Mainstreaming Climate Change in Drinking Water Source Protection Planning in Ontario

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Prepared by:

Rob de Loë and Aaron Berg

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Preface

This report was prepared under contract to Pollution Probe and the Canadian Water Resources Association by Rob de Loë (Rob de Loë Consulting Services) and Aaron Berg (Berg + Hobbs Consulting Inc.). Funding was provided by the Ontario Ministry of the Environment and Environment Canada. The body of the report was written by Rob de Loë, while Appendix A was prepared by Aaron Berg. Members of the project team for Rob de Loë Consulting Services included Liana Moraru, Erin Stratton, Janet Ivey, and Reid Kreutzwiser. The steering committee for this project included Rick Findlay (Pollution Probe), Craig Mather (Canadian Water Resources Association, Ontario Branch), Rob de Loë and Aaron Berg. We are grateful to Erik Veldman (Pollution Probe) for project management support and Krista Friesen (Pollution Probe) for the desktop publishing.

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Executive Summary

While uncertainty still exists regarding many of the fine details, most climate scientists now agree that climate change is real and is already happening. There is also broad agreement that human activities are primarily responsible for the changes to the global climate that have been observed during the last half of the 20th century, and that significant additional changes to the climate will occur in future decades.

Because of the way it affects the hydrologic cycle, *global* climate change is a *local* problem with which conservation authorities, municipalities, the Province and water users will have to deal. For example, land use and infrastructure planning decisions being made today should account for the ways in which climate change will affect water resources. Thinking now about the way in which climate change affects the hydrologic cycle, and how these changes affect human societies and ecosystems, will permit earlier and more effective adaptation.

This report focuses on ways in which climate change must be built into — or *mainstreamed* in — source protection planning in Ontario. The focus of the proposed *Clean Water Act* is protection of drinking water sources. Nonetheless, through developing source protection plans, municipalities, conservation authorities and other local stakeholders will have what may be the best opportunity in a generation to mainstream climate change into water management and land use planning in Ontario.

Source protection planning under the *Clean Water Act* will involve a diverse range of stakeholders with varying technical backgrounds. This report has been written for all of them.

- For non-technical readers, the report provides an overview of current projections of climate change in Ontario, highlights expected impacts on water resources, and draws attention to broad opportunities to mainstream climate change in source protection planning.
- For technical specialists, the report identifies specific opportunities to build climate change into watershed characterizations and water budgets, and, through a technical appendix, offers specific advice for building climate change into hydrological models pertinent to source protection planning in Ontario.

How is Ontario's Climate Expected to Change?

Ontario's current climate is not the same as the climate of a century ago. Measurable changes have been detected in climate variables such as air temperature and precipitation. For example, in southern Canada, mean annual temperature has increased by 0.9°C between 1900 and 1994. Total precipitation in the Canadian portion of the Great Lakes-St. Lawrence basin increased between 1895 and 1995, with more precipitation falling as rain and less as snow. Impacts on hydrology from these kinds of changes also are evident. For example, a significant trend to an earlier spring freshet has been detected in southern Canada.

These kinds of trends remind us that climates can — and do — change. What kinds of changes can we expect in future in Ontario? Using sophisticated Global Climate Models (GCMs), atmospheric scientists have created plausible projections of future climates based on a variety of greenhouse gas emissions scenarios. These scenarios reflect reasonable and internally consistent assumptions about future levels of economic development, population growth, and technology.

Recent projections suggest that Ontario's climate in a hundred years will be considerably different than the one we experience today.

- Substantial temperature increases are expected in all seasons by the end of the century. Confidence around this projection is very strong.
- Projections for precipitation vary among studies. However, studies consistently point to a change in the seasonal distribution of precipitation — with more expected in the winter, and less in summer. Extremes, in the form of droughts and high-intensity rainfall events, also are expected to become more common.
- Evapotranspiration also is expected to increase although confidence in this projection is lower than for temperature.

Anticipated changes are significant because they are outside of the historical or observed range of variability. Therefore, we should not assume that because we have coped with climatic variability in the past, we will automatically be able to cope with a new climatic regime in future.

How Will Expected Climate Change Affect Water Resources?

Broad-scale modelling of the impacts of climate change on the hydrologic cycle points to a series of potential impacts that should be of concern to water managers. The hydrologic cycle is very sensitive to changes in temperature, precipitation and evaporation. As a result, it is not appropriate to assume that future hydrological regimes will be statistical replicas of the past. This has enormous implications for water management in a number of areas pertinent to source protection planning. For example, studies of the impacts of climate change on the hydrologic cycle point to significant changes to streamflows, lake levels, water quality, groundwater infiltration, and patterns of groundwater recharge and discharge. To illustrate, using the case of the Great Lakes basin, the following impacts have been identified in previous studies:

- Winter runoff is expected to increase, but total annual runoff is expected to decrease; summer and fall low flows are expected to be lower, and longer lasting.
- Groundwater recharge is expected to decrease due to a greater frequency of droughts and extreme precipitation events. Shallow aquifers will be more sensitive to these changes than deep ones.
- Water temperature in rivers and streams is expected to rise as air temperatures increase, and as summer baseflow is reduced.

What Impacts can be Expected at the Local Level?

Changes such as these will have profound impacts on humans and ecosystems. For example, decreased runoff during summer is likely to lead to reduced water quality, increased water treatment costs, and greater competition and conflict for reduced water supplies during drought periods. Water users dependent on groundwater for their supplies may expect increased costs because of a need to drill deeper wells; in rural areas, the frequency of shallow wells drying up may increase. Changes to wetland form and function may be expected as groundwater discharge decreases, and stress on fish habitat is likely to increase as water temperature increases and flows decrease.

These kinds of impacts illustrate ways in which *global* climate change creates *local* problems that stakeholders in Ontario will have to confront. Considering climate change now in water management activities will permit earlier and more effective adaptation. For water managers, it has been difficult in the past to give climate change serious attention in part because of the challenges they have faced in dealing with existing and routine responsibilities. Through source water protection activities under the proposed *Clean Water Act*, an opportunity exists to make climate change part of our day-to-day water management activities and our long-term plans in Ontario.

Mainstreaming Climate Change into Source Protection

Source protection involves a wide range of activities that help to keep drinking water sources free from contamination. The logic of source protection is simple: water sources that are free from contamination need less treatment before being distributed, and are less likely to contain contaminants that conventional treatment processes cannot easily detect and remove. As the first line of defense in the multi-barrier approach to drinking water safety, source protection necessarily involves careful consideration of links between land use activities and water quality and quantity.

Under the proposed *Clean Water Act*, source protection plans will be developed at the watershed-scale by local stakeholders. Plans will build on detailed assessment reports. Two components of assessment reports that are especially pertinent for climate change are the *watershed characterization* and the *water budget*. In watershed characterizations, teams involved in source protection planning will develop watershed-wide overviews of land uses and activities, water resources, and threats to drinking water safety. In water budgets, relationships between inputs of water, withdrawals of water, and storage in watershed will be represented — at first, conceptually, but then quantitatively.

- In preparing watershed characterizations, Source Protection Committees should consider how climate change will influence vulnerable areas; the need for, and vulnerability of, future drinking water sources; and the quality of water sources that supply drinking water. Because watershed characterizations are the foundation of the assessment report, and because assessment reports will guide source protection plans and resulting activities, building climate change into watershed characterizations is critical.
- In creating detailed, quantitative water budgets, Source Protection Committees should be able to provide the detailed local understanding of the impacts of climate change on hydrology that has been difficult to incorporate in regional studies of climate impacts completed to date. While technical challenges exist relating to incorporating climate change in water budgets, the discussion in Appendix A demonstrates that these are resolvable. Indeed, several conservation authorities in Ontario already have been building climate change into their hydrologic and water quality models.

