in addition to four smaller subwatersheds, Urfe Creek, Ganatsekiagon Creek, Miller's Creek and Lower Duffins Creek (Cook & Clayton, 2004).

4.3.2 Land use

A majority of the Duffins Creek watershed remains rural or under natural cover, with 54% in agricultural use, 37% under natural cover, 7% has undergone urbanization, and the remaining 2% has been converted into golf courses (Cook & Clayton, 2004). Urbanization is concentrated in the lower reaches of the watershed, south of Taunton Road in the City of Pickering and Town of Ajax (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). The middle reaches of the watershed are predominantly agricultural, with large areas in the headwater regions to the north remaining as forests, meadows and wetlands (Duffins Creek and Carruthers Creek Watershed Task Force, 2003).

A large proportion of the watershed is under public ownership, with 8% owned by TRCA, 24% owned by the federal government, and 10% owned by the provincial government (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). TRCA lands are currently used for educational, recreational, agricultural and forestry purposes. Although the federal and provincial lands were initially acquired in the early 1970s for the purposes of developing a new airport and city, both plans have been suspended since 1975, and the continuation of both plans are heavily debated and remains undecided (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). These lands, consequently, remain undeveloped.

In 2001, the federal government has committed to protecting federally owned portions of the Oak Ridges Moraine and areas surrounding Rouge Park (Duffins Creek and Carruthers Creek Watershed Task Force, 2003), ensuring that at least a proportion of lands will remain undeveloped in the future. Moreover, the provincial government officially recognized the Oak Ridges Moraine region as an area of provincial interest in 1991, and in 2001, established a six month development moratorium in the area, and initiated the development of the Oak Ridges Moraine Conservation Plan (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). Additionally, the Duffins Creek corridor is designated as an Environmental Protection Area, ensuring the protection of natural areas along stream and valley corridors, as well as the Rouge-Duffins Wildlife Corridor (Duffins Creek and Carruthers Creek Watershed Task Force, 2003).

4.3.3 Habitat quality

The Duffins Creek watershed is one of the healthiest watersheds situated along the north shore of Lake Ontario (Duffins Creek and Carruthers Creek Watershed Task Force, 2003), and all of the streams are generally high in water quality with the exception of Stouffville Creek, Miller’s Creek, and Lower Duffins Creek (Cook & Clayton, 2004). A large number of the watercourses still have riparian vegetation along their stream banks (76%) (Cook & Clayton, 2004), helping to preserve the watershed’s coldwater aquatic habitats.

Despite the generally high water quality, agricultural and urban runoff, and the Stouffville sewage treatment plant still play a role in polluting aquatic habitats in the Duffins Creek watershed (Cook & Clayton, 2004). However, phosphorus concentrations decreased significantly in the West and Lower Duffins Creek in 1980 when improvements were made to the Stouffville sewage treatment plant, riparian vegetation, and agricultural practices (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). The Stouffville sewage treatment plant has since been decommissioned in 2007 (TRCA, 2007). Additionally, in a priority pollution study conducted by the Ontario Ministry of Environment in 2000, it was found that the Duffins Creek watershed had only a few organic pollutants that were detected in trace amounts, normal metal concentrations, and no evidence that the water quality would be toxic to fish communities (Duffins Creek and Carruthers Creek Watershed Task Force, 2003; Cook & Clayton, 2004).

In an analysis of current water quality of watersheds in the Toronto and surrounding region, the Duffins Creek watershed received the highest rating ("A") for its water quality (TRCA, 2010).

4.3.4 Brook Trout

Brook Trout is a target species for management in the small riverine coldwater habitats and the intermediate riverine coldwater habitats of the Duffins Creek watershed (Cook & Clayton, 2004). A large proportion of the watershed is fed by groundwater, resulting in a large number of coldwater streams that are able to support Brook Trout populations (Duffins Creek and Carruthers Creek Watershed Task Force, 2003). Additionally, the hydrology of the Duffins Creek watershed is characteristic of undeveloped areas, with peak flow occurring in the spring, due to the relatively small amount of urbanization and large percentage of natural cover in the region (Cook & Clayton, 2004). This feature of the Duffins Creek watershed is ideal for supporting populations of Brook Trout.

Despite the seemingly ideal habitat conditions for Brook Trout in the Duffins Creek watersheds, factors that impede Brook Trout populations still do exist. In-stream barriers can create on-line ponds that are often not shaded, and are susceptible to warming due to insolation (Cook & Clayton, 2004). On the other hand, barriers can also have a positive effect on Brook Trout populations by protecting them from downstream competitors, such as Sea Lamprey *(Petromyzon marinus)* and Rainbow Trout *(Oncorhynchus mykiss)* (Cook & Clayton, 2004). Three in-stream barriers are maintained in the Duffins Creek watershed for the specific purpose of managing Brook Trout populations (Cook & Clayton, 2004).

Brook Trout harvesting occurs in the form of recreational angling in the Duffins Creek watershed. The OMNR enforces fishing regulations in order to manage Brook Trout populations

(Cook & Clayton, 2004). Brook Trout have been stocked in the Duffins Creek watershed from 1950 to 1991 by the OMNR for rehabilitation purposes (Cook & Clayton, 2004). Brook Trout stocking has not occurred since 1991.

4.4 ROUGE RIVER WATERSHED

4.4.1 Watershed features

The Rouge River Watershed encompasses a total drainage area of 336km^2 (Rouge Watershed Task Force, 2007). It is made up of two subwatersheds: the Main Rouge River subwatershed, and the Little Rouge River subwatershed.

4.4.2 Land use

Approximately 40% of the Rouge River Watershed is rural, 35% is urban, and 24% still retains its natural cover (Rouge Watershed Task Force, 2007). The Rouge Park makes up a large portion of the lower watershed, urban development is underway and little natural cover is left in the middle and western sections of the watershed, and rural and agricultural lands dominate in the upper and eastern parts of the watershed (Rouge Watershed Task Force, 2007).

4.4.3 Habitat quality

Compared to the neighbouring Don River and Highland Creek watersheds, the Rouge River water quality is relatively good. Only a few pollutants have risen in concentration since the 1970s. Most pollutant concentrations have decreased since then (Rouge Watershed Task Force, 2007). Some pollutants of concern include the rising chloride concentrations from road salt during the winter, particularly near heavy traffic areas, the nutrient levels around agricultural lands, and the increase in suspended solids, metals, nitrates and phosphorus concentrations from surface runoff during rain periods near urban and agricultural areas (Rouge Watershed Task Force, 2007).

In an analysis of current water quality of watersheds in the Toronto and surrounding region, the Rouge River watershed received the second highest rating ("B") for its water quality (TRCA, 2010).

4.4.4 Brook Trout

Brook Trout has been listed as a target species for management in the Rouge River FMP (OMNR & TRCA, 2010). Brook Trout are located in the small coldwater streams at the headwaters in the northeast and northwest corners of the Rouge River watershed (OMNR & TRCA, 2010). These areas have the highest groundwater recharge rates in the entire watershed, and are able to support sensitive fish species, such as the Brook Trout (OMNR & TRCA, 2010). Brook Trout spawning has also been recorded in the western reaches of the watershed (OMNR & TRCA, 2010). However, online ponds may be causing thermal warming of one of the Fisheries Management Zones, potentially threatening populations of Brook Trout (OMNR & TRCA, 2010).

There are only a few areas with public access to allow for Brook Trout angling. Most of the headwaters are under private ownership, thereby restricting recreational angling of Brook Trout by the public (OMNR & TRCA, 2010).

Some stocking of Rainbow Trout at Brook Trout locations has occurred in the past. The current Fisheries Management Plan states that the OMNR should assess and document the negative impact of Rainbow Trout stocking on Brook Trout before any further action is taken (OMNR & TRCA, 2010). The Rouge River Watershed Plan has identified three Rainbow Trout stocking sites where Brook Trout will not be affected (OMNR & TRCA, 2010). Barriers exist in some areas to prevent stocked Rainbow trout from migrating to headwater sites where Brook Trout populations are present (OMNR & TRCA, 2010). Also, it has been determined that Rainbow Trout production should not impact Brook Trout populations in the Little Rouge River subwatershed.

CHAPTER 5: METHOD

5.1 DATA

5.1.1 Brook Trout data

The TRCA has an abundance of historical Brook Trout records in the Humber River, Rouge River, and Duffins Creek watersheds. In total, there are 410 records that span from 1946 to 2010. Most of the Brook Trout record entries included, at minimum, the sampling date, sample identification number, watershed and site sampled, UTM coordinates of the sample site, and the number of individuals observed at the sample site. The individual or agency that conducted the sampling was sometimes recorded. Earlier records from the 1940s and 1950s were collected by the now defunct Ontario Department of Planning and Development (ODPD) as a part of a series of watershed surveys (Martin-Downs, 2011). There is a lack of Brook Trout data during the 1960s. Records from the 1970s were mostly collected by the OMNR as a part of a sampling blitz. The majority of the records from the 1980s, 1990s and 2000s were collected by the OMNR and the TRCA. Many of the records from the 1980s were also collected by Robert Steedman as a part of his Ph.D. dissertation (Steedman, 1988). Brook Trout data collected by the TRCA in the 2000s were completed as a part of a fish community survey for their Regional Watershed Monitoring Program (TRCA, 2010). The data collected by TRCA in the 2000s were used for a variety of purposes: to assess general watershed health, to obtain a general picture of the fish community, to aid in fisheries management planning, and to develop tools and models in order predict the effects of landscape level disturbance on aquatic communities by the Southern Ontario Stream Monitoring and Research Team (SOSMART) (TRCA, 2010).

The initial impression of the Brook Trout dataset was that it was temporally and geographically broad, comprehensive, and of a high quality. However, upon further examination, it became clear that there were many gaps and inconsistencies in the collection and recording of the data that affected its quality. For example, in many cases the year and/or month of sampling, and the sampling methodology used to collect the fish were not recorded. Therefore, many records that had information gaps and inconsistencies were omitted from analysis. All records that had either the month and/or year of sampling missing were omitted from analysis.

Knowledge of the methodology that was used to collect the data was crucial to the interpretation of the data. The probability of detecting and/or catching an individual fish in a given stream reach will differ depending on the technique used to capture the fish, whether it be via seining or electrofishing (Nett, Campbell, Mandrak, & Tiegs, 2012). Therefore, in order to ensure that the detection probability of Brook Trout remains constant throughout the dataset, records included in the analysis must all be collected using the same sampling technique. Historically, both seining and electrofishing have been used to collect Brook Trout data. However, since a greater proportion of records were sampled using electrofishing, entries that indicated seining as the sampling technique were omitted from analysis. All records that did not specify the sampling methodology used to collect fish were also omitted from analysis.

5.1.2 Air temperature data

Air temperature data were obtained from the Environment Canada Toronto Buttonville A weather station located in Richmond Hill, Ontario. This particular weather station was selected because it was centrally located among the Humber River, Rouge River and Duffins Creek watersheds. The farthest location where Brook Trout were sampled was located approximately 49km away from the weather station. The Toronto Buttonville A weather station was also selected because it had all of the corresponding air temperature data for the years during which the Brook Trout data utilized for analysis were collected. No other single weather station in the region contained all the relevant air temperature data for the entire period of time during which the Brook Trout data, used for analysis, were collected.

Since Brook Trout survival is limited by high summer stream water temperatures (Xu, Letcher, & Nislow, 2010a) and stream water temperature is correlated with ambient air temperature (Caissie, El-Jabi, & Satish, 2001), the air temperature parameters of interest were the monthly mean maximum air temperature, and the monthly extreme maximum air temperature (highest air temperature recorded for the month) during the hot summer months. These two air temperature parameters have the greatest capacity to increase stream water temperature during the summer months.

Consequently, for the years that Brook Trout data were available for analysis, the monthly mean maximum summer air temperature was obtained for the months of June (from the 16^{th} to 30^{th}

only), July, August and September (from the 1st to 15th only). Also, for the years that Brook Trout data were available for analysis, the monthly extreme maximum summer air temperature was obtained for the months of June (from the 16th to 30th only), July, August and September (from the 1st to 15th only). Air temperature data were only taken for half of June and September because corresponding stream water temperature data were only available from June 16th up until September 15th.

5.1.3 Stream water temperature data

Stream water temperature data were provided by the TRCA. Stream water temperature data were obtained from three data loggers, each located in one of the three watersheds. All of the data loggers were located in second order streams in the headwaters of the watersheds where Brook Trout have recently been sampled. Data loggers cannot collect stream water temperature information in first order streams because they have intermittent reaches with no flow during dry conditions (Gomi, Sidle, & Richardson, 2002).

Stream water temperature data were only available for the years 2003, 2006 and 2009 for the Duffins Creek and Rouge River watersheds, and for the years 2004 and 2007 for the Humber River watersheds. A data logger was also placed at the Humber River watershed location in 2010, but the data logger was washed away mid-season so stream water temperature data for that year was incomplete. Stream water temperatures were taken intermittently by each of the data loggers from June 16th until September 15th. The daily stream water temperature at 4pm was obtained for analysis because the water temperature at that time represents the maximum water temperature for that day (Stanfield, 2007). The extreme maximum stream water temperature (highest stream water temperature recorded) for each month was also obtained for analysis.

5.1.4 Land cover change data

Land cover was also analyzed because of its influence on Brook Trout populations (Stanfield, Gibson, & Borwick, 2006), on groundwater discharge rates, and therefore on stream water temperature as well (Siitari, Taylor, Nelson, & Weaver, 2011). The change in land cover over time, in areas where Brook Trout were historically present in the Humber River, Rouge River, and Duffins Creek watersheds, was assessed by comparing land cover in historical aerial photographs with land cover in more recent satellite images. The method used to assess land cover change is outlined in Section 5.2.4 on page 30. Historical aerial photographs from 1954 were obtained from the Canada Topographic Survey's aerial photo collection at the University of Toronto's Map and Data Library (Canada Topographic Survey, 1954). More recent satellite images from 1999 to 2000 were obtained from Natural Resources Canada's collection of digital satellite images, accessed via www.geogratis.ca (Natural Resources Canada, 2003).

5.2 ANALYSIS

5.2.1 Catch Per Unit Effort (CPUE)

Catch Per Unit Effort (CPUE) was used as an estimate of the true abundance of Brook Trout. CPUE was used because the number of Brook Trout individuals caught during a single sampling event will differ depending on the amount of effort that is used to catch the fish (FAO, 1969). For example, if more time was invested into sampling Brook Trout during sampling event "A" than sampling event "B", then the catch for sampling event "A" may be greater only because more effort was invested into the sampling. Therefore, the sampling effort needs to be standardized by dividing the catch by the effort that was used during that particular sampling event (FAO, 1969).

In order to keep the detection probability of Brook Trout consistent across the records, only catch data from the first electrofishing sampling pass (single-pass survey) were used to calculate CPUE. Many of the Brook Trout records that utilized electrofishing as the sampling technique collected the data with only a single-pass. Multiple-pass electrofishing surveys were used more rarely than single-pass surveys, because multiple-pass surveys were more labour intensive, time consuming, and expensive than single-pass surveys (Reid, Yunker, & Jones, 2009). Therefore, in order to ensure that as many entries as possible were included in the analysis, and that the data remained consistent, only data collected using single-pass electrofishing surveys were used for analysis. Data collected from second-pass, third-pass, or forth-pass electrofishing surveys were omitted from analysis. Catch data obtained from single-pass electrofishing surveys have been shown to be a good predictor of trout abundance in various locations (Kruse & Hubert, 1998; Rosenberger & Dunham, 2005), including in southern Ontario (Jones & Stockwell, 1995).

Additionally, only Brook Trout samples that have the required variables recorded to calculate CPUE were included in the analysis. In this case, CPUE is the number of Brook Trout individuals that were caught within one square metre during one hour of electrofishing. Therefore, the required variables for each record were the number of Brook Trout individuals caught, the time spent electrofishing, and the area of the stream reach that was sampled. All records utilized in the analysis had the first two variables available. Most, but not all, of the records had the wetted channel width, the cross-sectional width of the water in a stream channel, and the length of stream reach sampled recorded in order to calculate the area sampled. For records that had the wetted channel width missing, the mean width of all the records for that same year was used to calculate the CPUE. For records that have the length of stream reach sampled missing, the mean length of all the records for that same year was used to calculate CPUE. Finally, for records that were missing both length and width of the sample area, the mean sample area of all the records for that same year was used to calculate CPUE.