Numerous other opportunities exist for addressing climate change in the source protection planning process. However, being able to address climate change in watershed characterizations and water budgets would represent significant progress towards mainstreaming climate change into water management.

Importantly, the fact that it may not be possible to address climate change satisfactorily in initial watershed characterizations in all source protection areas does not mean that the opportunity has been missed. Source protection planning should be an ongoing, long-term undertaking. Plans will have to be updated continually anyway because *everything else* is changing. Therefore, climate change can be mainstreamed in subsequent plans as data gaps are closed, skills are developed and experience is gained.

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Chapter 1: Introduction

In response to the contamination of the drinking water supply of the Town of Walkerton in May, 2000, the Government of Ontario committed to the multi-barrier approach to drinking water safety. Protecting the sources of water used for drinking is the first barrier in the multi-barrier approach to drinking water safety (see Sidebar 1 for an explanation of the multi-barrier approach). The law that will guide source protection planning in Ontario, the *Clean Water Act*, was introduced to the Legislative Assembly on December 5th, 2005. As of March 31, 2006, when this report was completed, the *Clean Water Act* had not yet been passed. Nonetheless, in anticipation of what would be required under the proposed act, source protection planning was already well underway in Ontario by early 2006.

Source water protection planning under the *Clean Water Act* will involve municipalities, conservation authorities (CAs), the Province, land owners, businesses and other stakeholders in partnerships designed to create and implement watershed-based source protection plans. These plans will guide current and future land uses and activities, and will help to ensure safe drinking water supplies by managing threats to the groundwater and surface water sources on which rural and urban people in Ontario depend.

Drinking water source protection planning is an important opportunity to change the way we manage water resources in Ontario. It is not a one-time undertaking. Instead, source protection plans will be developed, implemented, evaluated, and modified in a continuous cycle. Throughout this process, we will develop a much better understanding of Ontario's water resources, the risks that different kinds of land uses and activities pose for drinking water, and ways in which we can protect our drinking water sources.

Even though the focus is on drinking water safety, source protection planning will have broader benefits, including closer integration of land use planning and water management. However, there is

Sidebar 1: The Multi-Barrier Approach to Drinking Water Safety

In a 2003 study, a group of experts who had participated in the Walkerton Inquiry analyzed 15 waterborne disease outbreaks that occurred in Canada, the United States, England and Denmark between 1974 and 2001 (Hrudey, *et al.* 2003). They found that the outbreaks in these cases were caused by one or more problems or failures at the drinking water source, in the treatment system, in the distribution system, in the way systems were monitored, or in responses to the detection of contaminants.

Drinking water safety demands careful management at all points between the source and the tap. This "multi-barrier" approach is promoted by agencies around the world, including the United States Environmental Protection Agency, the Canadian Council of Ministers of the Environment (CCME 2003), and, since Walkerton, the Ontario Ministry of the Environment.

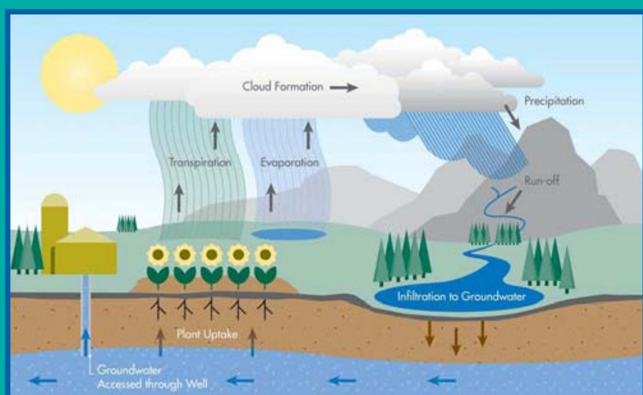
A multi-barrier approach involves five types of barriers (Ontario 2004):

- *Source water protection* to keep water sources as clean as possible
- *Drinking water treatment* to remove contaminants from water sources
- *Drinking water distribution system security* to prevent addition of contaminants in treated water and to ensure appropriate chlorine residuals
- *Monitoring and early warning systems* to detect contaminants in water sources and the water treatment and distribution system
- *Responses to adverse conditions* that can prevent negative health impacts and further degradation when other barriers fail

Source: Conservation Ontario (2006).

Sidebar 2: Watersheds and the Hydrologic Cycle

Watersheds are areas of land that drain surface water runoff into a common water body, such as a lake, river, stream, creek or estuary. As such, they are a key link between land and water. For instance, sediments, nutrients and contaminants move from the land surface to other parts of the watershed via runoff and infiltration to groundwater. In Ontario, watersheds define the boundaries of conservation authorities, and are building blocks for drinking water source protection planning.



Water circulates from the atmosphere to the Earth and back in a process known as the hydrologic cycle. The basic stages of this cycle include evaporation, transpiration, condensation and precipitation.

A basic overview of the workings of the hydrologic cycle in the context of watersheds is provided in another Pollution Probe publication, *The Source Water Protection Primer*.

Source: Pollution Probe (2004)

another potential benefit that we can achieve. Through the things that we will have to do *anyway* in developing, implementing and revising source protection plans, we have an outstanding opportunity to deal with climate change. In that sense, source protection planning under the *Clean Water Act* may prove to be the best opportunity in a generation to *mainstream* climate change into water management and land use planning in Ontario. At the same time, though, failing to address climate change in source protection planning will prove to be a serious, and probably costly, mistake that we will have to remedy in future.

Climate change is a reality that municipalities and conservation authorities increasingly will have to deal with on a daily basis. To illustrate, on August 19, 2005, a torrential storm dumped 103 mm of rain over northern parts of Toronto in the space of one hour. Extensive localized flooding occurred when storm sewers were overwhelmed by the volume of water, and flooding in Black Creek destroyed a portion of Finch Avenue. Specific extreme weather events such as this cannot yet be attributed to climate change. Nonetheless, they provide a taste of things to come: among other anticipated impacts, climate change in Ontario is expected to lead to more intense — and more severe — extreme weather events.

The opportunity to build climate change into day-to-day decisions made at the local level through initiatives such as source protection planning is one that should not be missed. Doing so will increase the likelihood that source protection plans will be relevant now and into the future, and will help to reduce the vulnerability of communities to the impacts of climate change.

> "Since climate change is only one of many issues, decision-making needs to consider climate change in conjunction with other issues affecting the same decision strategies."
>
> Pittock (2003, 7)

Pollution Probe and the Canadian Water Resources Association (Ontario Branch) have prepared this publication to help people involved in source protection planning understand climate change, its implications for Ontario, and ways in which climate change can be built into source protection planning. An underlying theme is that climate change *can be* mainstreamed in source protection planning, and that it *must be* in order for source protection planning to be effective.

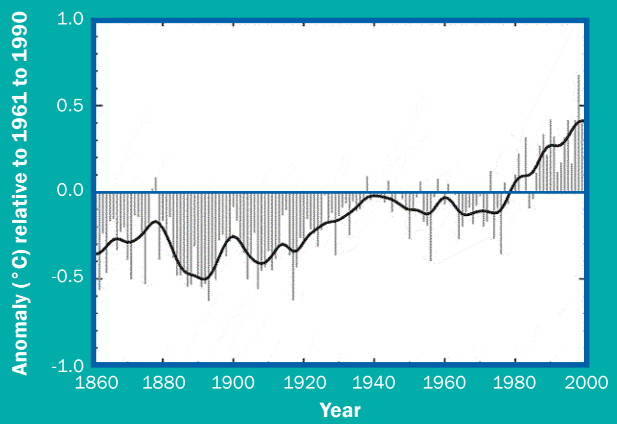
Some of the people involved in source protection planning in Ontario will have strong technical backgrounds, while others will participate as elected officials, representatives of non-government organizations, or simply as individual concerned citizens. This report has been designed to speak to all stakeholders, regardless of their technical backgrounds.