The effort for each Brook Trout record was calculated by multiplying the total hours spent electrofishing by the area that was sampled. The catch for that entry is then divided by the effort to get the CPUE (Morgan & Burgess, 2005). Therefore, the final equation used to calculate CPUE was:

$$\text{CPUE} = \frac{\text{number of individuals}}{\text{hours spent e-fishing x area sampled}}$$

The CPUE was calculated for every single Brook Trout record that was included in the analysis. The annual mean CPUEs were then calculated for all of the watersheds combined, as well as for the Humber River, Rouge River and Duffins Creek watersheds individually. Standard deviations were determined for each of the annual mean CPUEs.

5.2.2 Air temperature

A simple linear regression analysis was conducted on both air temperature parameters to determine if monthly mean maximum summer air temperature, and/or monthly extreme maximum summer air temperature was changing significantly over time.

5.2.3 Stream water temperature

For each year that stream water temperature data were available, the monthly mean maximum stream water temperature was calculated, and the monthly extreme maximum stream water temperature was extracted from the dataset. A simple linear regression analysis was conducted on both stream water temperature parameters to determine if monthly mean maximum stream water temperature, and/or monthly extreme maximum stream water temperature were changing significantly over time.

Additionally, a method was needed in this study to evaluate the thermal stress that the surrounding stream habitat was imposing on Brook Trout. A model framework that assessed the cumulative thermal stress of fish had been previously developed by Bevelhimer and Bennett (2000). However, this model was deemed inappropriate for use in this study because the model required knowledge of the period of time that the fish were exposed to thermal stress. During this period of time, either stress accumulation, when stressful temperatures remain elevated, or recovery, when temperature lowers to optimal levels, can occur, but not both (Bevelhimer & Bennett, 2000). In the data used in this study, only daily stream water temperature data at 4 pm were obtained. Since both thermal stress accumulation and recovery can occur within a day, the parameter that was required in the model by Bevelhimer and Bennett (2000) was not available for analysis. Additionally, since the model by Bevelhimer and Bennett (2000) was only a framework and had not been fully developed nor tested, the model was again considered inappropriate for use in this study. Since no existing thermal stress assessment method that was appropriate for use in this study was found, a weighted thermal stress indicator was developed in this study to gauge the incremental stress that increased temperatures were imposing on Brook Trout in a given year.

For the weighted thermal stress score that was developed in this study, days were grouped according to their maximum stream water temperature for each year that data were available. For example, days with maximum stream water temperatures between 16.0ºC to 18.9ºC were grouped within the same category. The other categories were days with maximum stream water temperatures between 19.0ºC to 21.9ºC, 22.0ºC to 24.9ºC, and 25.0ºC and over. The groups were then scored depending on the amount of thermal stress they would inflict on Brook Trout, with higher temperatures inflicting greater thermal stress. For example, the number of days in the

16.0ºC to 18.9ºC category was multiplied by only one because those days would not have imposed much thermal stress on Brook Trout. The number of days in the 19.0ºC to 21.9ºC category was multiplied by two, and the number of days in the 22.0ºC to 24.9ºC category was multiplied by three. Finally, the number of days in the 25.0ºC and over category was multiplied by four. Days in this final group were weighted most heavily by this scoring method because Brook Trout during these days were exposed to the greatest amount of thermal stress. The scores for each category were then added together each year to produce an annual total thermal stress score. As a result, years with the highest thermal stress scores have streams that were inflicting the greatest amount of thermal stress on Brook Trout.

5.2.4 Land cover change

Areas where Brook Trout populations were historically concentrated were delineated on the aerial photographs from 1954. The same corresponding areas were also delineated on the satellite images from 1999 to 2000. For each delineated area, land cover in each road block, the area bounded by major roads, from the 1954 aerial photographs were qualitatively compared to land cover in the same road block from the 1999 to 2000 satellite images. For example, qualitative observations were made on whether land cover has remained the same within a particular road block since 1954, or whether urbanization, agriculture or naturalization, the regrowth of vegetation, has increased within that particular road block since 1954. For each of the delineated areas, the percentages of road blocks that had experienced an increase in urbanization, agriculture, natural areas, or have remained the same were calculated.

5.2.5 Relationship between air temperature and stream water temperature

Stream water temperature data were only available from 2003 to 2009. There were no historical data on stream water temperature available for the Humber River, Rouge River and Duffins Creek watershed. Other studies have demonstrated that stream water and ambient air temperature were linearly correlated in certain environments, allowing air temperature to be a predictor of stream water temperature in the absence of sufficient stream water temperature data (Crisp & Howson, 1982; Mackey & Berrie, 1991; Caissie, El-Jabi, & Satish, 2001). Air temperature data were correlated with stream water temperature data to see if this relationship was also true in this context.

A Pearson r correlation analysis was calculated to determine if monthly mean maximum air temperature was correlated with monthly mean maximum stream water temperature. A Pearson r correlation analysis was also used to determine if monthly extreme maximum air temperature was correlated with monthly extreme maximum stream water temperature.

5.2.6 Relationship between CPUE, temperature and land cover change

A qualitative, descriptive analysis of the relationship between the change in CPUE, and the change in air and stream water temperature parameters over time was made. A similar analysis was made to describe the relationship between the change in CPUE over time, and the change in land cover over time.

CHAPTER 6: RESULTS

The objective of this research was to determine if Brook Trout population abundance has historically changed over an extended period of time, and whether this change has corresponded with historical changes in ambient air and stream water temperatures. Additionally, an assessment of land cover change over time was completed to see if these changes could have had an influence on Brook Trout population abundance changes over time as well. The results of these investigations are presented below.

The only other study that examined Brook Trout populations using a temporally large dataset was completed by Stanfield, Gibson and Borwick (2006). However, that study investigated the distribution and not the abundance of Brook Trout, only used the data to depict the current and not the historical change in distribution, and still only utilized seven years of data in its analysis (Stanfield, Gibson, & Borwick, 2006).

6.1 CHANGE IN CPUE OVER TIME

After all the appropriate omissions were made as described in the Method, the final number of Brook Trout records included for analysis was 129, and spanned a period of twenty-six years. The earliest record was collected in 1984, and the latest in 2010. All records collected before 1984 had inconsistent and/or missing data, and therefore could not be included in the analysis. The CPUE was calculated for all the remaining records, and the mean CPUE was calculated for all records within the same year. The resulting standard deviations that were obtained from the annual mean CPUE calculations were large for every year that data were available. Brook Trout records included in the analysis, and the corresponding calculated CPUE values can be found in Appendix A. The annual mean CPUE values for each of the individual watersheds and all the watersheds combined, as well as the corresponding standard deviations can be found in Appendix B to F.

A scatter plot of mean CPUE vs. Year for all of the watersheds combined reveals that the data are not normally distributed (Figure 3), and a simple linear regression analysis cannot be used to interpret the data. Descriptive statistics were therefore used to summarize the data instead. The scatter plot of mean CPUE vs. Year for all of the watersheds combined reveals that data between 1986 and 1995 were absent (Figure 3). When comparing pre-1986 and post-1995 mean CPUE, the mean CPUE values from before 1986 (mean = 0.983; standard deviation = 0.672) is greater than the mean CPUE values from after 1995 (mean = 0.124; standard deviation = 0.0895). However, the 1985 mean CPUE value is considerably higher than all the other mean CPUE values, and may therefore be considered an outlier (Figure 3). When the 1985 mean CPUE outlier was excluded from analysis, a difference between mean CPUE before 1986 (1984 mean CPUE = 0.508) and mean CPUE after 1995 (mean = 0.124; standard deviation = 0.0895) is still detectable, but not as apparent.

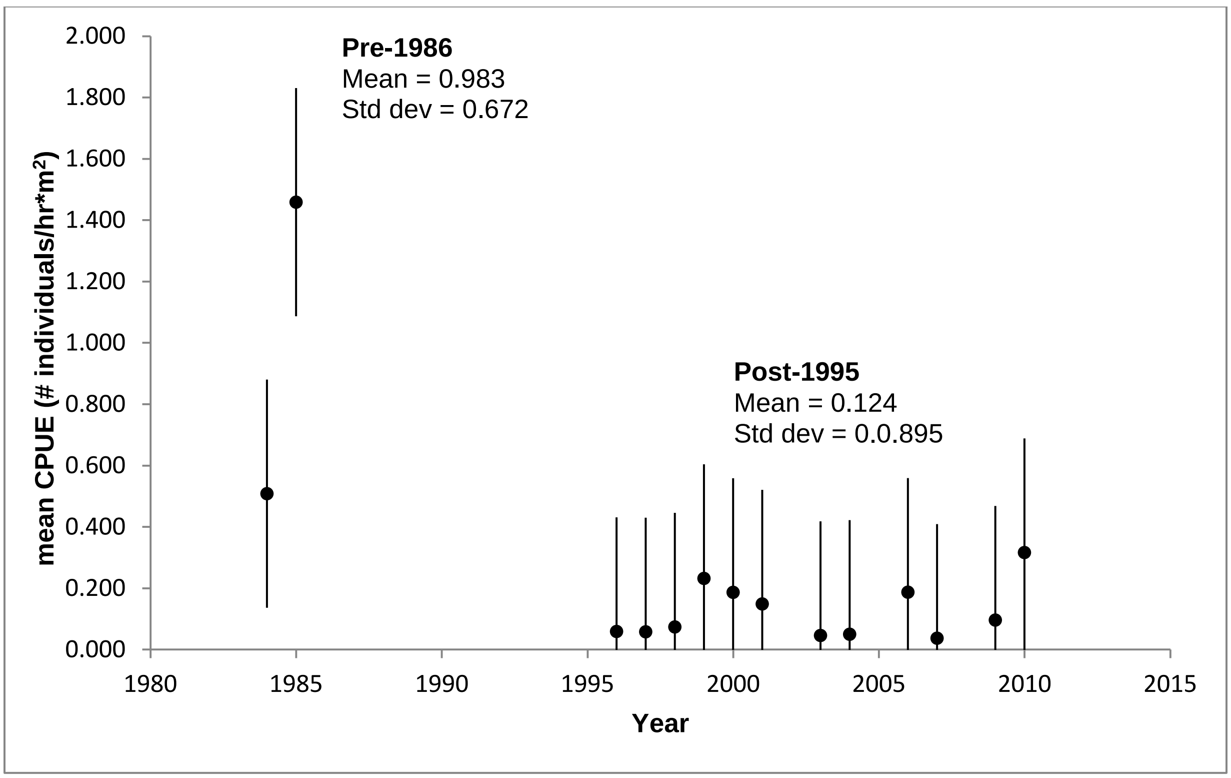

Figure 3: Annual mean CPUE of all of the watersheds combined from 1984 to 2010.

As previously mentioned, a drop in annual mean CPUE was observed between the years 1986 and 1995 (pre-1986 mean = 0.983; post-1995 mean = 0.124) in all of the watersheds combined (Figure 3). A scatter plot of mean CPUE values only from 1995 onwards was therefore completed to see if a change in mean CPUE can still be distinguished from 1995 to 2010. The scatter plot of mean CPUE values from 1995 onwards reveals that there are no distinguishable changes in mean CPUE from 1995 to 2010 (Figure 4).

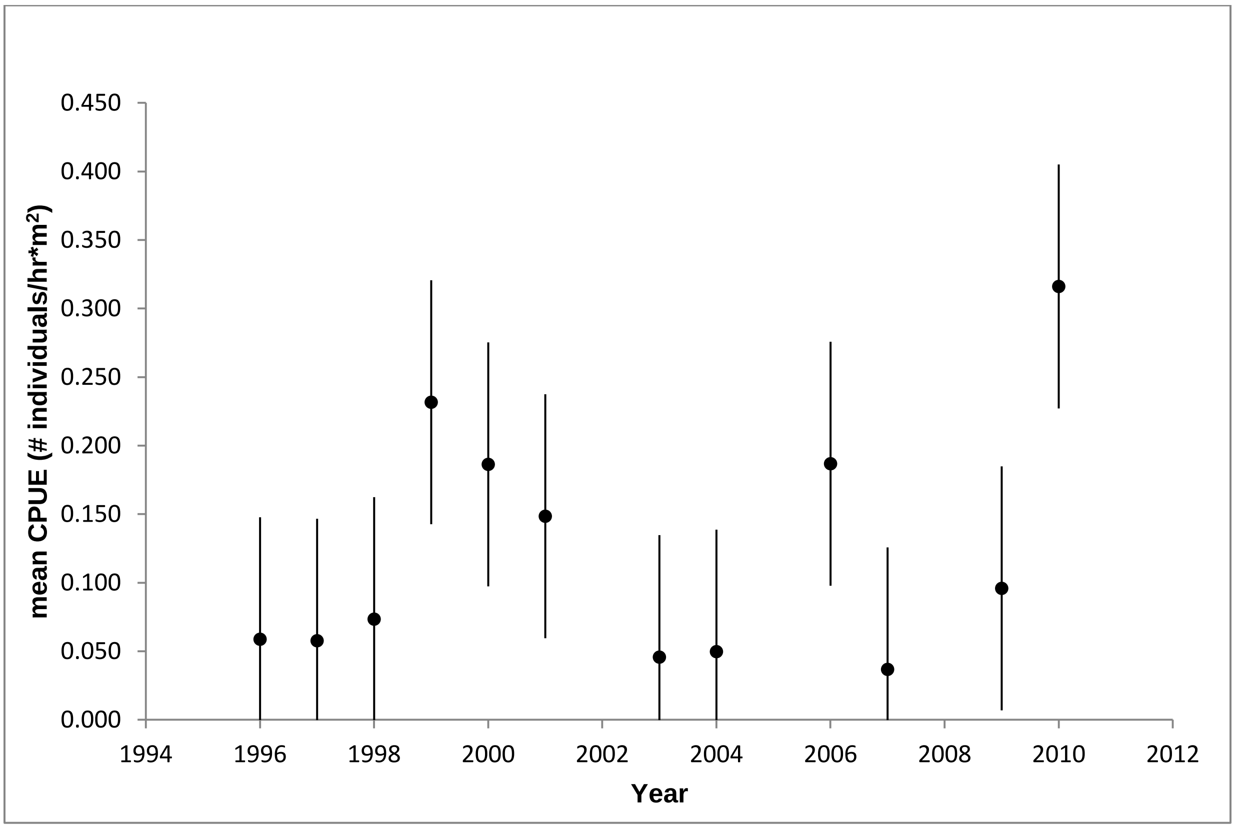

Figure 4: Annual mean CPUE of all of the watersheds combined from 1996 to 2010.

Brook Trout stocking occurred in the Duffins Creek watershed up until 1991 (Cook & Clayton, 2004), which would have artificially inflated Brook Trout populations in the 1984 and 1985 records. Consequently, mean CPUE values from the Duffins Creek watershed before 1991 were excluded from analysis to determine if a difference between mean CPUE before 1986 and after 1995 can still be observed. A scatter plot of mean CPUE vs. Year, excluding 1984 and 1985 values from the Duffins Creek watershed, reveals that the pre-1986 mean CPUE values (mean = 1.654; standard deviation = 0.514) are still distinctly greater than the post-1995 mean CPUE values (mean = 0.124; standard deviation = 0.0895) (Figure 5). In fact, the difference between pre-1986 and post-1995 mean CPUE values was even more distinct when stocked Brook Trout populations from the Duffins Creek watershed were excluded from analysis.

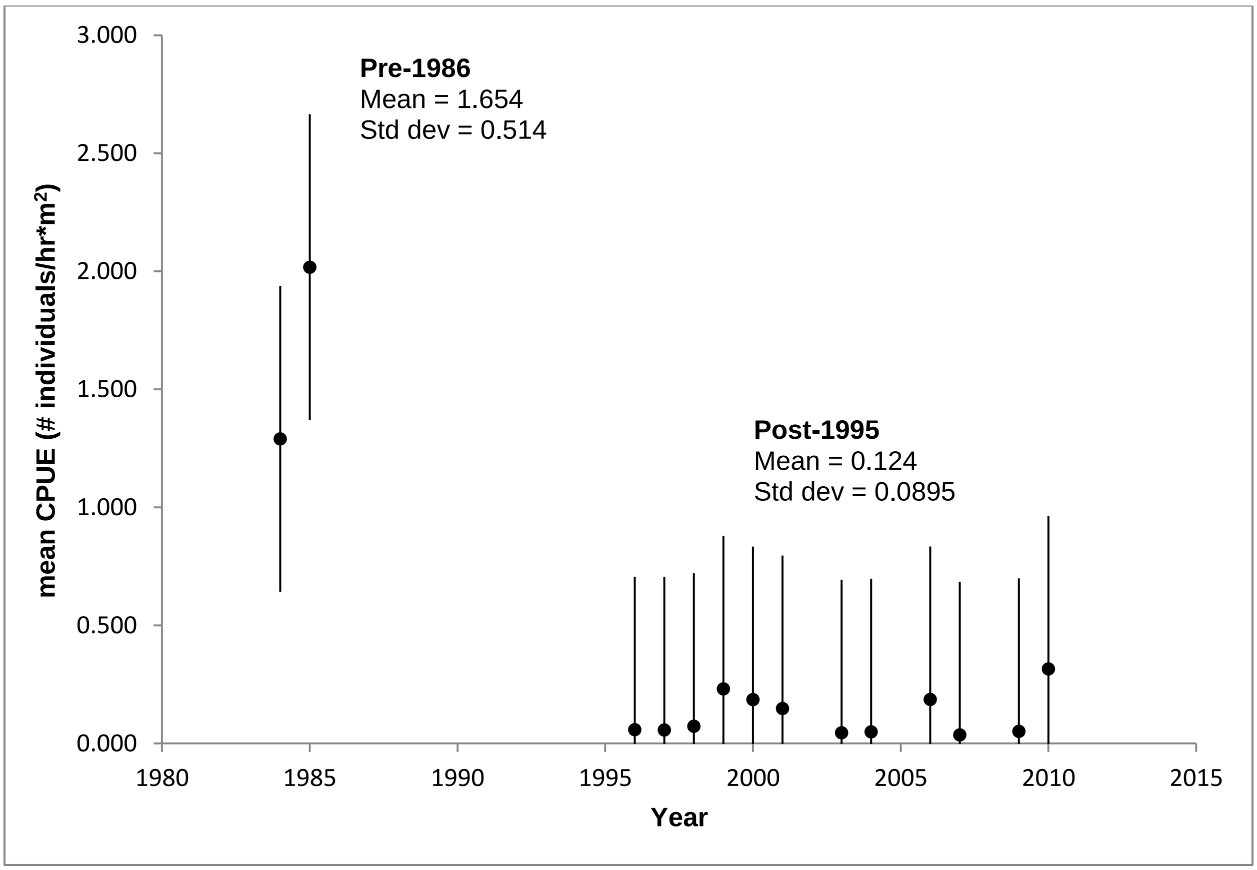

Figure 5: Annual mean CPUE for all of the watersheds combined from 1984 to 2010, excluding 1984 and 1985 records from the Duffins Creek watershed.

The difference between pre-1986 and post-1995 mean CPUE values was also examined in each of the watersheds individually to see if Brook Trout populations have changed in each of the watersheds over time. In the Duffins Creek watershed, pre-1986 mean CPUE values (mean = 0.803; standard deviation = 0.919) still appear to be greater than post-1995 mean CPUE values (mean = 0.123; standard deviation = 0.0839) (Figure 6a). However, the 1985 mean CPUE value is again much greater than all the other mean CPUE values, and is therefore considered to be an outlier. When the 1985 mean CPUE outlier was excluded from analysis, the pre-1986 mean CPUE (1984 mean CPUE = 0.153) was no longer distinguishable from the post-1995 mean CPUE values (mean = 0.123; standard deviation = 0.0839). It was therefore no surprise that when the inflated Brook Trout records from 1984 and 1985 were excluded from analysis, no distinct change in mean CPUE can be detected in the Duffins Creek watershed from 1996 to 2010 (Figure 6b).

However, the difference between pre-1986 mean CPUE values (mean = 2.280; standard deviation = 0.373) and post-1995 mean CPUE values (mean = 0.179; standard deviation = 0.115) was considerable in the Humber River watershed (Figure 7). Likewise, the difference between pre-1986 mean CPUE (1984 mean CPUE = 0.977) and post-1995 mean CPUE values (mean = 0.0887; standard deviation = 0.0887) was also great in the Rouge River watershed (Figure 8).

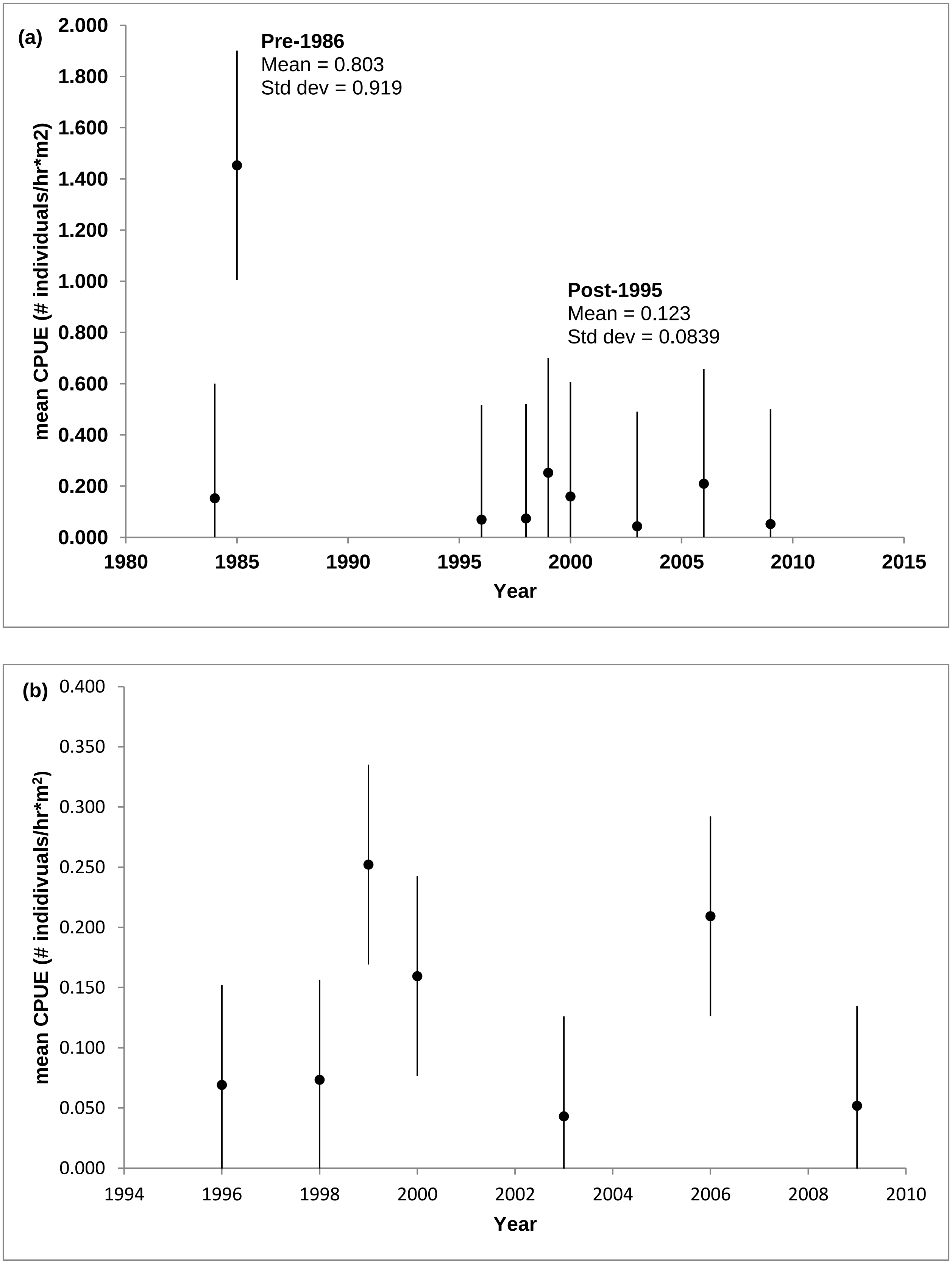

Figure 6: Annual mean CPUE for the Duffins Creek watershed from 1984 to 2009 (a), and from 1996 to 2009 (b).

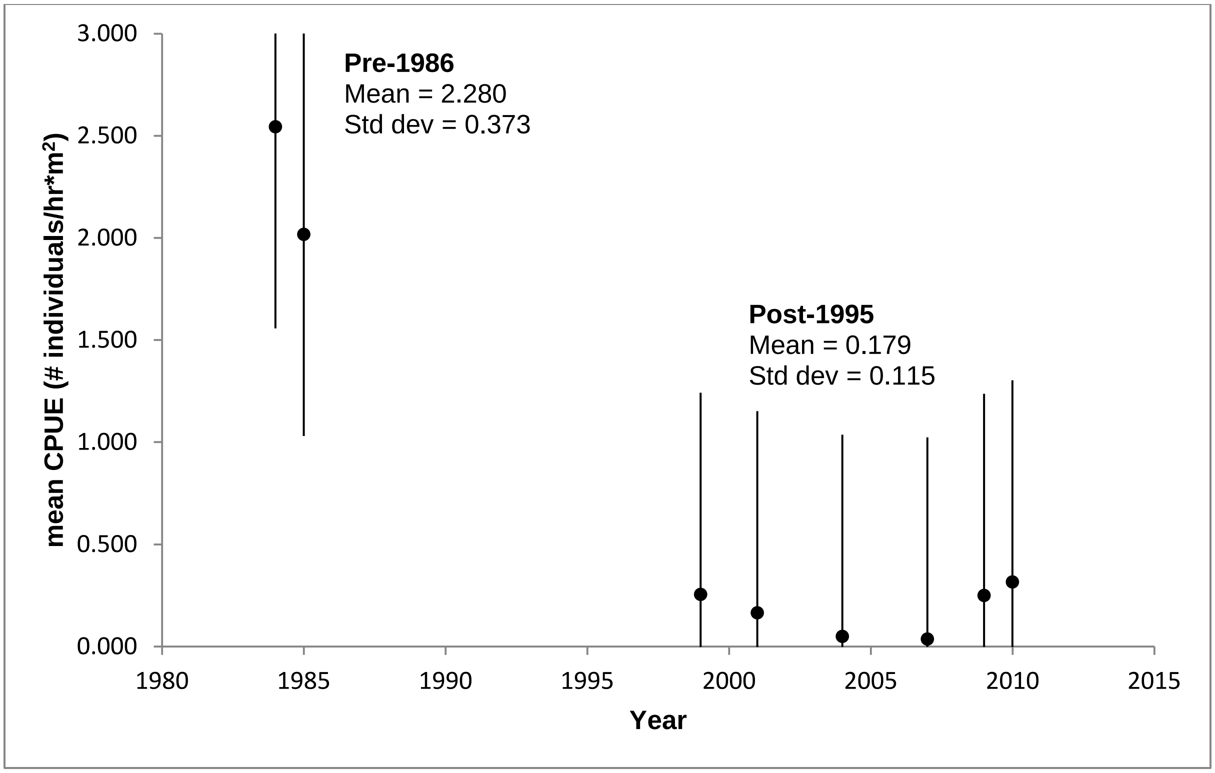

Figure 7: Annual mean CPUE for the Humber River watershed from 1984 to 2010.

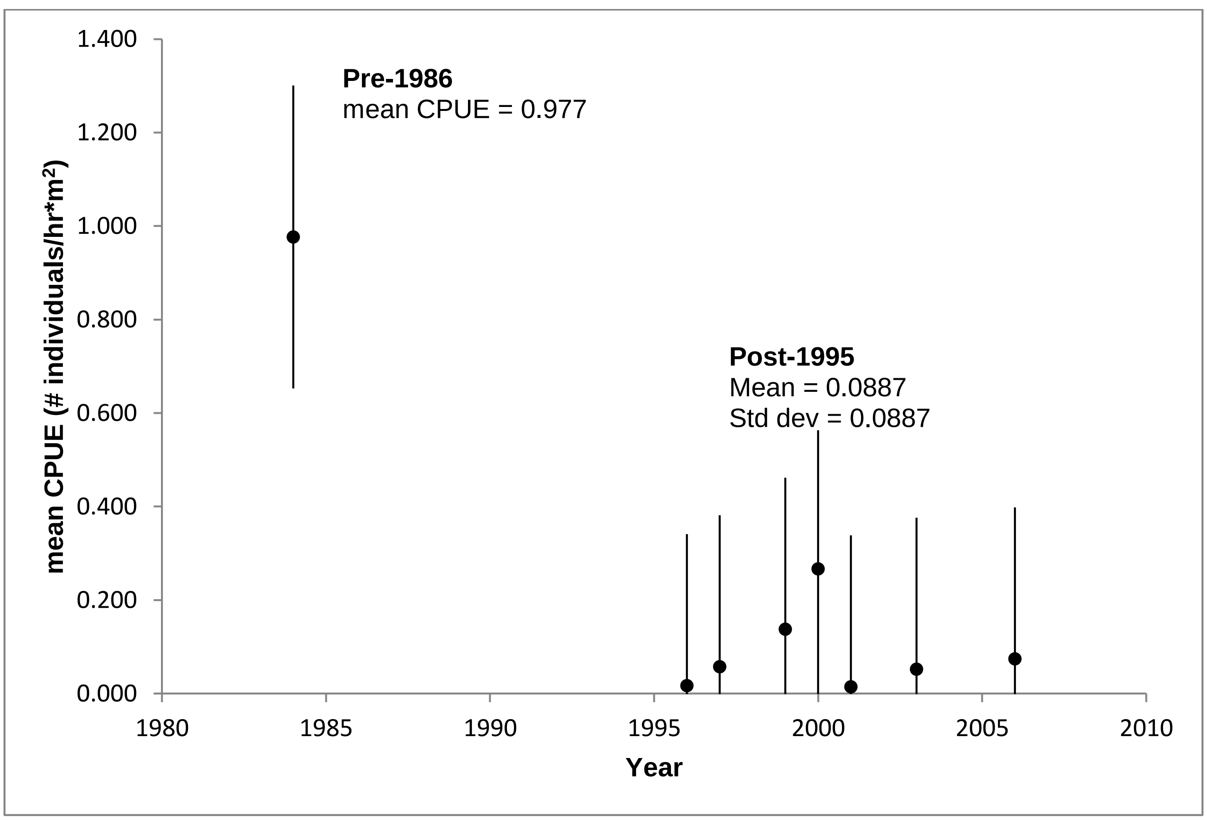

Figure 8: Annual mean CPUE for the Rouge River watershed from 1984 to 2006.

6.2 CHANGE IN AIR TEMPERATURE PARAMETERS OVER TIME

Monthly mean maximum summer air temperature and monthly extreme maximum summer air temperature were retrieved from the Environment Canada Toronto Buttonville A weather station for the period of time that Brook Trout records were available for analysis. Air temperature data were only available beginning in 1986. Air temperature data included for analysis can be found in Appendix G.

A linear regression was performed to determine if air temperature has changed significantly from 1986 to 2010. Two separate analyses were performed for the two separate air temperature parameters: monthly mean maximum summer air temperature, and monthly extreme maximum summer air temperature. Monthly mean maximum summer air temperature increased, but not significantly, over time ($F_{1,98}$ = 1.219; p = 0.272) (Figure 9). Likewise, the monthly extreme maximum summer air temperature also did not increase significantly over time ($F_{1,98}$ = 0.463; p = 0.498) (Figure 9).

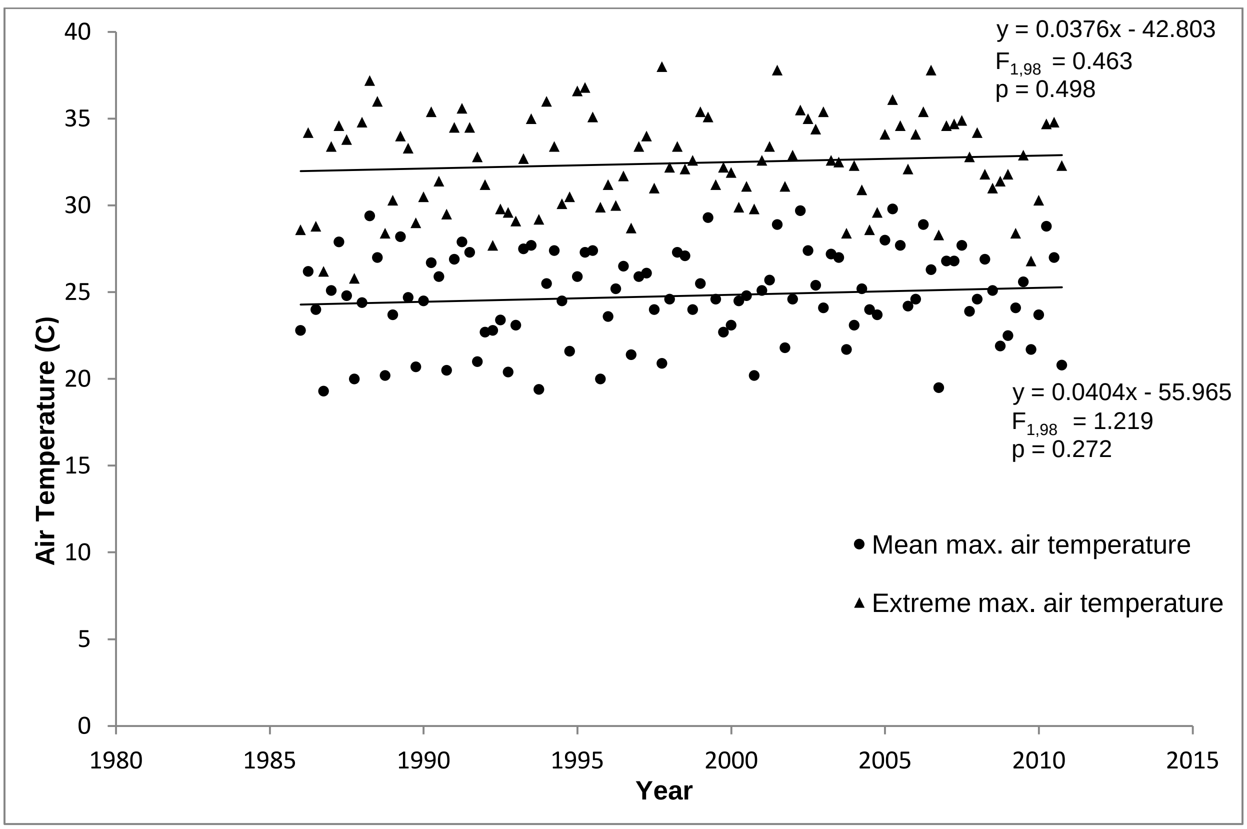

Figure 9: Monthly mean maximum summer air temperature, and monthly extreme maximum summer air temperature values from 1986 to 2010 at the Toronto Buttonville A Environment Canada weather station.