- For non-technical readers, the report provides an overview of current projections of climate change in Ontario, highlights expected impacts on water resources, and draws attention to broad opportunities to mainstream climate change in source protection planning.
- For technical specialists, the report identifies specific opportunities to build climate change into watershed characterizations and water budgets, and, through a detailed technical appendix, offers specific advice for building climate change into hydrological models that are pertinent to source protection planning in Ontario.
- “Sidebars” are used throughout the report to provide additional detail about key topics discussed in the text.

Sidebar 3: How Has the Climate Changed During the Past Century?

Global climate trends during the past century have been documented in the Intergovernmental Panel on Climate Change's (IPCC) *Third Assessment Report*. For example, in addition to an observed increase in global surface temperature of approximately 0.6°C since the late 19th century, Folland, *et al.* (2001) described an increase in precipitation over land areas in much of the northern hemisphere of 0.5 to 1 per cent per decade during the 20th century. These changes are real and observable in the instrumental record.

Departures in Temperature in °C From the 1961–1990 Average



Source: Folland, *et al.* (2001)

Trends at the global scale do not necessarily provide insight into changes at the regional scale. Recognizing this concern, several recent studies have summarized observed changes in Ontario's climate during the past century (e.g., Bruce, *et al.* 2000; Mortsch, *et al.* 2000; Great Lakes Water Quality Board [GLWQB] 2003). To illustrate, in the context of the Great Lakes Basin, the following trends have been noted:

- Mean annual air temperature increases evident across the Basin, with most warming occurring in winter and spring, and less occurring in fall
- Annual precipitation increased, but ratio of snow to rain decreased; since 1970, a trend towards heavier rain events and more frequent intense events evident in the southern Ontario portion of the Basin
- Frost-free period has lengthened
- Snow cover (depth, area covered, and duration) has reduced
- Both wet and dry periods have increased

Chapter 2: Climate Change in Ontario

The Earth's atmosphere is warming. Analysis of evidence from tree rings, ice cores, tropical corals and other sources has led to an international scientific consensus that the average temperature of the atmosphere at the Earth's surface has warmed by approximately 0.6°C since the late 19th century (Folland, *et al.* 2001). The amount of warming has not been uniform around the world. For example, in southern Canada, mean annual temperature has increased by 0.9°C between 1900 and 1994 (Zhang, *et al.* 2000). These changes already have reshaped the climate of Ontario during the last half of the 20th century (see Sidebar 3).

There is a broad consensus in the scientific community that the Earth's climate will continue to change in future. Atmospheric scientists believe that the average global temperature will increase by 1.4°C to 5.8°C during the next century (Cusbach, *et al.* 2001). Shifts in average climatic conditions are expected, for instance, in mean (average) annual precipitation. At the same time, there will be changes in climatic variability, for example, the times of year during which precipitation normally falls, or the intensity of rainfall events.

Changes in climatic *variability* are likely to be much more significant for human beings and ecosystems than changes in annual means. To illustrate, if the amount of annual precipitation remains the same in a year, but it falls in a few torrential downpours rather than during many smaller events throughout the year, then farmers may see increased crop failures, while municipalities may see more flood events like the one resulting from the August 19, 2005 storm in the North York area of Toronto.

Major climatic shifts have occurred since the last ice age, approximately 10,000 years ago. However, most atmospheric scientists now agree that temperature increases in the last half of the 20th century have been much more rapid than previous warming events, and that the projected rate of temperature change will be

> "...in most regions of the country Canadians are now experiencing climates that are recognizably different from those that were familiar to their grandparents."
>
> Canadian Council of Ministers of the Environment (2003, 10)

faster than any that has been experienced during the last 10,000 years. Furthermore, there is broad agreement that the changes occurring now are, for the most part, a direct result of the production of greenhouse gases and aerosols from human activities. These include carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O) and halocarbons (such as chlorofluorocarbons). Consequently, in 2001 the Intergovernmental Panel on Climate Change concluded that there is new and stronger evidence that "most of the warming observed over the last 50 years is attributable to human activities" (IPCC 2001).

As noted in Sidebar 3, warming of the Earth's atmosphere has already led to observable changes in the global climate. *Projected* warming will produce many more changes. For example, in some parts of the world extreme rainfall events may become more common, while in others more severe droughts may occur more often. Anticipated changes are significant because they are outside of the historical or observed range of variability. Therefore, we should not assume that because we have coped with climatic variability in the past, we will automatically be able to cope with a new climatic regime in future.

Efforts are underway around the world to slow global warming, for instance, through *mitigation* initiatives such as the Kyoto Protocol to which Canada is a signatory (see Sidebar 4). Unfortunately, even under the most optimistic scenarios of reductions in greenhouse gas emissions, projections show that the global climate will change dramatically. Accepting the inevitability of these changes, many governments, businesses and non-government organizations around the world have decided that we must take steps now to *adapt* to the kinds of changes that will occur (Sidebar 4).

Sidebar 4: Responding to Climate Change: *Mitigation* and *Adaptation*

When climate change is discussed by politicians or addressed in the media, the focus is primarily on *mitigation*. For instance, the Kyoto Protocol is an international treaty to which 156 countries, including Canada, are signatories.

The aim of the Kyoto Protocol is to slow down the rate of global warming by reducing greenhouse gas emissions and by increasing sinks of greenhouse gases. By signing the treaty, Canada has agreed to reduce its emissions of greenhouse gases by 6 percent compared to 1990 by the period between 2008 and 2012. This is a daunting challenge. By the end of 2005, Canada's rate of emission of greenhouse gases was actually 24 percent higher than the 1990 level.

To help meet Canada's target, governments have instituted a variety of greenhouse gas emission reduction programs. For example, individual Canadians have been encouraged to implement mitigation measures including energy retrofits, choosing fuel-efficient vehicles or using public transit, and using energy more efficiently.

Mitigation through reducing greenhouse gas emissions will slow the rate of global warming somewhat. However, mitigation measures alone cannot prevent further global warming that will occur as a result of the gases that already are present in the atmosphere. As a result, *adaptation* to climate change is essential.

Adaptation involves responding to a changing climate by altering the way we do business, manage resources and live our lives so that we're less likely to be harmed or otherwise affected by the changes. Water managers have always had to adapt to a variable climate, and to too much or too little water. Thus, in the water sector, numerous adaptations to climate change exist that also happen to be best water management practices. To illustrate, water conservation, which is now seen as an essential part of water supply planning, also may be an effective adaptation to future water shortages resulting from climate change.

In this publication, the focus is on *adaptation* to climate change. Drinking water source protection in Ontario offers many opportunities to build adaptation to climate change into day-to-day water management and land use planning activities.