6.3 CHANGE IN STREAM WATER TEMPERATURE PARAMETERS OVER TIME

The mean of the daily maximum stream water temperatures (temperatures taken at 4pm) for each month was calculated. Additionally, the extreme maximum stream water temperature for each month was also retrieved for analysis. Monthly mean maximum stream water temperature, and monthly extreme maximum stream water temperature data included for analysis can be found in Appendix H.

Linear regression analyses were performed on the two stream water temperature parameters to determine how stream water temperatures were changing over time in the study areas. The stream water temperature data in all three of the watersheds were combined to increase the sample size for analysis.

Both monthly mean maximum stream water temperature, and monthly extreme maximum stream water temperature decreased from 2003 to 2009, albeit not significantly ($F_{1,18}$ = 0.344; p = 0.565) ($F_{1,18}$ = 0.015; p = 0.903) (Figure 10). A decrease in stream water temperature over time was unexpected and contrary to previous studies that found that stream water temperature was correlated with air temperature (Crisp & Howson, 1982; Mackey & Berrie, 1991; Caissie, El-Jabi, & Satish, 2001). Since air temperature displayed an increasing trend over time, albeit not significantly, it was expected that stream water temperature would increase as well. However, the 2009 monthly mean maximum and monthly extreme maximum stream water temperature data points were presumed to be outliers because Ontario experienced a much cooler and wetter summer than normal in 2009. In July, Toronto experienced its coldest mean temperature reading since 1992, with mean temperature sitting at 2.4°C lower than normal seasonal temperatures (Saunders, 2009a). Additionally, although temperatures were seasonal in August, Toronto received 64.4mm more precipitation than normal, making that month it's wettest since 1992 (Saunders, 2009b). Both lower than normal mean air temperature, and greater than normal precipitation would lower stream water temperature, and potentially skew any developing patterns in stream water temperature before 2009. Therefore, in order to see if the abnormal temperature and precipitation trends in 2009 affected the analysis of stream water temperature change over time, stream water temperature data from 2009 were omitted from analysis. When data from 2009 were omitted, monthly mean maximum stream water temperature increased over time instead of decreasing, but the trend remained not significant ($F_{1,14}$ = 1.802; p = 0.201)

(Figure 11). However, when data from 2009 were omitted, monthly extreme maximum stream water temperature increased significantly over time (monthly extreme maximum stream water temperature = 1477.164 + 0.747*year; adjusted r^2 = 0.239; p = 0.031) (Figure 11).

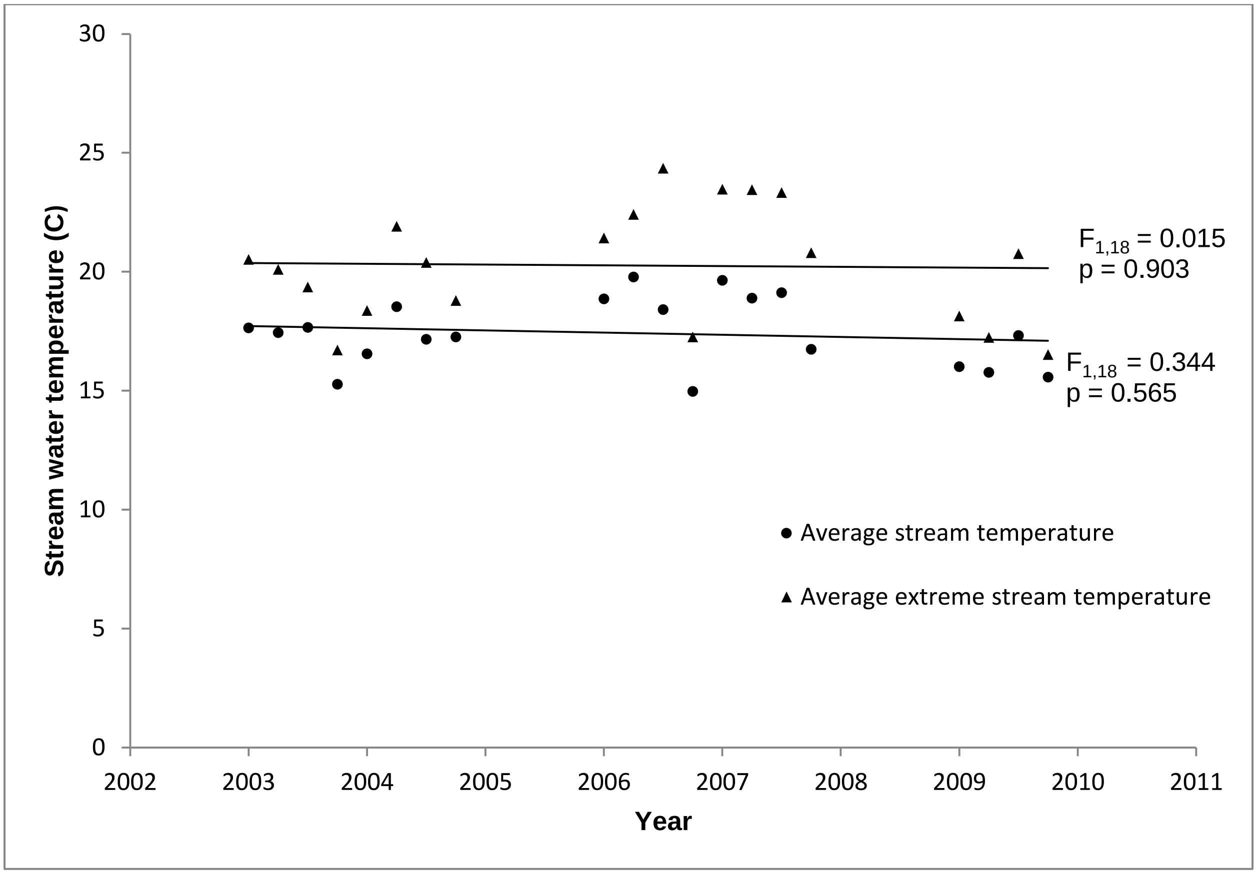

Figure 10: Monthly mean maximum stream water temperature, and monthly extreme maximum stream water temperature from 2003 to 2009 in three headwater stream locations in the Humber River, Rouge River, and Duffins Creek watersheds.

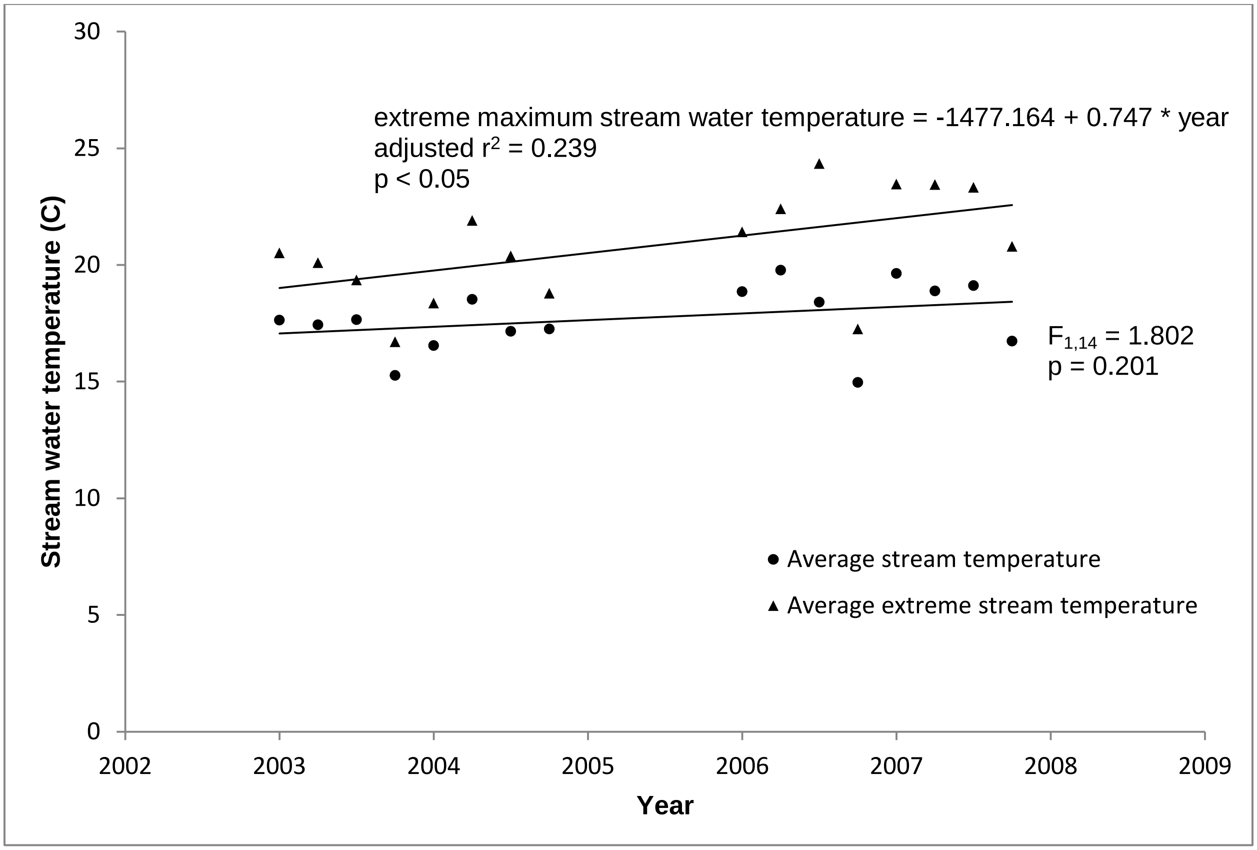

Figure 11: Monthly mean maximum stream water temperature, and monthly extreme maximum stream water temperature from the same stream locations as Figure 10, but with 2009 temperature readings excluded.

Annual thermal stress scores can be found in Table 1. The method used to determine the thermal stress scores was outlined in Section 5.2.3 on page 29. For the years 2003, 2006 and 2009, stream water temperature data were available for more than one watershed. Therefore for those years, the average thermal stress scores of the watersheds was taken as the annual total thermal stress score. Graphical representation of these scores revealed that there was no obvious increasing or decreasing trend in the thermal stress scores when the 2009 score was included (Figure 12a). This was similar to trends in stream water temperature when 2009 data was included (Figure 10). However, when the 2009 thermal stress score was omitted, thermal stress scores were undoubtedly observed to be increasing (Figure 12b). Statistical analyses were not conducted on thermal stress scores because the weighted scoring method assumed that thermal stress was increasing in a linear fashion as the stream water temperatures approach the upper lethal thermal limit when it is not known if this is the case in reality.

Table 1: Thermal stress scores of all of the watersheds combined from 2003 to 2009.

	Stream water temperature (°C) between:									
	16-18.99		**19-21.99**		**22-24.99**		**25+**		**Total**	
Year	**# Days**	**Score (x1)**	**# Days**	**Score (x2)**	**# Days**	**Score (x3)**	**# Days**	**Score (x4)**	**#days**	**Score**
2003	43.5	43.5	21.5	43	0	0	0	0	65	86.5
2004	62	62	14	28	0	0	0	0	76	90
2006	31	31	22.5	45	12.5	37.5	1.5	6	67.5	119.5
2007	36	36	37	74	8	24	0	0	81	134
2009	43.5	43.5	6.5	13	0	0	0	0	50	56.5

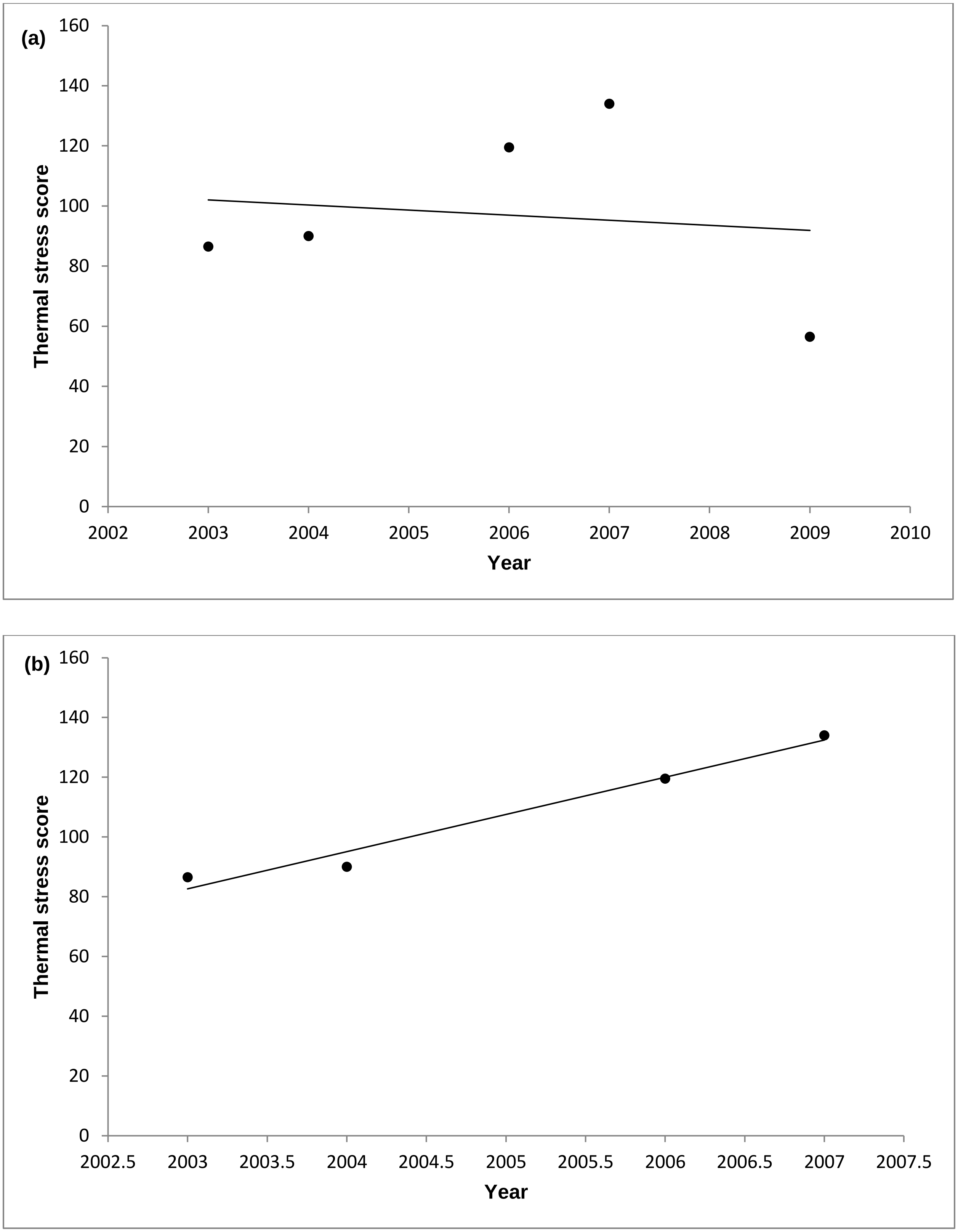

Figure 12: Thermal stress scores of all of the watersheds combined from 2003 to 2009 (a), and 2003 to 2007 (b).

6.3 CHANGE IN LAND COVER OVER TIME

Two separate areas where Brook Trout populations were historically concentrated were delineated on the historical and recent aerial photographs/satellite images. The first area was situated within the Town of Caledon in the Humber River watershed (Figure 13). This delineated area was bound by Highway 9 to the north, County Road 50 to the east, Old Church Road to the south, and Airport road to the west. This area was selected for analysis because it is where the majority of the Brook Trout records occurred in the Humber River watershed, and both historical and recent aerial photographs/satellite images were available for this area. The second area was situated within the City of Pickering in the Duffins Creek watershed (Figure 14). This delineated area was bound by Pickering Uxbridge Townline Road to the north, Westney Road to the east, Concession Road 5 to the south, and York Durham Line to the west. This area was selected for analysis because it is also where the majority of Brook Trout records occurred in the Duffins Creek watershed, and both historical and recent aerial photographs/satellite images were available for this area. Additionally, the majority of the Brook Trout records in the Rouge River watershed were located in the Town of Richmond Hill and the Town of Whitchurch-Stouffville, but the 1954 aerial photograph of this region was missing from the Canada Topographic Survey's aerial photograph collection at the University of Toronto Map and Data Library. Therefore, an analysis of land cover change over time in the Rouge River watershed could not be made.

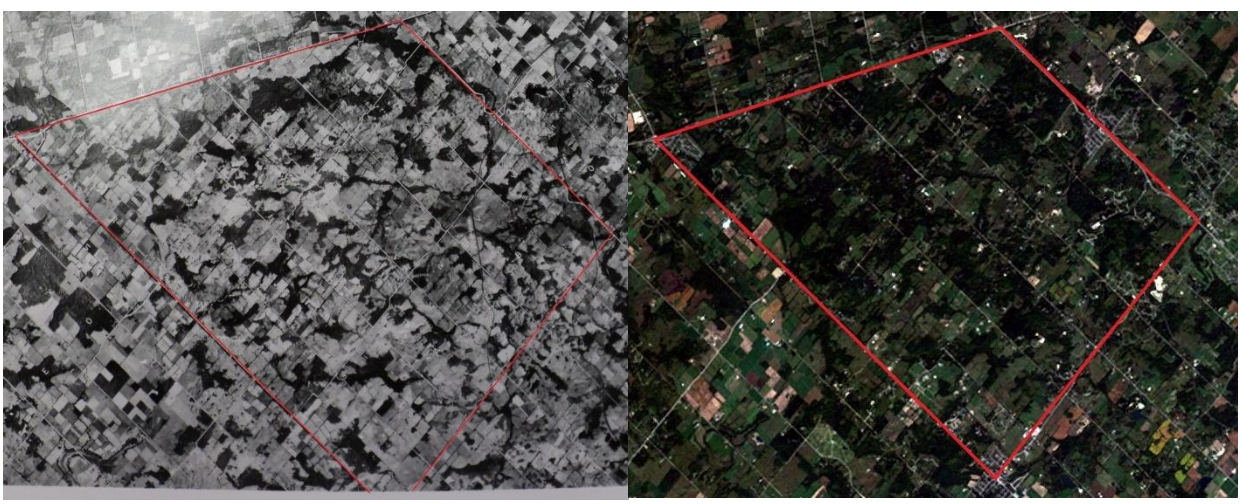

Figure 13: Aerial photograph from 1954 of an area in the Humber River watershed where Brook Trout have historically been found (left), and satellite image from 1999/2000 of the same area (right). Sources: Canada Topographic Survey. (1954). *The Southern Part of the Province of Ontario – Aerial Photo Collection.* Province of

Ontario, Department of Lands and Forests., and Natural Resources Canada (2003, April 10). CanImage – Landsat 7 Orthoimages of Canada, 1:50000. Sherbrooke, Quebec, Canada. Retrieved from GeoGratis: http://www.geogratis.ca/.

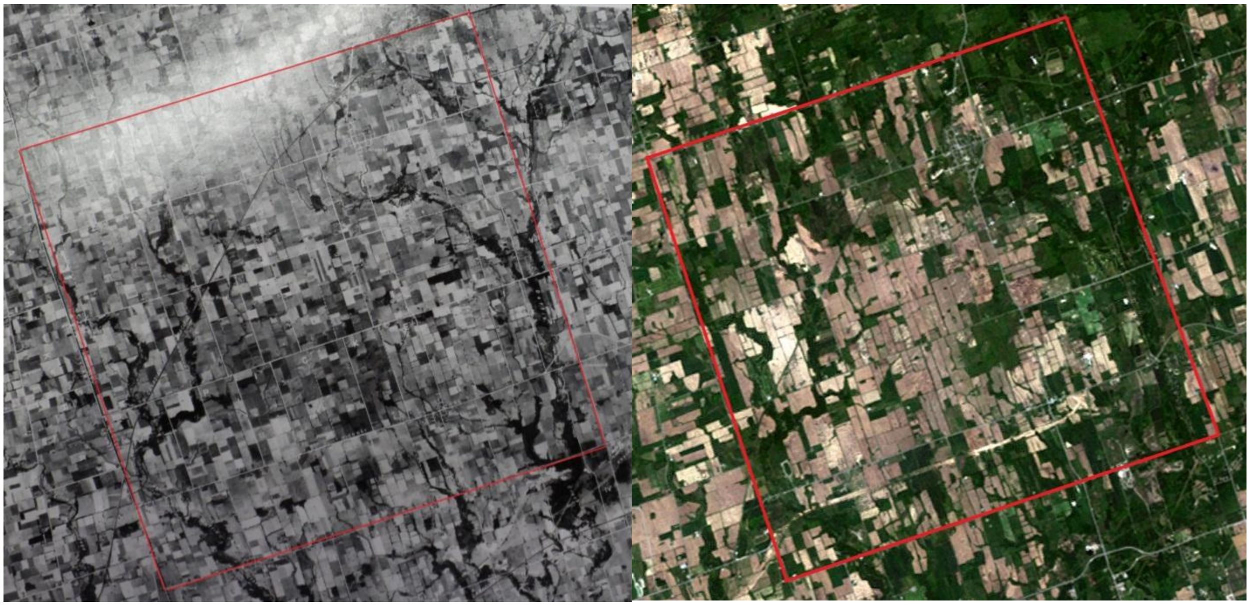

Figure 14: Aerial photograph from 1954 of an area in the Duffins Creek watershed where Brook Trout have historically been found (left), and satellite image from 1999/2000 of the same area (right). Sources: Canada Topographic Survey. (1954). *The Southern Part of the Province of Ontario – Aerial Photo Collection.* Province of Ontario, Department of Lands and Forests., and Natural Resources Canada (2003, April 10). CanImage – Landsat 7 Orthoimages of Canada, 1:50000. Sherbrooke, Quebec, Canada. Retrieved from GeoGratis: http://www.geogratis.ca/.

In the first delineated area in the Humber River watershed, land cover remained the same in 50% of the road blocks, urbanization has increased in 17.5% of the road blocks, and 32.5% of the road blocks have undergone naturalization and experienced a recovery in vegetation. There has been no increase in agricultural lands within this delineated area. Increase in road density and sprawl, and therefore urbanization, in this area occurred primarily in Palgrave along County Road 50, and in Caledon East at the intersection of Airport Road and Old Church Road (Figure 13).

In the second delineated area in the Duffins Creek watershed, land cover remained the same in 64.4% of the road blocks, and naturalization has occurred in 35.6% of the road blocks. No increase in urban or agricultural lands occurred within this delineated area (Figure 14). Although not within the area where Brook Trout records predominantly occurred, it is noteworthy to mention that urban sprawl and intensification has increased drastically from the north shore of Lake Ontario to two road blocks north of Highway 401 in the Town of Pickering and Town of Ajax.

It is also noteworthy to mention that although no Brook Trout records were found south of Major Mackenzie Drive in the City of Vaughan, urban sprawl and intensification has also increased significantly south of Major Mackenzie Drive on the west side of Highway 400, and south of Teston Road on the east side of Highway 400. The urbanization in this area extends south and is contiguous with urbanization in the City of Toronto.

Although historical aerial photographs from 1954 were not available where Brook Trout populations were historically located in the Rouge River watershed, an area within the Town of Richmond Hill where numerous Brook Trout records were found was delineated to determine the current (circa 1999/2000) land cover in the region (Figure 15). This delineated area was bounded by Stouffville Road to the north, Highway 404 to the east, Major Mackenzie Drive to the south, and Yonge Street to the west. 40% of the road blocks within this area were urbanized, 40% of the road blocks were under agricultural land use, and the remaining 20% were naturalized.

Figure 15: Satellite image from 1999/2000 of an area in the Rouge River watershed where Brook Trout have historically been found. Sources: Natural Resources Canada (2003, April 10). CanImage – Landsat 7 Orthoimages of Canada, 1:50000. Sherbrooke, Quebec, Canada. Retrieved from GeoGratis: http://www.geogratis.ca/.

6.4 Relationship between air temperature and stream water temperature

A Pearson r correlation analysis was used to determine how closely air temperature was correlated with stream water temperature. A highly significant positive relationship exists between both monthly mean maximum air temperature and monthly mean maximum stream water temperature ($r = 0.864$; $p < 0.001$), and monthly extreme maximum air temperature and monthly extreme maximum stream water temperature ($r = 0.839$; $p < 0.001$). This supports the findings of previous studies that detected a linear correlation between ambient air temperature and stream water temperature, and their conclusion that it was possible to use ambient air temperatures to predict stream water temperatures (Caissie, El-Jabi, & Satish, 2001).

6.5 Relationship between CPUE and temperature parameters

The overall annual mean Brook Trout CPUE of all watersheds combined, and monthly extreme maximum stream water temperature (excluding 2009 data) changed significantly over time (Figure 5 and 11). Thermal stress scores (excluding the 2009 score) also appear to be increasing over time. The overall Brook Trout CPUE for all of the watersheds combined decreased by 37.8% from 1984 to 2010. However, since stream water temperature data that were included in the analysis were only recorded from 2003 to 2007, the percentage of decrease in overall CPUE was adjusted to reflect this time span. Thus from 2003 to 2007, the overall CPUE for all of the watersheds combined decreased by 19.6%. For each year, the mean of the monthly extreme maximum stream water temperature values was calculated to produce an annual extreme maximum stream water temperature value. The resulting values revealed that annual extreme maximum stream water temperature increased by 18.8% from 2003 to 2007. Thus, overall CPUE and annual extreme maximum stream water temperature experienced a similar proportion of decrease and increase respectively between 2003 and 2007. In general, CPUE decreased over time while extreme maximum stream water temperature and thermal stress score increased over time.

6.6 Relationship between CPUE and land cover change

Between 1954 and 2000, land cover in the delineated area within the Humber River watershed displayed a 17.5% increase in urbanization, while experiencing a 32.5% increase in naturalized areas at the same time (Figure 13). Over the period of time that Brook Trout records were available in the region from 1984 to 2010, CPUE decreased substantially by 87.6% in the Humber River watershed (Figure 7).

During the same time period between 1954 and 2000, the Duffins Creek watershed experienced less land cover change with 64.4% of the land within the delineated area of interest remaining the same (Figure 14). Similarly, the results indicated that annual mean CPUE from the Duffins Creek watershed did not significantly change over time either (Figure 6a and b). However, a substantial proportion of the Duffins Creek watershed at 35.6% did experience naturalization during the same period. Therefore, land cover changes in the Duffins Creek watershed are less likely to have had an effect on CPUE than air and stream water temperature changes.

CHAPTER 7: DISCUSSION

The results suggested that Brook Trout population abundance has diminished since the mid-1980s. This decrease was mainly driven by Brook Trout populations in the Humber River, and Rouge River watersheds since those were the watersheds that exhibited a significant change in annual mean CPUE over time. Additionally, the only climate parameter that revealed significant changes over time was the extreme maximum stream water temperature parameter. Similarly, the thermal stress score, a measure that reflects extreme maximum stream water temperature, also increased over time. No significant change in air temperature was detected from 1986 to 2010.

7.1 INFLUENCE OF TEMPERATURE CHANGES ON BROOK TROUT POPULATIONS

7.1.1 Influence of stream water temperature changes on Brook Trout

Many other studies had previously attributed changes in Brook Trout populations to changes in temperature. These population changes include changes in Brook Trout distribution (Meisner, 1990a; Meisner, 1990b), biomass (Stoneman & Jones, 2000), survival (Xu, Letcher, & Nislow, 2010a), and growth rate (Xu, Letcher, & Nislow, 2010b). The results of this research in particular have detected a decrease in Brook Trout abundance over time. Temperature has already previously been deemed as the lethal and most important variable influencing Brook Trout populations (Magnuson J. J., 1991). The upper lethal thermal limit of Brook Trout is 24ºC (Meisner, 1990b), with Brook Trout individuals becoming absent when stream water temperatures increase above 24ºC making temperature an optimal index for Brook Trout populations (Picard, Bozek, & Momot, 2003).

This research had revealed that, although the mean maximum stream water temperature had not changed significantly over time, extreme maximum stream water temperature had experienced a notable increase between 2003 and 2007 in areas where Brook Trout have historically inhabited. This finding suggests that although the stream water temperature mean had remained constant, more extreme temperature fluctuations were occurring around this mean. Consequently, despite the apparent stability in stream water temperature over time in the watersheds, Brook Trout populations were still under increasing threat as stream water temperature approached its upper lethal thermal limit more frequently over time. This progressive increase in the frequency at which Brook Trout populations were exposed to temperatures nearing their upper lethal thermal limit was again demonstrated in the significant increase in thermal stress scores over time. Similarly, this result revealed that although maximum stream water temperature means remained constant between 2003 and 2007, the number of days where temperatures approached the upper lethal thermal limit was increasing, thereby inflicting greater thermal stress on Brook Trout populations over time. These findings underline the importance of examining different parameters that represent different changes when evaluating climatic factors.

From 2003 to 2007, extreme maximum stream water temperatures increased by 18.8%. The overall CPUE for all the watersheds combined made a corresponding change in magnitude, decreasing by 19.6% from 2003 to 2007. This suggests that decreases in Brook Trout population abundance from 2003 to 2007 can conceivably be related to the corresponding increases in extreme maximum stream water temperature.

7.1.2 Influence of air temperature changes on Brook Trout

Ambient air temperature can also have an indirect impact on Brook Trout populations by influencing stream water temperatures. In fact, annual maximum air temperature has been found to account for a significant amount of variation in cold water fish distribution in southern Ontario (Chu, Jones, Mandrak, Piggot, & Minns, 2008). Ambient air temperature directly influences the temperature of stream water by heating up or cooling down surface water (Sullivan & Adams, 1991).

Past studies have shown that ambient air temperature was positively correlated with stream water temperature, making it possible to predict stream water temperatures from ambient air temperature (Crisp & Howson, 1982; Mackey & Berrie, 1991; Caissie, El-Jabi, & Satish, 2001). The results from this research confirmed these findings and demonstrated that this relationship was also true for southern Ontario streams. The results revealed that a significant positive correlation between air temperature and stream water temperature parameters existed. Consequently, as other studies have concluded upon finding a significant positive relationship between air and stream water temperature, air temperature can sufficiently be used to predict stream water temperature. For this research, the available stream water temperature spanned a short period of time from 2003 to 2007. However, air temperature data were available for a longer period of time from 1986 to 2010. Since a high correlation exists between air and stream water temperatures and the availability of historical stream water temperature data was limited, it can be assumed that historical stream water temperature before 2003 fluctuated in conjunction with historical changes in air temperature.

However, the results from this research had revealed that summer air temperature had not changed significantly over time, implying that stream water temperature also had not changed significantly over time. These results were unexpected as they contradicted other studies that have detected increases in historical air temperature. The Intergovernmental Panel on Climate Change (IPCC) reported an increase of annual mean air temperature of 0.33°C per decade from 1979 to 2005 in the Northern hemisphere (Solomon, et al., 2007). At a more regional and local scale, annual mean air temperatures have also increased significantly in the Great Lakes/St. Lawrence area from 1895 to 1993 (Magnuson, et al., 1997), in the Greater Toronto Area (GTA) from 1970 to 2000 (Mohsin & Gough, 2010), and in the Toronto area from 1968 to 2002 (Dobiesz & Lester, 2009). However, annual mean air temperature measures may mask seasonal differences in warming. Air temperatures have been observed to increase the most during the spring and fall in North America (Solomon, et al., 2007), the spring and winter in the Great Lakes/St. Lawrence area (Magnuson, et al., 1997), and the winter in Ontario and the GTA (Mohsin & Gough, 2010; Dickinson, Rudra, & Amili, 2012). In all cases, air temperature increases were less prominent during the summer season than during other seasons. This may be the reason why a significant increase was not detected in mean maximum and extreme maximum summer air temperatures in this study. Consequently, as was the case with stream water temperature, detection of significant changes in climatic factors, such as air and stream water temperature, depend on the parameter that was being measured.