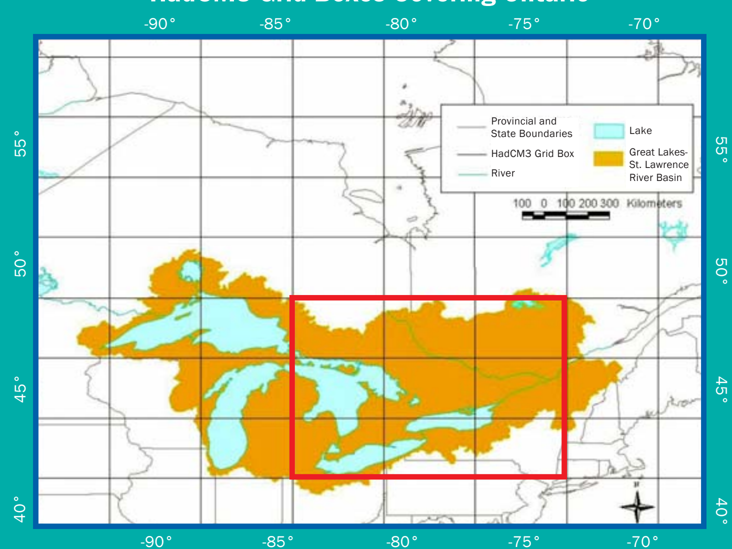
Sidebar 5: Global Climate Models and Emission Scenarios

Climate scientists create projections of the Earth's future climate using mathematical representations of the climate system known as Global Climate Models (GCMs). Currently, approximately 20 different GCMs exist in modelling centres around the world.

Plausible projections of future climate conditions are created when greenhouse gas emissions scenarios are used as inputs in GCM experiments (Mortsch, *et al.* 2005). Emissions scenarios incorporate different internally consistent assumptions about drivers of greenhouse gas emissions, including population change, economic growth, and technological developments. Standard scenarios are contained in the Intergovernmental Panel on Climate Change's *Special Report on Emissions Scenarios* (SRES) (IPCC 2000). Appendix A provides more information about GCMs and the SRES scenarios used in contemporary climate change studies.

GCMs currently operate at a coarse resolution. In the example below, grid boxes from the HadCM3 GCM are shown. Most of southern Ontario falls within the 9 grid boxes highlighted in red. Therefore, to generate useful insights at sub-regional or local scales, it is necessary to create climate change scenarios using techniques discussed in Appendix A.

HadCM3 Grid Boxes Covering Ontario



Source: Mortsch, *et al.* (2005)

In the water sector, the need for adaptation to climate change is especially strong. For people and organizations involved in water management in Ontario, climate change is not a remote problem that can be left to future generations. It is a present-day reality that should be (and can be) addressed in day-to-day activities and in long-term plans.

2.1 How is Ontario's Climate Expected to Change?

This section provides a broad overview of climate change projections, and a brief picture of what Ontario's climate is expected to be like in future. The focus is on climate variables that will be important at the watershed scale. These include temperature, precipitation and evaporation. Other natural climate drivers, such as changes to ocean surface temperature patterns (e.g., El Niño and La Niña) and the amount of solar radiation reaching the Earth's surface, also influence Ontario's climate. However, these are not addressed here.

Projecting Future Climates

Projections of average changes to the *global* climate, such as the kind discussed earlier, do not help us to understand what *Ontario's* climate will be like in future. Fortunately, using Global Climate Models (GCMs), climate scientists are able to offer projections for specific regions, such as the Province of Ontario (see Sidebar 5). These projections are still too coarse to be useful on their own in local planning because they do not capture local or regional conditions and processes. Nevertheless, they do offer insights into what Ontario can expect in terms of its future climate.

Projections of climate change are based on models of the global climate system and scenarios that make assumptions about future rates of greenhouse gas emissions, technology and population. Therefore, it is not surprising that individual projections for the same region can be different. This should not be taken as evidence that the science underlying climate change is flawed, or that projections of future climates are not useful. We accept this kind of uncertainty in many situations where we need some idea of plausible futures. To illustrate, the Ontario Ministry of Finance's population forecasts for Ontario — which are used for long-term planning by municipalities and other agencies — are based on scenarios of future fertility rates and levels of immigration. If these assumptions prove to be incorrect, then the population forecasts will be inaccurate. Nonetheless, the Ministry's population projections are used by municipalities and other agencies for long-term land use and infrastructure planning in Ontario because assuming that future populations will be the same as present populations clearly does not make sense.

Recognizing the level of uncertainty in climate change projections, the Intergovernmental Panel on Climate Change (IPCC 2000) recommends that studies of future climates should not rely on one model or one scenario. Instead, projections from multiple models and scenarios should be used to determine a realistic range of future climates for a particular region. Using this approach, it is possible to identify projections for which there is consistency among models, and, therefore, increased confidence in the projections. At the same time, this approach promotes flexibility because it reinforces the fact that even when confidence exists in projections, it remains important that societies prepare for different realistic futures. For example, where possible, we should avoid irreversible allocations of resources.

Projections of Climate Change For Ontario

The bulk of Ontario's population lives in southern Ontario, close to the Canada-US border. As a result, much more attention has been given to this region in climate change studies than to northern Ontario, which has the majority of Ontario's land area, but low population relative to southern regions of the province. Several recent studies have projected climate changes in the Great Lakes-St. Lawrence Basin (GLSLB). Because this basin includes a considerable portion of southern Ontario, these studies provide valuable insights into expected climate changes in southern Ontario. Recent major assessments were undertaken in 2003 by the Union of Concerned Scientists and the Ecological Society of America (Kling, *et al.* 2003), and by the Great Lakes Water Quality Board (Great Lakes Water Quality Board 2003).

In the GLSLB, all studies project increases in air temperature on an annual basis, with longer and more intense heat waves. For example, the recent comprehensive study by the Union of Concerned Scientists and the Ecological Society of America (Kling, *et al.* 2003) indicates that by 2025–2035, projected spring and summer temperatures in the Great Lakes region are expected to be 1.5 to 2°C above current averages (see Sidebar 6 for changes specific to southern Ontario). For the same period, this study showed ambiguous temperature changes in fall and winter. However, by the end of the century, substantial temperature increases were expected in all seasons. In winter, the most warming is expected at higher latitudes in the basin, while in summer the lower latitudes will experience the most warming. Other studies project temperature changes of similar magnitudes. Confidence in projections for temperature is high in recent studies.

Projections for precipitation vary among studies, with some suggesting slight increases in annual precipitation, and some pointing to decreases. Even within individual studies, projections do not signal a clear long-term trend over the next century beyond increased year-to-year variability (see Sidebar 6). Hence, confidence among atmospheric scientists in the

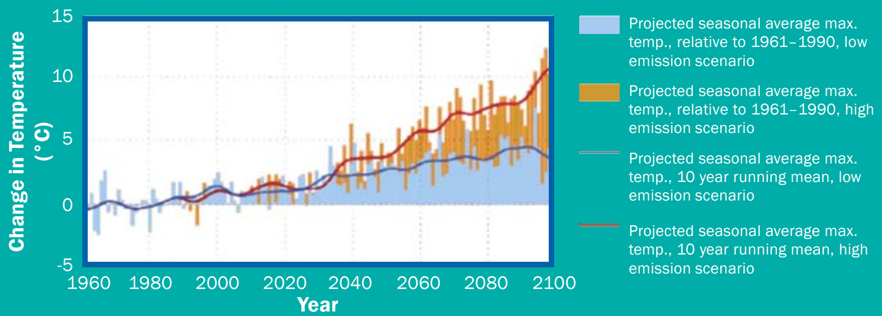
> "All models show warming with increasing greenhouse gases, so we can begin to say with some certainty how some critical components of the hydrological cycle will respond in the future."
>
> Barnett, *et al.* (2005, 303)

Sidebar 6: Projected Summer (June-August) Temperature and Precipitation for Southern Ontario

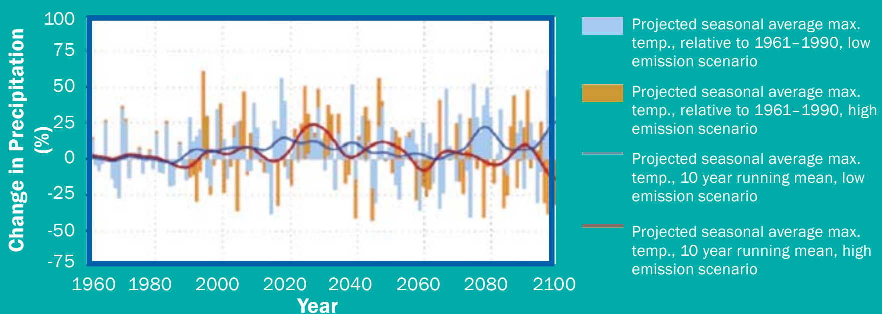
In a 2003 study of the Great Lakes Basin, the Union of Concerned Scientists and the Ecological Society of America (Kling, *et al*. 2003) presented projections to 2100 of the climate of the portion of Ontario south of 46° North. The study used output from two GCMs (HadCM3 and the Parallel Climate Model) based on SRES emissions scenarios representing a wide range of plausible future scenarios of greenhouse emissions, population growth and technological development.