Additionally, although this research has not detected a significant increase in summer air temperature between 1986 and 2010, the slope of the air temperature parameter linear regressions (Figure 9) are similar to those of other studies that did observe a significant increase in air temperature. For example, in Dobiesz and Lester’s (2009) observations of significant annual mean air temperature increase from 1968 to 2002 in the Toronto area, the slope of their regression line was 0.033. Similarly, Mohsin and Gough (2010) also observed significant increases in air temperature parameters in the Greater Toronto Area, and their regression slopes of annual maximum air temperature and annual mean air temperature were 0.04 and 0.01 to 0.06, respectively. The regression slope of annual extreme maximum summer air temperature observed in this research was 0.038, and the regression slope of annual mean maximum summer air temperature was 0.0404 (Figure 9). Despite the lack of significant change observed in extreme maximum and mean maximum summer air temperature, the regression slopes of air temperature parameters in this research coincide with those observed in other studies. Therefore, the inability to detect a significant increase in air temperature parameters in this research is not necessarily due to a lack of air temperature change from 1986 to 2010, but may instead be a result of an insufficient number of air temperature records in the dataset.

However, significant change in air temperature parameters was still not detected in this research. And since there was no significant historical change in either mean maximum or extreme maximum summer air temperature, adult Brook Trout populations in the region are not likely to be threatened by increasing summer air temperatures. However, since significant air temperature increases have been observed during other seasons in the region (Magnuson, et al., 1997; Mohsin & Gough, 2010; Dickinson, Rudra, & Amili, 2012), Brook Trout populations may be negatively affected during other life stages. For example, increases in air temperature, and therefore stream water temperature as well, during the fall and/or early winter may decrease Brook Trout reproductive success by creating suboptimal thermal conditions for spawning. Additionally, increases in air temperature during the spring may negatively impact emerging Brook Trout fry, especially since Brook Trout are most susceptible to mortality during the first few months after emergence (Power, 1980). Rising temperatures can also impact Brook Trout indirectly by altering the hydrology of streams. Increasing winter temperature and rainfall, and decreasing snowfall detected in Ontario will have an impact on winter runoff volumes and peaks (Dickinson, Rudra, & Amili, 2012). As well, the overall rate of groundwater recharge is expected to increase as a result of increases in winter temperature and precipitation (Jyrkama & Sykes, 2007). These changes in the hydrology of streams during the winter may potentially have an impact on Brook Trout populations. Therefore, although it may seem intuitive for hot summer temperatures to harm Brook Trout the most because of their sensitivity to high temperatures, increases in temperature during other cooler seasons may actually prove to have more of an impact on Brook Trout populations.

The significant increase in annual mean air temperature in the region reported by other studies (Magnuson, et al., 1997; Dobiesz & Lester, 2009; Mohsin & Gough, 2010) may also negatively impact Brook Trout populations by affecting the temperature of groundwater. Groundwater temperature can be approximated by adding 1-2ºC to the annual mean air temperature of the local area (Meisner, 1990a). Since groundwater temperature reflects annual mean air temperature, groundwater temperature is expected to increase as annual mean air temperature continues to increase (Power, Brown, & Imhof, 1999). This may prove to be problematic as groundwater has been shown to be important in maintaining optimal stream temperatures for Brook Trout (Meisner, 1990a), and areas of groundwater discharge have served as areas of thermal refugia for Brook Trout when the surrounding stream water temperature rises to intolerable levels (Cunjak & Power, 1986; Biro, 1998). Increases in annual mean air temperature may therefore threaten the ability of groundwater to moderate and lower stream water temperatures, and to act as sites of thermal refugia.

7.2 Influence of land cover change on Brook Trout populations

7.2.1 Influence of land cover on stream water temperature, flow, and quality

Land cover may impact Brook Trout populations by affecting stream water temperature. A reduction in overhanging vegetation along stream banks allows solar warming of surface water, and a resulting increase in stream water temperature (Meisner, 1990a; Picard, Bozek, & Momot, 2003). Moreover, the type of land cover in areas beyond stream banks can impact Brook Trout populations as well. An increase in the PIC negatively impacts Brook Trout (Stanfield, Gibson, & Borwick, 2006) by reducing the ability of precipitation to percolate through soil, and replenish groundwater aquifers (Siitari, Taylor, Nelson, & Weaver, 2011). The resulting lack of groundwater discharge into streams increases stream water temperature, thereby reducing its ability to moderate and keep water temperatures low. It also increases the input of warm surface run-off that has increased in temperature via insolation or through the absorption of heat from the impermeable pavement surfaces that are characteristic of urban areas (Webb, Hannah, Moore, Brown, & Nobilis, 2008).

A decrease in groundwater input as a result of an increase in PIC will also impact Brook Trout by reducing stream flow since groundwater input makes up the minimum baseflow in streams (Siitari, Taylor, Nelson, & Weaver, 2011). Low stream flow can negatively impact both adult Brook Trout individuals, and their eggs. Low flow can threaten the survival of Brook Trout adults in small headwater tributaries (Xu, Letcher, & Nislow, 2010a). Additionally, female Brook Trout individuals spawn over areas of groundwater upwelling (Blanchfield & Ridgway, 2005), and low groundwater flow has been shown to increase egg mortality (Warren, Sebestyen, Josephson, Lepak, & Kraft, 2005).

A change in land cover also affects the water quality of nearby streams. Water quality indicators, such as macroinvertebrate diversity, have been shown to be positively correlated with forest land cover, and negatively correlated with urban and/or agricultural land cover (Miserendino, et al., 2011). Once again, this effect on water quality is related to the PIC of the surrounding area. The proportion of the watershed with poorly drained soils has been shown to be related to the concentration of dissolved organic carbon in streams (Wilson & Xenopoulos, 2008). Additionally, degradation of water quality has been observed in watersheds that contain at least 10% impervious surface cover (Miller, Schoonover, Williard, & Hwang, 2011).

7.2.2 Land cover change since the 1950s

The results have revealed that many agricultural lands in both the Humber River and Duffins Creek watersheds have under gone naturalization since 1954 in areas where Brook Trout populations have historically been found. Urbanization has concurrently increased in the Humber River watershed, generally around areas of existing settlement such as Palgrave and Caledon East. Urbanization in the Duffins Creek watershed also increased notably since the 1950s, but only in the areas surrounding the City of Pickering and Town of Ajax from the shore of Lake Ontario up to the area surrounding Highway 401. Urbanization in the Duffins Creek watershed, however, did not reach areas where Brook Trout were found, and therefore, would not impact the populations. There was no net increase in agricultural lands in either of the Humber River or Duffins Creek watersheds.

These results were supported by Cheng and Lee (2008) in their analysis of land cover change from 1993 to 2007 across Ontario’s Greenbelt, a 750 000 ha area of land across the Niagara

Escarpment and Oak Ridges Moraine. In their analysis, Cheng and Lee (2008) found that the most significant land cover change that occurred during this period of time was the conversion of agricultural land to urban land. On the other hand, very little conversion or loss of forests and wetlands was observed from 1993 (Cheng & Lee, 2008). Additionally, a similar analysis of land cover change in the City of Hamilton and Halton Region within the Niagara Escarpment observed that forested areas and urban lands have increased from 1986 to 2006, while agricultural lands have decreased during the same time period (Waite, 2009). Similarly, another study has also found an average 19% decrease of agricultural lands across southern Ontario from 1961 to 1981 (MacNeil, 1984). The findings of these previous studies suggest that there has been a net loss of agricultural lands, an increase in natural areas, and an increase in urbanization over the past half century in southern Ontario.

Although land cover change could not be assessed in the Rouge River watershed, the results have revealed that a large proportion of the area where many Brook Trout populations were historically located is currently urbanized (~40%). This was supported in Cheng and Lee's (2008) analysis of land cover change across the Greenbelt where they found that the Municipality of York, which includes the Town of Richmond Hill and Town of Whitchurch-Stouffville within the Rouge River watershed, has undergone the greatest amount of land use conversion out of all the municipalities situated in the Greenbelt. Furthermore, population density in the Municipality of York is documented to be higher than that of other nearby municipalities (OMNR, 1994)

The increase in urban development in the Rouge River and Humber River watersheds can be explained by an increase in urban and residential development pressure in the region. A review of existing land use and future land use projections based on official plan designations, illustrate the direction and intensity of development that has persisted since the mid-1990s in regions within the Oak Ridges Moraine (OMNR, 1994). At the time the review was published in 1994, parts of the Oak Ridges Moraine that falls within the Region of York, a large part of which is located within the Rouge River watershed, had experienced the greatest amount of development pressure when compared existing development in others parts of the moraine (OMNR, 1994). This pattern of land use is also evident in the satellite image of a portion of the Rouge River watershed where a significant proportion of the area where Brook Trout were located in the Oak

Ridges Moraine was under urban and/or residential development. Although development in the Town of Caledon, within the Humber River watershed, was lower than the Region of York at the time of the review in 1994, a significant portion of land (11%) was slated for development in the near future (OMNR, 1994). Again, this confirmed the observation of increased urbanization in the aerial photograph/satellite image of the Humber River watershed. The lack of change in the Duffins Creek watershed, as observed in the aerial photograph/satellite image, was also confirmed. At the time of the review in 1994, the Region of Durham, part of which is located within the Duffins Creek watershed, had the highest proportion of undeveloped lands within the Oak Ridges Moraine, and existing and projected developed land use was minimal (OMNR, 1994).

In addition to the development of agricultural land as a result of urban and/or residential developmental pressure, the overall decrease in agricultural lands in the watersheds can also be explained by a pattern of agricultural land abandonment that has been occurring over the past half century. Between 1961 and 1981, decreases in agricultural land have not only been a result of expanding urban development, but also a result of changes in the economics and practices within the agricultural industry (MacNeil, 1984). The economic conditions of the 1960s in particular drove many individuals in the agriculture industry to sell off their farms, which were subsequently converted into non-agricultural land uses (MacNeil, 1984). Alternatively, technological advances during the same period allowed others to farm their land more intensively, which decreased the area of land necessary to produce the same amount of food (MacNeil, 1984). From 1961 to 1981, the Region of Peel experienced a 34.2% decrease, the Region of York experienced a 20.9% decrease, and the Region of Durham experienced a 18.6% decrease in agricultural lands (OMNR, 1994).

The increase in naturalization in both the Humber River and Duffins Creek watersheds were a result of changes in land use planning policy and legislation in the region over the past half century. Increasing urban sprawl and development pressure in the Greater Toronto Area during the 1990s instigated a chain of policy and legislation changes that aimed to protect ecologically sensitive natural features such as the Niagara Escarpment and Oak Ridges Moraine, within which many of the historical Brook Trout populations persisted. Establishment of policies and legislation to preserve the Niagara Escarpment preceded those that aimed to protect the Oak

Ridges Moraine. The Niagara Escarpment Planning and Development Act (NEPDA) was established in 1973, ensuring that only development that is compatible with the environment is undertaken (Waite, 2009). Planning policy and legislation changes to protect the Oak Ridges Moraine proceeded more slowly, and were fueled by conflict between environmental groups and local residents, and developers (Hanna & Webber, 2010). Concern surrounding development in the Oak Ridges Moraine intensified in the late 1980s and early 1990s, and culminated in the formation of groups dedicated to protecting the ecological integrity of the Oak Ridges Moraine, such as the Save the Oak Ridges Moraine (STORM) Coalition, and the recognition of the Oak Ridges Moraine as an area of provincial interest (Hanna & Webber, 2010). A turning point in the protection of the Oak Ridges Moraine occurred in 1999 when the Regions of Durham, Peel and York released a report that established an inter-jurisdictional initiative to protect the Oak Ridges Moraine (Hanna & Webber, 2010). Shortly afterwards, ecologically-based planning legislation was introduced with Oak Ridges Moraine Conservation Act first in 2011, and the Greenbelt Act following in 2005 (Hanna & Webber, 2010).

7.2.3 Influence of land cover changes on Brook Trout

Brook Trout abundance in both the Humber River and Rouge River watersheds decreased over time from the mid 1980s. Brook Trout abundance in the Duffins Creek watershed, however, did not experience any significant change. The major landscape difference between the Humber River and Rouge River watersheds, and the Duffins Creek watershed was that the former watersheds experienced increases in urban land use over the past half century in areas where Brook Trout occurred, while the latter did not. The negative impact of urban landscapes on Brook Trout abundance has been supported by previous studies. Steedman (1988) concluded that both Brook Trout absence and a high proportion of urbanization were indicators of degraded stream health. Research by Stanfield, Gibson and Borwick (2006) has found that high PIC, a characteristic of urban landscapes, has a negative impact on Brook Trout distribution. Additionally, Hudy, Thieling, Gillespie and Smith (2008) determined that road density, another characteristic of urban landscapes, was a reliable predictor of Brook Trout distribution in the eastern United States. Finally, Siitari, Taylor, Nelson and Weaver (2011) found that impermeable landscapes, such as urban lands, prevent groundwater recharge which subsequently increases stream water temperatures, and impedes Brook Trout populations.

Moreover, a notable decrease in Brook Trout abundance occurred between the mid-1980s and the mid-1990s, with abundance stabilizing thereafter. The sudden drop in Brook Trout abundance coincided with the rapid urban growth and developmental pressure in the suburban areas surrounding the City of Toronto in the 1990s (Hanna & Webber, 2010). Decreases in Brook Trout abundance in the Humber River watershed in particular also coincided with increases in groundwater taking, by a magnitude of three to four, in the region from the 1970s to the 1990s (Humber Watershed Task Force, 1997). The subsequent Brook Trout population abundance stabilization beginning in the mid-1990s also overlapped with shifts to more ecologically-based land use planning policies and legislation in the Oak Ridges Moraine which sought to protect natural areas from development in regions where Brook Trout populations were located (Hanna & Webber, 2010). The corresponding changes in Brook Trout population abundance and land use policy and legislation suggested that land cover and use has an influence on Brook Trout population abundance.

Brook Trout population abundance in the Duffins Creek watershed did not change significantly, which was not surprising considering that the majority of the area where Brook Trout were located did not experience change in land cover, and that no increases in urbanization were evident. However, the Duffins Creek watershed did experience increases in natural areas and corresponding decreases in agricultural land over time. Hudy, Thieling, Gillespie and Smith (2008) had demonstrated that Brook Trout distribution in the eastern United States was negatively impacted when the percent agricultural land use of a particular area increased beyond a threshold of 12%. Brook Trout could have, therefore, been expected to be positively impacted by a decrease in agricultural land in the Duffins Creek watershed. Brook Trout populations in the Duffins Creek watershed, however, did not respond to the decreases in agricultural land as expected. There are, however, other studies that contradicted Hudy, Thieling, Gillespie and Smith's conclusions. Siitari, Taylor, Nelson and Weaver (2011) had discovered that Brook Trout populations were able to tolerate a higher percent area of agricultural land if high levels of groundwater discharge were maintained. Since agricultural land does not increase the PIC of a given area, it is not expected to alter the degree of groundwater discharge into nearby streams. Therefore, changes in land cover from agricultural to natural would neither alter the PIC of a given area, nor impact the amount of groundwater discharge into nearby streams. Consequently, Brook Trout population abundance in the Duffins Creek watershed would not necessarily be expected to increase as a result of land cover changes from agricultural land to natural areas. Similarly, Waco and Taylor (2010) have found that changes in land cover from forest to pasture had little to no impact on the water temperature of nearby streams, and therefore little impact on Brook Trout populations as well. This was likely due to the marginal differences in recharge rates between forest land cover types (0.19 m/year) and pasture land cover types (0.16 m/year) (Waco & Taylor, 2010). Furthermore, although it can be expected that agricultural land use would have a negative impact on water quality, Slivia and Williams (2001) have instead found that agricultural land use influences on nearby stream water quality were minor and variable. It has also been demonstrated that agricultural land use generally has a minimal influence on overall fish community composition (Fitzgerald, 1998).

7.3 OTHER CONTRIBUTING FACTORS

Although stream water temperature and the factors that impact it, such as climate and land cover, was considered to be the major stressor on Brook Trout populations, other factors have likely played a role in influencing Brook Trout populations in the Humber River, Rouge River, and Duffins Creek watersheds as well.

7.3.1 Brook Trout stocking

Stocking of Brook Trout individuals may artificially increase the abundance of Brook Trout populations, and mask the negative impact of increasing stream water temperature as a result of changing climate and land cover in the region. Brook Trout have been stocked in the Humber River watershed from 1923 to 1972 (OMNR & TRCA, Humber River Fisheries Management Plan, 2005), but no stocking occurred during the years that Brook Trout were sampled for this study. Stocked Brook Trout individuals would not have, therefore, directly influenced abundance measures in this study. Even if stocked individuals had facilitated the long-term persistence of Brook Trout populations in the Humber River watershed, Brook Trout populations still experienced a decline over time during the study period. Additionally, mitochondrial DNA analyses of Brook Trout individuals have revealed that individuals from Brook Trout stocks no longer remain in the region, further confirming that Brook Trout stocking has not influenced abundance measures in this study (McLaughlin, 2001).

In the Duffins Creek watershed, Brook Trout were stocked until 1991 (Cook & Clayton, 2004). Therefore, stocked individuals may have been included in Brook Trout records in 1984 and 1985, and potentially increased abundance measures artificially during those years. However, despite stocking activities up until the early 1990s, Brook Trout abundance still did not change significantly over time from 1984 until 2009. Moreover, when Brook Trout records that potentially included stocked individuals from 1984 and 1985 were omitted from analysis, abundance still remained the same over time. It is possible that although stocked individuals did not enhance Brook Trout populations in the Duffins Creek watershed, they may have prevented populations from declining as they did in the Humber River and Rouge River watersheds. Therefore, Brook Trout populations may have potentially decreased if individuals have not been stocked until 1991. If this is the case, then decline would have been more likely to be a result of a significant increase in monthly extreme maximum summer stream water temperatures since land cover had not experienced much change in the Duffins Creek watershed since the mid-1950s.

Nonetheless, it remains unlikely that Brook Trout stocking would have had a significant long-term impact on resident Brook Trout population abundance in the region. Hatchery-reared Brook Trout individuals have been shown to have low spawning and survival success once they are released into the wild (Ersbak & Haase, 1983; Danzmann & Ihssen, 1995). Similarly, stocking of other trout species have also been shown to have no long-term impact on total trout density with stocked individuals diminishing after three years in the wild (Naslund, 1992; Borgstrom, Skaala, & Aastveit, 2002).

7.3.2 In-stream barriers

Brook Trout that reside in streams do not tend to migrate between feeding, overwintering and spawning sites (Power, 1980). However, individuals have been known to migrate to stream reaches with cooler water temperature when stream water temperatures increase to intolerable levels during the summer (Meisner, 1990b). In-stream barriers can have both negative and positive impacts on Brook Trout. During the summer when stream water temperatures can approach the upper lethal thermal limit for Brook Trout, barriers may prevent Brook Trout individuals from migrating to stream reaches with cooler thermal regimes (Picard, Bozek, & Momot, 2003; Xu, Letcher, & Nislow, 2010a). In fact, there is evidence that in-stream barriers have an impact on the distribution (Stanfield, Gibson, & Borwick, 2006) and density (Pepino, Rodriguez, & Magnan, 2012) of Brook Trout populations. Additionally, in a study by Letcher, Nislow, Coombs, O'Donnell and Dubreuil (2007) that tested the fragmenting effects of in-stream barriers on Brook Trout population dynamics with a projection model, it was found that barriers that isolate stream reaches can cause local extinction that can only be prevented if a sufficient number of individuals from downstream reaches are able to migrate in. On the other hand, another study by Stanley, Catalano, Mercado-Silva and Orr (2007) found that removing barriers in streams did not necessarily lead to Brook Trout population rebound. Instead, the impact of in-stream barriers on Brook Trout population dynamics proved to be complex. It was found that the removal of in-stream barriers led to declines in adult Brook Trout populations, while young-of-year recruitment increased (Stanley, Catalano, Mercado-Silva, & Orr, 2007). While many have found the impact of barriers on Brook Trout populations to be negative or inconclusive, others still have found that barriers can have positive effects. In-stream barriers can prevent Brook Trout from being outcompeted by other fish species. The Great Lakes Fishery Commission has been using in-stream barriers to prevent the parasitic Sea Lamprey from decimating upstream native fish populations since 1958 (Lavis, Hallett, Koon, & McAuley, 2003). Additionally, it has also been demonstrated that barriers are effective at separating Brook Trout from competitive species, such as Rainbow Trout (Stanfield, Gibson, & Borwick, 2006). In fact, a number of in-stream barriers in both the Rouge River and Duffins Creek watersheds are maintained for the sole purpose of protecting Brook Trout populations from parasitic or competitive fish species, such as Sea Lamprey and Rainbow Trout (Cook & Clayton, 2004; OMNR & TRCA, 2010).

7.3.3 Competitors

Brook Trout individuals in stream reaches that lack in-stream barriers to prevent the infiltration of competitors may be outcompeted and their populations may suffer as a result. Competition with non-native trout species, such as Rainbow Trout and Brown Trout *(Salmo trutta)*, have in fact been known to be one of the factors that threaten Brook Trout populations (Huckins, Baker, Fausch, & Leonard, 2008; Johnson, 2008; Lynch & Taylor, 2010). Additionally, it has also been demonstrated that Brook Trout populations tend to be more abundant in stream reaches when other species are absent, although this scenario is not always true in every case (Stanfield, Gibson, & Borwick, 2006). Furthermore, it has been found that Brook Trout are not predominant in streams where the biomass of other trout species is greater than 0.3 g/m^2 (Stoneman & Jones, 2000). However, despite the negative impact that other competitive fish species can have on Brook Trout populations, Brook Trout individuals are still able to persist against this competition when stream water temperature is within their suitable range. When water temperature is less than 20^{o}C, Brook Trout had a competitive edge that is equal to, if not greater than other fish in the stream. If the water temperature rises to over 22^{o}C, that competitive advantage disappears (Kerr & Grant, 2000). In fact, Brook Trout have been found to be the dominant species over Rainbow Trout in stream reaches with cooler water (Kerr & Grant, 2000). Therefore, stream water temperature, and the factors that affect it, continues to be the dominant driver that influences Brook Trout populations.

7.4 Limitations

This research has met the objectives of identifying long-term changes in Brook Trout population abundance in the Humber River, Rouge River and Duffins Creek watersheds, and of relating these changes to variations in local climate and land cover overtime. However, there were some unavoidable limitations in this study that may have affected the quality of the results.

First of all, none of the Brook Trout populations in this study were situated in pristine environments, making it difficult to discern the effects of climate from the effects of land use intensification. Analysis of a population in a pristine environment would have served as a reference site for the study, and eliminated the impact of urbanization so that it would have been clear that any detectable changes in Brook Trout populations would have been a result of changes in the surrounding climate. Unfortunately, no such reference site exists in Toronto and/or the area surrounding it. Instead, the changes observed in all of the study areas were a result of multiple factors with varying degrees of influence on Brook Trout populations, which were likely to have contributed to the high standard deviation observed in the CPUE figures in the results. The Duffins Creek watershed was relatively pristine when compared to the other watersheds as the study area has experienced relatively less urbanization over time and has been able to maintain a relatively high proportion of natural areas. The Duffins Creek watershed, therefore, may be able to act as a relative reference site, although the influence of land use intensification was still not absent because it was still not a perfectly pristine environment.

However, Brook Trout stocking that has taken place in the Duffins Creek watershed up until 1991 compromises the study area as a reference site since Brook Trout populations have been artificially inflated during the early phases of the study period.

Another limitation that would have likely contributed to the high standard deviations observed in the CPUE calculations in the results was the large number of gaps and inconsistencies present in the Brook Trout dataset. Gaps and inconsistencies in the dataset resulted in the need to omit many Brook Trout records, which greatly decreased the overall sample size. This decrease in the overall sample size of Brook Trout may have led to an increase in the standard deviation in the CPUE calculations. Additionally, many of the Brook Trout records included in the CPUE calculations were missing the length, width or area of the stream reach that was sampled. As a result, annual averages of length, width or area were used to calculate the CPUE for Brook Trout records that were missing these parameters. CPUE values for those records, therefore, were only estimations of the CPUE of Brook Trout for that sample site, and did not reflect the true abundance. The error present in these estimations would have contributed to the high standard deviations observed the CPUE values.

Furthermore, although a decrease in mean CPUE was observed from pre-1986 Brook Trout populations to post-1995 populations, the lack of usable data in the years between 1986 and 1995 prevented the exact year that Brook Trout population abundance began to diminish to be determined. Additionally, the lack of data before 1984 prevented any investigation on whether Brook Trout populations have just begun to decrease in the mid-1980s or if populations have been on a downward trend during the years prior to the mid-1980s. Therefore, the lack of quality data has prevented a more detailed picture of historical Brook Trout population change from being depicted.

Finally, the weighted thermal stress score method developed in this study made the assumption that stress experienced by Brook Trout individuals, as a result of increasing stream water temperatures, increased along a linear scale. In actuality, rising water temperatures are unlikely to impact Brook Trout in a linear fashion. Instead, Brook Trout individuals are more likely to experience less stress if temperature increases occur at its optimal thermal temperature, than if the same degree of temperature increase occurs near its upper lethal thermal limit. For example, a Brook Trout individual is likely to experience less stress as a result of a stream water temperature increase from 15ºC to 18ºC, and more stress when temperature rises from 22ºC to 25ºC. Therefore, the thermal stress score method developed in this study can only be used to indicate a change in thermal stress, and does not measure the actual degree of thermal stress change experience by Brook Trout individuals as a result of changing stream water temperatures.

CHAPTER 8: CONCLUSION

Knowledge of the changes that Brook Trout populations have experienced in the past, and the factors that have influenced these changes is imperative to help guide future management of this species in southern Ontario. This study sought to detect the changes in Brook Trout abundance in the Humber River, Rouge River and Duffins Creek watersheds over the past quarter century, and to relate these changes to variations in climate and land cover that have occurred over the same period of time.

This study revealed that Brook Trout populations in the areas surrounding Toronto have experienced an overall decrease, and that these decreases were driven by populations in the Humber River and Rouge River watersheds. Brook Trout in the Duffins Creek watershed, on the other hand, did not experience a notable decrease in abundance. Decreases in abundance were likely due to increases in both the degree and frequency of extreme maximum stream water temperatures. These changes in stream water temperature regimes were, in turn, likely due to increases in impermeable land cover types in the Humber River and Rouge River watersheds.

Climate had little influence on Brook Trout populations in this study as no notable changes were detected in summer air temperature over the past quarter century. It is possible that increases in air temperature during other seasons could have resulted in decreases in Brook Trout abundance. After all, other studies have detected historical increases in annual mean air temperature in the region (Magnuson, et al., 1997; Dobiesz & Lester, 2009; Mohsin & Gough, 2010; Dickinson, Rudra, & Amili, 2012), and it has been demonstrated that these increases were most substantial during the spring, fall and winter seasons (Magnuson, et al., 1997; Solomon, et al., 2007; Mohsin & Gough, 2010; Dickinson, Rudra, & Amili, 2012). However, increases in air temperature during other seasons would have impacted Brook Trout populations across all watersheds, including those in the Duffins Creek watershed. Nevertheless, Brook Trout abundance in the Duffins Creek watershed has continued to remain unaffected despite any possible increases in air temperature during seasons other than the summer. Consequently, change in Brook Trout abundance can still be mostly attributed to alterations in land cover over time, and not to climate change.

Stabilization in Brook Trout abundance from the mid-1990s and onwards reflected the efficacy of the more ecologically-based land use planning policies that were beginning to take shape in the Oak Ridges Moraine in the late 1980s and early 1990s. This apparent relationship between Brook Trout populations and land use policies emphasizes the importance of implementing ecologically-based planning strategies in order to maintain both healthy Brook Trout populations and high quality stream habitats. The corresponding stabilization of Brook Trout populations and changes in land use policies also further verified that changes in Brook Trout abundance in the past can generally be attributed to changes in land cover and not climate.

Although land cover has been found to have a bigger impact on Brook Trout populations historically and in the short-term in this study, changes in air temperature and other climate variables may still have an impact on Brook Trout populations in the future and in the long-term. Many studies have speculated that increases in temperature due to climate change are likely to affect the thermal habitat of fisheries in the Great Lakes (Jones, Shuter, Zhao, & Stockwell, 2006; Chu, Jones, Mandrak, Piggot, & Minns, 2008). As a result, thermal habitat for cold water fish species, including Brook Trout, is expected to decrease (Meisner, 1990b; Stefan, Fang, & Eaton, 2001; Casselman, 2002). Therefore, suitable thermal habitat and Brook Trout populations are expected to become increasingly threatened as temperatures increase as a result of climate change in the future.

Climate change projections for southern Ontario predict that ambient summer temperatures will experience an increase of 3-5ºC on average (Colombo, McKenney, Lawrence, & Gray, 2007). Therefore, although land cover was found to be the more significant factor in this study, the potential impact of future long-term climate change cannot be ignored.

8.1 RECOMMENDATIONS FOR FUTURE RESEARCH

Further research to identify air temperature changes during other seasons is important to discern the potential impact of climate change on other life stages of Brook Trout. For example, if air temperature is increasing significantly during the spring and/or fall seasons, the survival of emerging Brook Trout fry during the spring, and/or the success of Brook Trout spawning may be compromised because both life stages require optimal cold water habitats in order to persist.

Additionally, climate variables other than air and stream water temperature can have an impact on Brook Trout as well. Further analysis on the impact of climate change on precipitation levels, and the effect of these changing precipitation patterns on stream and groundwater temperature and discharge is warranted. Altered stream and groundwater temperature and discharge, as a result of changes in precipitation patterns, will affect the thermal habitat of Brook Trout, and may have negative implications on Brook Trout spawning and survival. Precipitation can influence stream water temperature through direct input of rainwater into streams, and indirectly through surface/subsurface runoff and groundwater discharge (Subehi, et al., 2010). Increased precipitation may have the potential to increase groundwater discharge, thereby decreasing stream water temperature. Therefore, if a trend of increased precipitation is occurring, this phenomenon may negate any potential negative impacts of increasing air temperature. On the other hand, if precipitation trends are decreasing instead, groundwater discharge is likely to decrease, causing stream water temperatures to increase. If a net loss of precipitation occurs, the impact of an overall increase in annual mean air temperature on Brook Trout may be further exacerbated. In fact, stream water temperature has been found to be influenced by changes in specific discharge, a factor that is affected by precipitation levels, more than by changes in air temperature (Subehi, et al., 2010). Therefore, further investigation into the influence of precipitation on both stream water temperature and Brook Trout populations is needed to determine if precipitation is indeed a better predictor of stream water temperature, and therefore Brook Trout populations as well, than air temperature.

In this study, the amount of thermal stress that Brook Trout populations were exposed to was measured with a weighted thermal stress scoring method that gauged the amount of thermal stress the habitat was imposing on Brook Trout individuals. In this scoring method, thermal stress was defined by the number of days that Brook Trout were exposed to extremely high stream water temperatures in a particular year. There are, however, other ways of interpreting thermal stress. For example, streams whose water temperature reaches 23ºC for three consecutive days would impose greater thermal stress on a Brook Trout individual than a stream whose water temperature only reaches 23ºC for one day. Therefore, it would be of interest to examine the relationship between Brook Trout populations and the number of consecutive days that a stream is thermally suboptimal for the species. Additionally, the thermal stability of streams is also important to the health of Brook Trout populations. Thermally stable streams are those whose water temperature does not fluctuate considerably over a short period of time. Streams that receive a large amount of groundwater are more thermally stable as the groundwater helps to moderate the temperature of the stream. Consequently, the relationship between Brook Trout populations and the thermal stability of their habitat is also a subject that necessitates further study. Finally, the thermal stress scoring method developed in this study can only be used as an indicator since it assumed that thermal stress is increasing in a linear fashion as stream water temperatures increase. Therefore, further study is necessary to determine how thermal stress in Brook Trout is actually changing in relation to increasing stream water temperatures.

Furthermore, the challenges encountered with the quality of the data in this study highlights the importance of implementing a standardized protocol for fish data collection, and practicing diligent collection of data in the field in order to minimize the number of gaps and inconsistencies that can occur in ecological field datasets. Many of the Brook Trout records in this study had to be eliminated because of differences in collection practices and techniques, and failures to practice diligent record keeping in the field. Since its initial publication in 2005, the Ontario Stream Assessment Protocol (OSAP) has been providing standardized methodologies for the collection of fish community and physical stream habitat data for natural resource managers and field crews (Stanfield, 2007). Training and certification courses are now also available to help ensure that high quality data are collected and recorded in the field. Although the quality of historical data cannot be corrected, the continued implementation of standardized methodologies, such as OSAP, and emphasis on training in diligent record collection and keeping will help ensure that issues with poor data quality are not encountered in the future.