In the accompanying stacked bar charts, projections using a high (A1FI) and low (B1) emissions scenario were used. Bars represent maximum positive and negative changes in temperature and precipitation.

Change in Southern Ontario Daily Average Summer Temperature Relative to 1961–1990 Seasonal Mean



Change in Southern Ontario Daily Average Summer Precipitation Relative to 1961–1990 Seasonal Mean

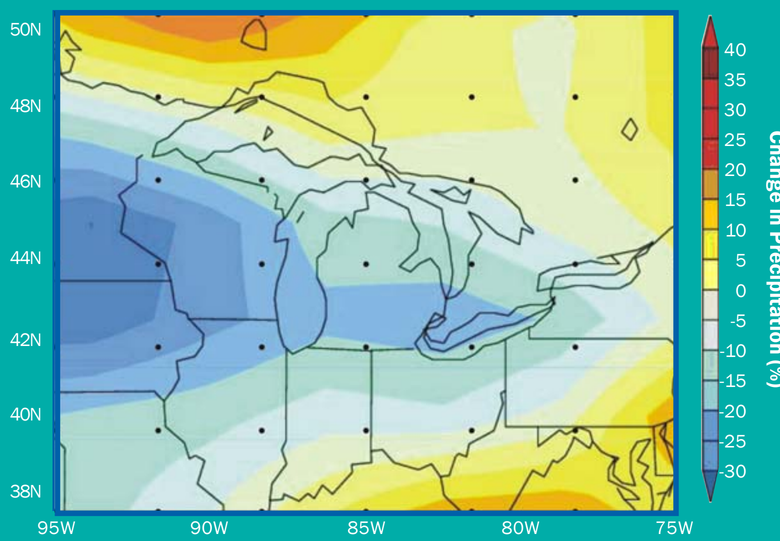


Source: Kling, *et al.* (2003, Technical Appendix)

The study authors used these scenarios to represent realistic upper and lower projections of climate change in the Great Lakes Basin (GLB). For southern Ontario, the projections suggest a gradual, but still significant, increase in daily average summer temperature between 2003 and 2100, while the high scenario shows a gradual increase until approximately 2030, and then a rapid increase, with 2100 having a daily average summer temperature more than 10°C warmer than the 1961–1990 average. For precipitation, the long-term trend is less clear. In both scenarios, annual variability increases relative to the 1961–1990 period, but, unlike temperature, no steady upwards or downwards trend is indicated.

The long-term trends in temperature and precipitation shown in the above charts will not occur uniformly across Ontario. Depending on the emissions scenarios used, climate models show different spatial patterns in changes in temperature, precipitation and evaporation. Consequently, projections of future regional climates often include maps showing spatial variation in climate variables such as temperature, precipitation and evaporation at particular future points in time.

Change in Summer Precipitation Over the GLB in 2090–2099 under the "B2" Scenario (% Relative to 1960–1991 Summer Average)



Source: Modified from Kling, *et al.* (2003, Technical Appendix) direction of projected precipitation changes for the Great Lakes basin is lower than for temperature. In contrast, studies do consistently point to a change in the *seasonal distribution* of precipitation. More precipitation is expected to occur in the winter, and more of the winter precipitation is expected to fall as rain rather than snow. Some studies suggest that winter precipitation could exceed summer precipitation by 50 percent, meaning that drier summers may be likely in the region. Another change related to precipitation that will be particularly important for local level water management is an expected increase in the frequency and severity of extreme events such as droughts and floods. The interval between heavy precipitation events also is expected to decline during the next century (Viatcheslav, *et al.* 2005) — meaning that they will occur more often.

Most recent studies agree that evapotranspiration will increase in the basin. The greatest evaporation losses are likely to occur from large upper Great Lakes, such as Superior and Huron. However, confidence in these projections is lower than for temperature because of some uncertainty regarding the relationship between increased temperature and evaporation in studies of future climates. For example, some studies suggest that increased temperatures will lead to more evaporation, while others indicate that increased cloudiness associated with higher temperatures may lead to decreased evaporation (Bruce, *et al.* 2003). Nonetheless, the balance of evidence to date indicates that evaporation will increase with higher temperatures.

Much less has been written about anticipated climate change in northern Ontario. The 2003 study by the Union of Concerned Scientists and the Ecological Society of America covered the region between 46° and 53° North (see Sidebar 6). Thus, projected climate changes in this part of northern Ontario are addressed by the above discussion. However, very few studies have provided comprehensive projections for areas north of 53°. It is expected that in this part of the province, climate change will have effects similar to those experienced on the northern prairies (Bruce, *et al.* 2000).

Temperatures are projected to rise by between 2°C and 3°C by 2050 as the ice-free period on Hudson Bay increases. As in southern Ontario, evaporation is expected to increase as the temperature rises. Little change in total precipitation is expected, although the general trends discussed for the northern portion of the Great Lakes basin may hold.

Four key lessons emerge from recent studies:

1. Studies of the impacts of climate change on southern Ontario consistently point to a future climate that will be characterized by higher average annual temperatures; changes in the seasonal distribution of precipitation (with more winter precipitation falling as rain, and with less summer precipitation); a greater frequency of high intensity rainfall; more frequent summer dry spells; and increased evaporation.
2. For both northern and southern Ontario, projected climate changes will occur at different rates, depending on rates of emissions of greenhouse gases. And, they will not occur uniformly across the province. This emphasizes the fact that people considering the impacts of climate change on the hydrologic cycle should pay attention to ways in which projected climate changes affect specific watersheds.
3. The fact that projections vary depending on the model and scenario reinforces the need to use multiple projections to capture the range of plausible futures. As noted earlier, this is an approach that should already be familiar to people involved in long-term planning at the local level who use the Ontario Ministry of Finance's population projections to create plausible scenarios of growth.
4. Projections from GCMs are only a starting point for understanding regional or local changes in climate. Methods such as the ones described in Appendix A are needed to move beyond the broad-scale understanding that results from GCM projections.

2.2 How Will Climate Change Affect Ontario's Water Resources?

Human beings have altered the hydrologic cycle since time immemorial. We build dams across rivers to store water for hydro power generation, irrigation, urban water supply and flood control. We drain wetlands and clear forests to create farms and cities. And we divert water from where it flows naturally to where it is needed. As demands for water grow in future, so too will impacts on the hydrologic cycle through these kinds of interventions. Climate change will create additional changes to the hydrologic cycle *over and above* changes created through direct human interventions.

Unfortunately, water managers and climate scientists often do not communicate with each other as much as they should (Kabat and van Schaik 2003). As a result, many water managers are not yet taking climate change into account in their activities. From determining the risk of floods and droughts, to assessing the reliability and availability of water resources for various uses, water managers traditionally have relied on historical climate and hydrology records, which reflect past variability. This is no longer a realistic option. Due to climate change, the past may no longer provide a reliable guide for future water decisions.