Finally, further study on the long-term trends of aquatic organisms is not possible without continued monitoring programs. Establishment of consistent, long-term monitoring programs for Brook Trout and other aquatic organisms is vital to understanding how aquatic biota interact with their surrounding environment.

APPENDICES

Appendix A: Brook Trout Records and CPUE Values

Year	Date	Watershed	#Individuals	# E-fish. Hr.	Area	CPUE
1984	25/06/1984	Duffins	6	0.169	75.000	0.473
1984	25/06/1984	Duffins	2	0.199	150.000	0.067
1984	27/06/1984	Humber	6	0.079	30.000	2.544
1984	05/06/1984	Duffins	3	0.208	150.000	0.096
1984	05/06/1984	Duffins	8	0.201	390.000	0.102
1984	05/06/1984	Duffins	1	0.155	450.000	0.014
1984	13/06/1984	Duffins	1	0.200	160.000	0.031
1984	13/06/1984	Duffins	2	0.109	150.000	0.122
1984	18/05/1984	Duffins	15	0.135	450.000	0.247
1984	18/05/1984	Duffins	17	0.193	875.000	0.101
1984	18/05/1984	Duffins	5	0.105	125.000	0.380
1984	23/05/1984	Duffins	1	0.155	150.000	0.043
1984	29/05/1984	Rouge	1	0.169	150.000	0.040
1984	29/05/1984	Rouge	4	0.130	50.000	0.617
1984	29/05/1984	Rouge	20	0.130	50.000	3.084
1984	30/05/1984	Rouge	1	0.171	35.000	0.168
1985	16/09/1985	Duffins	12	0.184	75.000	0.869
1985	17/09/1985	Duffins	1	0.167	100.000	0.060
1985	18/09/1985	Duffins	14	0.207	87.500	0.774
1985	23/09/1985	Duffins	10	0.180	75.000	0.741
1985	02/07/1985	Duffins	16	0.175	84.380	1.085
1985	02/07/1985	Duffins	1	0.069	85.000	0.170
1985	02/07/1985	Duffins	14	0.131	51.000	2.098
1985	02/07/1985	Duffins	10	0.131	84.380	0.908
1985	02/07/1985	Duffins	39	0.149	84.380	3.093
1985	22/07/1985	Duffins	39	0.120	84.380	3.861
1985	22/07/1985	Duffins	45	0.080	204.000	2.757
1985	22/07/1985	Duffins	8	0.089	84.380	1.063
1985	22/07/1985	Duffins	4	0.142	84.380	0.333
1985	22/07/1985	Duffins	8	0.129	102.000	0.610
1985	22/07/1985	Duffins	26	0.091	84.380	3.372
1985	17/07/1985	Humber	1	0.179	84.380	0.066
1985	23/07/1985	Humber	27	0.069	84.380	4.626
1985	23/07/1985	Humber	3	0.073	84.380	0.487
1985	23/07/1985	Humber	15	0.082	84.380	2.162
1985	23/07/1985	Humber	38	0.143	84.380	3.154
1985	24/07/1985	Humber	1	0.076	85.000	0.156
1985	25/07/1985	Humber	15	0.107	84.380	1.667
1985	25/07/1985	Humber	3	0.124	85.000	0.286
1985	25/07/1985	Humber	5	0.098	84.380	0.606

1985	25/07/1985	Humber	40	0.068	84.380	6.966
1996	9/4/1996	Duffins	7	0.334	191.940	0.109
1996	7/18/1996	Duffins	1	0.123	132.790	0.061
1996	7/24/1996	Duffins	1	0.126	137.330	0.058
1996	7/26/1996	Duffins	1	0.133	154.800	0.048
1996	18/07/1996	Rouge	1	0.306	190.000	0.017
1997	14/10/1997	Rouge	2	0.267	130.000	0.058
1998	01/10/1998	Duffins	5	0.469	145.000	0.073
1999	02/09/1999	Duffins	10	0.303	92.000	0.359
1999	02/09/1999	Duffins	29	0.282	80.000	1.287
1999	03/09/1999	Duffins	5	0.271	200.000	0.092
1999	03/09/1999	Duffins	8	0.308	172.000	0.151
1999	22/09/1999	Duffins	1	0.459	318.500	0.007
1999	22/09/1999	Duffins	6	0.378	240.000	0.066
1999	23/09/1999	Duffins	1	0.338	180.000	0.016
1999	23/09/1999	Duffins	2	0.324	160.000	0.039
1999	05/08/1999	Humber	18	0.606	200.000	0.148
1999	26/07/1999	Humber	16	0.931	281.600	0.061
1999	25/08/1999	Humber	15	0.657	176.000	0.130
1999	14/09/1999	Humber	43	0.341	180.400	0.699
1999	23/09/1999	Humber	7	0.167	176.000	0.238
1999	19/08/1999	Rouge	1	0.153	182.500	0.036
1999	19/08/1999	Rouge	10	0.166	182.500	0.330
1999	09/09/1999	Rouge	2	0.229	182.500	0.048
2000	2000/07/04	Duffins	26	0.969	230.160	0.117
2000	2000/07/04	Duffins	14	0.389	91.890	0.391
2000	2000/07/06	Duffins	12	1.004	297.920	0.040
2000	2000/07/07	Duffins	14	0.474	104.320	0.283
2000	2000/07/10	Duffins	3	0.282	73.700	0.144
2000	2000/07/12	Duffins	7	0.293	58.590	0.408
2000	2000/07/13	Duffins	18	0.788	183.230	0.125
2000	2000/07/19	Duffins	1	0.613	124.680	0.013
2000	2000/07/19	Duffins	2	0.709	179.520	0.016
2000	2000/07/25	Duffins	2	1.032	227.460	0.009
2000	2000/07/26	Duffins	24	0.362	133.840	0.496
2000	2000/07/27	Duffins	4	0.946	257.450	0.016
2000	2000/07/28	Duffins	9	1.056	285.540	0.030
2000	2000/08/11	Duffins	7	0.315	73.950	0.300
2000	2000/08/14	Duffins	2	1.319	321.600	0.005
2000	2000/08/18	Rouge	3	0.295	49.105	0.207
2000	2000/08/24	Rouge	7	0.200	54.000	0.648
2000	2000/08/24	Rouge	2	0.589	122.400	0.028
2000	2000/08/31	Rouge	7	0.303	56.280	0.410
2000	2000/09/01	Rouge	4	0.979	98.400	0.042
2001	2001/08/09	Humber	6	0.371	238.770	0.068

2001	2001/08/23	Humber	3	0.411	144.267	0.051
2001	2001/08/27	Humber	1	0.550	155.600	0.012
2001	2001/08/29	Humber	15	0.237	87.894	0.721
2001	2001/08/30	Humber	29	0.525	297.320	0.186
2001	2001/09/07	Humber	1	0.544	211.700	0.009
2001	2001/09/10	Humber	11	0.459	136.625	0.175
2001	2001/09/13	Humber	15	0.633	235.040	0.101
2001	09/07/2001	Rouge	2	0.316	431.000	0.015
2003	2003/07/09	Duffins	2	0.349	159.692	0.036
2003	2003/07/09	Duffins	3	0.563	185.617	0.029
2003	2003/07/11	Duffins	4	0.312	106.632	0.120
2003	20a03/07/14	Duffins	28	0.203	79.007	1.748
2003	2003/07/21	Duffins	1	0.466	119.680	0.018
2003	2003/07/22	Duffins	4	0.856	367.206	0.013
2003	2003/08/05	Rouge	2	0.262	109.250	0.070
2003	05/08/2003	Rouge	1	0.262	109.200	0.035
2004	2004/07/06	Humber	2	0.452	199.732	0.022
2004	2004/07/06	Humber	5	0.298	116.899	0.143
2004	2004/07/08	Humber	34	0.454	125.311	0.597
2004	2004/07/13	Humber	4	0.782	406.628	0.013
2004	2004/07/14	Humber	4	0.611	238.681	0.027
2004	2004/07/23	Humber	12	0.583	248.466	0.083
2004	2004/07/28	Humber	1	0.541	182.498	0.010
2006	2006/07/14	Duffins	2	0.382	287.374	0.018
2006	2006/07/24	Duffins	4	0.253	97.820	0.162
2006	2006/08/03	Duffins	3	0.296	135.725	0.075
2006	2006/08/10	Duffins	1	0.436	183.452	0.013
2006	2006/08/16	Duffins	17	0.256	85.353	0.779
2006	2006/07/11	Rouge	4	0.397	135.335	0.074
2007	2007/06/27	Humber	1	0.766	205.426	0.006
2007	2007/06/28	Humber	6	0.432	124.808	0.111
2007	2007/06/28	Humber	3	0.644	241.589	0.019
2007	2007/06/29	Humber	3	0.834	349.718	0.010
2009	2009/07/03	Duffins	2	0.626	308.836	0.010
2009	2009/07/06	Duffins	1	0.696	394.070	0.004
2009	2009/07/27	Duffins	8	0.356	113.620	0.198
2009	2009/07/27	Duffins	7	0.305	178.704	0.128
2009	2009/07/28	Duffins	1	0.719	399.400	0.003
2009	2009/09/25	Duffins	1	0.366	158.842	0.017
2009	2009/06/25	Duffins	1	0.922	513.972	0.002
2009	08/25/09	Humber	14	0.174	213.120	0.377
2009	08/25/09	Humber	8	0.250	259.200	0.124
2010	30/08/2010	Humber	17	0.160	213.120	0.499
2010	30/08/2010	Humber	8	0.232	259.200	0.133

Appendix B: Annual Mean CPUE Values from All Watersheds Combined

Year	n	Mean CPUE	Std. Dev.
1984	16	0.508	0.922
1985	24	1.458	1.349
1996	5	0.059	0.033
1997	1	0.058	na
1998	1	0.073	na
1999	16	0.232	0.333
2000	20	0.186	0.196
2001	9	0.149	0.225
2003	7	0.046	0.038
2004	6	0.050	0.053
2006	6	0.187	0.295
2007	4	0.037	0.050
2009	9	0.096	0.128
2010	2	0.316	0.259

Appendix C: Annual Mean CPUE Values from All Watersheds Combined, Excluding 1980s Records from Duffins Creek Watershed

Year	n	Mean CPUE	Std. Dev.
1984	5	1.290	1.420
1985	10	2.017	2.293
1996	5	0.059	0.033
1997	1	0.058	na
1998	1	0.073	na
1999	16	0.232	0.333
2000	20	0.186	0.196
2001	9	0.149	0.225
2003	7	0.046	0.038
2004	6	0.050	0.053
2006	6	0.187	0.295
2007	4	0.037	0.050
2009	7	0.052	0.079
2010	2	0.316	0.259

Appendix D: Annual Mean CPUE Values from Duffins Creek Watershed

Year	n	Mean CPUE	Std. Dev.
1984	11	0.153	0.150
1985	15	1.453	1.246
1996	4	0.069	0.027
1998	1	0.073	na
1999	8	0.252	0.433
2000	15	0.160	0.171
2003	5	0.043	0.044
2006	5	0.209	0.324
2009	7	0.052	0.079

Appendix E: Annual Mean CPUE Values from Humber River Watershed

Year	n	Mean CPUE	Std. Dev.
1984	1	2.544	na
1985	10	2.017	2.293
1999	5	0.255	0.256
2001	8	0.165	0.234
2004	6	0.050	0.053
2007	4	0.037	0.050
2009	2	0.250	0.179
2010	2	0.316	0.259

Appendix F: Annual Mean CPUE Values from Rouge River Watershed

Year	n	Mean CPUE	Std. Dev.
1984	4	0.977	1.426
1996	1	0.017	na
1997	1	0.058	na
1999	3	0.138	0.166
2000	5	0.267	0.263
2001	1	0.015	na
2003	2	0.052	0.025
2006	1	0.074	na

Appendix G: Air Temperature Data

Year	Month	Mean Max. Temp. (ºC)	Extreme Max. Temp. (ºC)
1986	June	22.8	28.6
1986	July	26.2	34.2
1986	August	24.0	28.8
1986	September	19.3	26.2
1987	June	25.1	33.4
1987	July	27.9	34.6
1987	August	24.8	33.8
1987	September	20.0	25.8
1988	June	24.4	34.8
1988	July	29.4	37.2
1988	August	27.0	36.0
1988	September	20.2	28.4
1989	June	23.7	30.3
1989	July	28.2	34.0
1989	August	24.7	33.3
1989	September	20.7	29.0
1990	June	24.5	30.5
1990	July	26.7	35.4
1990	August	25.9	31.4
1990	September	20.5	29.5
1991	June	26.9	34.5
1991	July	27.9	35.6
1991	August	27.3	34.5
1991	September	21.0	32.8
1992	June	22.7	31.2
1992	July	22.8	27.7
1992	August	23.4	29.8
1992	September	20.4	29.6
1993	June	23.1	29.1
1993	July	27.5	32.7
1993	August	27.7	35.0
1993	September	19.4	29.2
1994	June	25.5	36.0
1994	July	27.4	33.4
1994	August	24.5	30.1
1994	September	21.6	30.5
1995	June	25.9	36.6
1995	July	27.3	36.8
1995	August	27.4	35.1
1995	September	20.0	29.9
1996	June	23.6	31.2
1996	July	25.2	30.0
1996	August	26.5	31.7
1996	September	21.4	28.7
1997	June	25.9	33.4
1997	July	26.1	34.0
1997	August	24.0	31.0
1997	September	20.9	38.0
1998	June	24.6	32.2
1998	July	27.3	33.4

1998	August	27.1	32.1
1998	September	24.0	32.6
1999	June	25.5	35.4
1999	July	29.3	35.1
1999	August	24.6	31.2
1999	September	22.7	32.2
2000	June	23.1	31.9
2000	July	24.5	29.9
2000	August	24.8	31.1
2000	September	20.2	29.8
2001	June	25.1	32.6
2001	July	25.7	33.4
2001	August	28.9	37.8
2001	September	21.8	31.1
2002	June	24.6	32.9
2002	July	29.7	35.5
2002	August	27.4	35.0
2002	September	25.4	34.4
2003	June	24.1	35.4
2003	July	27.2	32.6
2003	August	27.0	32.5
2003	September	21.7	28.4
2004	June	23.1	32.3
2004	July	25.2	30.9
2004	August	24.0	28.6
2004	September	23.7	29.6
2005	June	28.0	34.1
2005	July	29.8	36.1
2005	August	27.7	34.6
2005	September	24.2	32.1
2006	June	24.6	34.1
2006	July	28.9	35.4
2006	August	26.3	37.8
2006	September	19.5	28.3
2007	June	26.8	34.6
2007	July	26.8	34.7
2007	August	27.7	34.9
2007	September	23.9	32.8
2008	June	24.6	34.2
2008	July	26.9	31.8
2008	August	25.1	31.0
2008	September	21.9	31.4
2009	June	22.5	31.8
2009	July	24.1	28.4
2009	August	25.6	32.9
2009	September	21.7	26.8
2010	June	23.7	30.3
2010	July	28.8	34.7
2010	August	27.0	34.8
2010	September	20.8	32.3

Appendix H: Stream Water Temperature Data

Watershed	Year	Month	Mean Max. Temp. (˚C)	Extreme Max. Temp. (˚C)
Duffins	2003	June	18.98	21.62
		July	18.81	21.45
		August	19.30	21.12
		September	16.49	17.72
Duffins	2006	June	21.10	23.35
		July	21.89	23.98
		August	20.33	25.99
		September	16.22	18.44
Duffins	2009	June	16.97	19.19
		July	16.83	17.95
		August	18.66	21.76
		September	16.85	18.04
Humber	2004	June	16.55	18.37
		July	18.53	21.92
		August	17.16	20.39
		September	17.26	18.79
Humber	2007	June	19.64	23.47
		July	18.89	23.45
		August	19.12	23.33
		September	16.74	20.84
Humber	2010	June	17.05	20.62
		July	20.70	23.58
		August	na	na
		September	na	na
Rouge	2003	June	16.29	19.41
		July	16.07	18.75
		August	16.01	17.61
		September	14.06	15.70
Rouge	2006	June	16.61	19.48
		July	17.67	20.84
		August	16.49	22.71
		September	13.72	16.08
Rouge	2009	June	15.05	17.09
		July	14.72	16.52
		August	15.99	19.76
		September	14.29	15.00

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