The hydrologic cycle is very sensitive to changes in temperature, precipitation and evaporation. Therefore, as the global climate changes, so too will the hydrologic cycle. For example, in regions such as Ontario, where snowmelt is an important factor determining the volume and timing of stream flow, warmer air temperatures likely will lead to earlier spring or winter runoff, and thus reduced flows in rivers and streams during summer and autumn even if the amount of precipitation remains constant (Barnett, *et al.* 2005). Thus, the future will not necessarily be a "statistical replica of the hydrological regime observed in the past" (Kabat and van Schaik 2003). Complicating matters even further, anticipated hydrologic changes may be non-linear, meaning that sudden or abrupt shifts in hydrologic conditions are possible. For water management, the implications are clear: long-term investments in water infrastructure that assume that past hydrological conditions will exist in future are no longer sensible. By the same token, long-term plans for the protection of source waters that do not take into account anticipated future hydrologic conditions also are imprudent.

> "Already faced with formidable challenges of water scarcity and an anticipated increase in water demand of 25–50 per cent in the next 25 years, water managers have shown little enthusiasm for factoring long-term climate predictions into their calculations. *Now, as the evidence mounts, ignoring the problem is no longer an option.*"
>
> Kabat and van Schaik (2003, vi; emphasis added)

In Ontario, climate change is expected to affect water quality, streamflow, lake levels, groundwater infiltration, and patterns of groundwater recharge and discharge to streams (see Sidebar 7). The most comprehensive studies that are pertinent to Ontario have concentrated on the Great Lakes basin. Using techniques discussed in Appendix A, hydrologists have identified expected changes in key hydrologic parameters such as runoff, lake levels, water quality and groundwater recharge for the Great Lakes basin. Given that these studies typically begin with the outputs of GCMs, and in light of the strengths and limitations of the techniques used, it should not be surprising that some uncertainty exists in projected changes to hydrology. Nevertheless, there is growing confidence among hydrologists and climate scientists in the conclusion that the hydrologic cycle in Ontario will intensify, meaning that greater extremes of high and low flows can be expected, and that on an annual basis, less water will be available in lakes, rivers and aquifers.

What is less certain is how the hydrologic cycle in *specific* watersheds and subwatersheds will be affected by climate change. For example, the influence of soil types and land cover in specific watersheds is not captured in the kind of modelling that produced the impacts identified in Sidebar 7. At the same time, modelling does not

Sidebar 7: Expected Hydrological Changes, Great Lakes Basin

The following table summarizes commonly identified hydrological changes expected in the Great Lakes Basin. (For a more detailed evaluation of expected hydrological changes in the Great Lakes Basin, see Appendix A.)

Hydrologic Parameter	Expected Changes in the 21st Century, Great Lakes Basin
Runoff	• Decreased annual runoff, but increased winter runoff • Earlier and lower spring freshet (the flow resulting from melting snow and ice) • Summer and fall low flows are lower and last longer • Increased frequency of high flows due to extreme precipitation events
Lake levels	• Lower net basin supplies and declining levels due to increased evaporation and timing of precipitation • Increased frequency of low water levels
Groundwater recharge	• Decreased groundwater recharge, with shallow aquifers being especially sensitive
Groundwater discharge	• Changes in amount and timing of baseflow to streams, lakes and wetlands
Ice cover	• Ice cover season reduced, or eliminated completely
Snow cover	• Reduced snow cover (depth, area, and duration)
Water temperature	• Increased water temperature in surface water bodies
Soil moisture	• Soil moisture may increase by as much as 80 percent during winter in the basin, but decrease by as much as 30 percent in summer and autumn

These changes are closely interrelated. For example, groundwater recharge is expected to decrease due to a greater frequency of both droughts and extreme precipitation events. In turn, reductions in groundwater levels may reduce streamflow and raise water temperature as baseflow declines. Similarly, reductions in snow cover and warmer air temperatures are expected to contribute to an earlier and lower freshet.

In some cases, signs of these changes already have been observed in hydrological records. For example, studies of the spring freshet across Canada (including Ontario) show that the freshet has occurred progressively earlier as the 20th century drew to a close. Similarly, studies of ice cover on the Great Lakes have shown a decline in the duration of ice cover and a progressively earlier data of ice breakup. In contrast, no trends in Great Lakes levels attributable to climate change have been detected.

Sources: Lavender, *et al.* (1998); Bruce, *et al.* (2000); Mortsch, *et al.* (2000); Kling, *et al.* (2003); GLWQB (2003); Bruce, *et al.* (2006).

currently capture the role of management. To illustrate, in a study of the impacts of climate change on hydrological systems dominated by snow melt, published recently in the journal *Nature*, Barnett, *et al.* (2005) specifically excluded the Grand River watershed from their overall findings about snowmelt because of the importance of reservoirs in regulating streamflow. Water budget modelling, as discussed in Section 3.3, can provide a detailed level of understanding at the watershed scale.

2.3 How Will Ecosystems and Human Societies be Affected?

Anticipated changes to water quality, runoff, lake levels, and groundwater recharge and discharge will affect both human and natural systems. Potential impacts on human and natural systems in the Great Lakes basin resulting from the changes to the hydrologic cycle that were discussed in section 2.2 are identified in Sidebar 8. The list is by no means complete, and should be treated as a starting point for considering the potential impacts of climate change at the local scale. Nevertheless, many of the potential impacts can reasonably be expected to occur. To illustrate, the Great Lakes have experienced historical periods of high and low levels. During times of low levels, marina operators have had to dredge their harbours and channels, and commercial vessels have had to carry lighter cargos due to shallower drafts. During years when summer droughts were experienced in southern Ontario (including 1998, 1999, 2001 and 2002), in some areas shallow wells dried up, fish habitat was compromised due to low stream flow and higher water temperatures, and water quality degraded. As was stressed earlier, it is not appropriate to assume that future hydrological regimes will be statistical replicas of the past. Nonetheless, we can learn from past extreme events that are illustrative of plausible future conditions.

Studies suggest that climate change will have both beneficial and harmful effects in some sectors. For example, warmer air temperatures during winter will mean reduced heating costs, and fewer extremely cold days may lead to reduced cold weather mortality rates. In agriculture, warmer temperatures and an earlier and longer frost-free season are expected to increase yields from warm weather crops such as corn, soybeans and tomatoes, and may permit farmers to cultivate these crops farther north if soil conditions permit (Government of Canada 2005).

Unfortunately, in places such as the southern Ontario portion of the Great Lakes basin, most of the expected impacts on the hydrologic cycle are expected to be negative (Sidebar 8). Furthermore, many of the expected impacts will be synergistic, in the sense that they will make problems with other causes worse. For instance, water shortages already are being experienced in some parts of Ontario now, and these will become more severe in future as demands for water from a growing economy and population increase. Similarly, significant water quality problems already exist in many lakes and rivers. Climate change will exacerbate these problems.

The focus in this document is the link between climate change and source protection. Not all of the expected impacts identified in this section are pertinent to source protection. For example, impacts on commercial navigation due to reduced lake levels likely will not be addressed in source protection plans. However, the majority of the impacts identified are directly or indirectly relevant. For example, impacts on the quantity and quality of water supplies for urban and rural residents are directly relevant. Similarly, impacts of climate change on ecosystems are important considerations in source protection planning. If a watershed is susceptible to reduced stream flows, then the impacts on fish habitat will have to be accounted for in source protection plans and in water allocation decisions. Impacts on agriculture, such as the potential for increased irrigation water demand, may not seem directly relevant — but should be considered in developing source protection plans in watersheds where soils are drought-prone because an increase in irrigation water use may lead to greater competition for water. As is true for the specific effects of climate change on the hydrologic cycle, local-level studies of impacts will be necessary to determine how climate change will affect human and natural systems in specific watersheds.

Sidebar 8: Potential Impacts on Humans and Ecosystems With Implications for Source Protection Planning, Great Lakes Basin

Climate change will have many impacts on human and natural systems. For instance, studies have considered the impacts of climate change on terrestrial and aquatic ecosystems, energy consumption, and the spread and occurrence of diseases.

The focus here is on impacts that may be pertinent to source protection planning. Selected examples from recent major studies are presented below. Economic, social and other impacts on human beings are purposefully blended together with impacts on ecosystems to reinforce the fact that they are not independent of each other.

*Changes in the **frequency of extreme rainfall events** may lead to…*

- Greater frequency of waterborne diseases
- Increased transportation of contaminants from the land surface to water bodies

*Changes to **runoff** may lead to…*

- Increased stress on fish habitat due to reduced streamflows
- Reduced water quality because less water is available for dilution of sewage treatment plant effluents and runoff from agricultural and urban land
- Increased erosion from flashier stream flows
- Increased water treatment costs due to decreased water quality
- Increased competition and conflict over reduced water supplies during drought periods
- Increased frequency of flooding-related damage due to more high intensity storms

*Changes to **groundwater recharge and discharge** may lead to…*

- Changes to wetland form and function as discharge decreases
- Greater costs for groundwater-dependent communities, industries and rural residents associated with deepening wells
- Increased conflict because of additional competition for scarcer supplies
- Increased frequency of shallow wells drying up in rural areas
- Greater frequency of low flows in streams dependent on baseflow, causing increased competition and conflict, and increased stress on aquatic ecosystems

*Changes to **lake levels** may lead to…*

- Changes to coastal wetland form and function because of declining lake levels
- Decreased water quality resulting from lower water volume, increased non-point source pollution, and increased chemical reactions between water, sediments and pollutants
- Increased water treatment costs due to reduced lake water quality
- Increased costs associated with moving water supply intakes
- Greater costs to marina operators due to increased need for dredging of harbours and channels
- Increased costs to commercial navigation due to lighter cargos as a result of shallower water levels
- Reduced hydropower production due to lower flows between connecting channels

*Changes to **ice cover** may lead to…*

- Longer navigation season due to reduced ice thickness and shorter ice cover season
- Increased shore erosion and sedimentation
- Increased water temperatures due to decreased ice cover

*Changes to **water temperature** may lead to…*

- Increased stress on fish habitat due to increases in water temperature
- Reduced water quality resulting from greater biological activity (e.g., algae production) as water temperature increases
- Greater frequency of taste and odour problems in drinking water supplies

*Changes to **soil moisture** may lead to…*

- Increased stress on plants due to decreased summer soil moisture
- Increased demand for irrigation to supplement soil moisture on drought-prone soils

Sources: Lavender, *et al.* (1998); Bruce, *et al.* (2000); GLWQB (2003); Kling, *et al.* (2003); Auld, *et al.* (2004); Bruce, *et al.* (2006).

Sidebar 9: It is Being Done: Recent and Ongoing Studies in Ontario That Build Climate Change into Modelling

An important message in this report is that *it can be done*. Section 3 and Appendix A provide advice and suggestions for incorporating climate change into work relating to source protection planning. However, conservation authorities in Ontario already have undertaken studies, or are in the process of completing studies, that build climate change into watershed planning.

- In 2002, the Grand River Conservation Authority published a study of the impacts of climate change on the Grand River watershed (Bellamy, *et al.* 2002). Impacts of climate change on the hydrologic cycle were modelled at the watershed scale. The study's authors highlighted several key knowledge gaps, but they also drew attention to a variety of concerns with implications for present-day decision making.

- As part of its Credit River Water Quality Strategy, Credit Valley Conservation recently completed an evaluation of the impacts of climate change on hydrology and water quality using two scenarios (warmer and drier; warmer and wetter). Potential impacts on water quality varied between the two scenarios, but the study reinforced the importance of considering climate change in infrastructure and land use planning decision making occurring today (Hazel Breton, personal communication).

- In the context of its Rouge River Study, the Toronto Region Conservation Authority has been building climate change into modelling exercises designed to contribute to water budgets. The aim is to integrate the results of this modelling into watershed planning documents (Don Haley, personal communication).

2.4 Summary

Through its impacts on the hydrologic cycle, *global* climate change is transformed into a *local* problem that conservation authorities, municipalities, the Province and water users in Ontario will have to address. Thinking now about the way in which climate change affects the hydrologic cycle, and how these changes affect human societies and ecosystems, will permit earlier and more effective adaptation.

A key challenge for all stakeholders will be to move beyond general discussions of impacts, such as the one presented here, to specific — local — understanding of the ways in which climate change will affect the hydrologic cycle, and how those changes will impact human and natural systems that depend upon those water resources. As has been suggested throughout Section 2, this will require studies of the effects of climate change on the hydrologic cycle in specific watersheds, and the impacts these changes will have on human and natural systems. Importantly, these kinds of studies not just *possible.* They already are underway in several watersheds in the province (Sidebar 9).

Drinking water source protection planning, under the *Clean Water Act*, is an ideal opportunity to mainstream this work in Ontario. Through the things that they will have to do *anyway* in developing, implementing and revising source protection plans, municipalities, conservation authorities and water users in Ontario have an ideal opportunity to address climate change in their day-to-day activities and long-term plans. In the remainder of this document, the focus is on practical, realistic ways in which this can be achieved.

> "Forecasts of climate change may remain debatable for some time... [but] evidence of increased climate variability is incontestable, and the severity of that variability demands urgent responses from water managers. *The reassuring aspect of this argument is that adaptation options for coping with climate variability now will also help to reduce the impact of climate change in the future*."
>
> Kabat and van Schaik (2003, vii; emphasis added)

Chapter 3: Mainstreaming Climate Change Through Source Water Protection

The new *Clean Water Act* will create an excellent opportunity to mainstream climate change by incorporating it into source protection planning activities. This section provides a brief overview of basic concepts relating to source protection (Section 3.1), summarizes key features of the proposed *Clean Water Act* (Section 3.2), and then highlights opportunities for mainstreaming climate change in source protection planning (Section 3.3).

As of March 31, 2006, the *Clean Water Act* had not yet received second reading, regulations had not been created, and the Ontario Ministry of the Environment's (OMOE) guidance material was still in draft form. Nonetheless, source protection planning was underway across Ontario. The advice offered in section 3.3 reflects the provisional nature of much of the published material on source protection. In other words, section 3.3 was written in such a way that it could offer useful advice to people already immersed in source protection planning, without attempting to anticipate what the final form of the law, regulations, and guidance material would be.

3.1 Source Waters and Source Water Protection

Source waters are the lakes, rivers and aquifers that provide the water that Ontario's 12.3 million residents drink every day. Surface water bodies (e.g., lakes and rivers) provide the drinking water supply for most Ontario residents. However, approximately 25 percent of the population of Ontario relies on groundwater for its drinking water (Singer, *et al.* 2003). Some drinking water supply systems in Ontario are entirely dependent on one kind of source water. For instance, the cities of Barrie and Guelph are served entirely by groundwater; the Grand River is the sole water supply source for the City of Brantford; and Lake Ontario is the only source of drinking water for the City of Toronto. At the same time, many water supply systems draw on a mix of surface and groundwater

Sidebar 10: When Has Climate Change Been "Mainstreamed"?

The term "mainstream" has been used in this document to describe the way in which climate change should be considered in water management. When climate change is an afterthought, at the end of a study, or when a project has been completed, then it has not been mainstreamed. Climate change is mainstreamed in water management, and in water-related land use planning, when it influences decisions from the outset.

In Section 3, ways in which climate change can be mainstreamed into source protection activities are identified. At this point, it is worth illustrating the concept of "mainstreaming" climate change using an important local water management concern: stormwater management.

In 2001, Kije Sipi Limited completed a study of climate change and urban drainage systems. Drainage infrastructure, the authors noted, are designed "based on the premise that the climate is not changing and that historical climate data can be effectively used to predict future drainage design requirements." This is a problem for municipalities because increased rainfall intensities due to climate change are likely to lead to more drainage system failures and increased flood damage.

The August 19, 2005 storm that overwhelmed storm sewers in Toronto is illustrative of the kind that the study authors had in mind when they suggested that "If global warming increases the occurrence of damage causing rainfall intensities, then the cost savings obtained from maintaining current design standards will be outweighed by the costs of future damages."

Historical or observed climate currently is mainstreamed into on-the-ground actions through design standards for drainage systems. Thus, changing those standards in light of projected climate change is a tangible way to mainstream climate change into local water management. Of course, the challenge is to know what changes to make, because new design standards may lead to increased costs. Kije Sipi Limited (2001) recognized this concern, and suggested that new methods of analysis and design for drainage infrastructure were needed to adapt drainage system designs to climate change.

Source: www.pulse24.com

Sidebar 11: Source Water Protection Measures

A vast range of source water protection tools and approaches exists. Some are designed specifically for groundwater, others are meant to protect surface water sources, and still others are generally applicable to all sources. The following chart provides some examples of source protection measures that have been used in Ontario (de Loë, *et al.* 2005). The Xs in the chart indicate whether or not the measure applies to groundwater sources, to surface water sources, or to both.

Example Measure	**Water Source**	
	Ground	**Surface**
Wellhead protection zones around municipal wells	X	
Land acquisition, easements and covenants	X	X
Contingency plans for responding to spills	X	X
Location and proper sealing of old wells	X	
Riparian buffer strips around sensitive watercourses		X
Inspection and monitoring of private wells	X	
Inspection and monitoring of septic systems	X	X
Water conservation education programs	X	X
Environmental farm plans that promote best management practices	X	X

Due to concern for contamination, source water protection commonly emphasizes measures that protect water quality. However, under the *Clean Water Act*, threats to drinking water are activities that adversely affect the quality or quantity of drinking water sources. Therefore, actions that focus on wise use of water, for instance, also are considered source protection measures.

In most cases, multiple stakeholders are involved in implementation of these measures. For example, highly vulnerable areas can be protected effectively through land acquisition or easements. A voluntary program could be developed where individual land owners agree to place easements on their land, and are compensated with funds provided by a provincial or federal program, which is then delivered by a local agency (municipality or conservation authority). Similarly, water conservation educational programs targeted to individual consumers could be developed by non-government organizations and delivered by municipal drinking water utility staff.

Finally, it is important to emphasize that measures such as these should be selected in a coordinated fashion, to ensure that they complement each other and address all significant threats to drinking water sources.

sources. To illustrate, the Regional Municipality of Waterloo takes approximately 80 percent of its water from groundwater sources, but 20 percent comes from the Grand River. The cities of Kingston, Ottawa and Sudbury are primarily dependent on surface water sources but their drinking water supply systems also use some groundwater.

Land and water are closely interrelated. What we do on the land — on our roads, in our cities, and on our farms — affects water quality and quantity. *Source water protection*, therefore, includes a wide range of activities designed to keep drinking water sources free from contamination, and to ensure that they are used sustainably. These range from simple measures that rural landowners can use to prevent contaminants from entering aquifers through their wells, to sophisticated land use controls that municipalities implement to protect sensitive areas such as recharge areas and riparian zones (see Sidebar 11). Importantly, source protection challenges differ significantly depending on the type of source water.

The logic of source protection is simple: water sources that are free from contamination need less treatment before being distributed, and are less likely to contain contaminants that conventional treatment processes cannot easily detect or remove. It is for this reason that source protection is typically described as the first barrier in the multi-barrier approach to drinking water safety (see Sidebar 1). However, source water protection is important not simply because it helps to protect human health.

- Drinking water source protection also makes good financial sense. To illustrate, in a study of seven groundwater dependent communities in the United States, the United States Environmental Protection Agency (USEPA) found that, on average, it cost 30 to 40 times more to develop alternative supplies, to improve water treatment, and to clean up contaminated water sources than it cost to protect those drinking water sources from contamination in the first place (USEPA 1995).
- Protecting drinking water sources also benefits the environment and other users of water. For instance, rivers that are cleaner because steps were taken to make them safer drinking water sources also will be cleaner for swimmers, anglers and boaters. Similarly, in areas where streams depend on groundwater for baseflow, wise use of water by urban residents relying on groundwater also benefits the environment by helping to ensure that streams flow during dry summers.

Specific source water protection activities that will be needed to manage risks to drinking water safety in any particular community will vary based on many factors, including the type of water supply and the nature of land uses in the community. Ideally, individual source water protection activities of various watershed stakeholders will be coordinated. Thus, *source water protection planning* ties together the actions of individuals and organizations in a region into a coherent strategy or plan.

Drinking water source protection plans can be developed at various scales, and for various kinds of planning regions. For instance, in the United States, each state is required under the *Safe Drinking Water Act* to prepare a comprehensive Source Water Assessment Program. Depending on the state, these are based on wellhead protection zones, aquifers, watersheds, or zones around reservoirs (USEPA 2005). Sidebar 12 provides an example from New York State. In Ontario, under the *Clean Water Act*, *watersheds* are the basic unit of planning for source protection.

3.2 Source Protection Planning Under the *Clean Water Act*

Together, the *Clean Water Act* and its regulations will provide the legal framework for source protection planning in Ontario. Barring major changes to the bill that was introduced to the Legislature on December 5, 2005, source protection planning in Ontario will have the following characteristics:

Sidebar 12: Source Water Protection in the United States

Source water protection in the United States involves all levels of government (federal, state and local).

- Through a number of key laws, the federal government has defined a national framework for drinking water safety and source protection. Key legislation includes the *Clean Water Act* (CWA); *Safe Drinking Water Act* (SDWA); *Resource Conservation and Recovery Act*; and the *Comprehensive Environmental Response, Compensation, and Liability Act*. These laws create standards, incentives, regulations and numerous funding and planning programs. Examples of programs include the United States Environmental Protection Agency's (USEPA) Sole Source Aquifer Program; Well Head Protection Program; Source Water Assessment and Protection Program; and the Clean Water State Revolving Fund. The USEPA is the most important federal agency.

- States play key leadership roles because they are specifically responsible for implementing many of the federal programs. Additionally, through their own legislation, they also usually have authority for the use, management and protection of water resources, along with major responsibilities for pollution control.

- Local governments (cities, towns and villages), counties and various regional resource management and planning agencies also can play important roles. For instance, public water supply in the United States is typically a local responsibility. Also, as is the case in Canada, local governments have major responsibilities for land use planning that bear on source water protection.

New York City's source protection program is a renowned example of a coordinated approach to source water protection. The City operates a system that provides drinking water to some nine million people (just under half the state's total population), using surface water from three upstate watersheds. In the 1990s, because of microbial contamination, the USEPA planned to order the City to build filtration plants costing $US 3–6 billion. To avoid this expense, New York City entered into a Memorandum of Agreement in 1997 with the USEPA, the New York Department of Environmental Conservation, and various upstate interests. This agreement committed roughly US$1.5 billion dollars over 10 years to implementing source water protection initiatives in watersheds located in 7 counties north of the city.

New York City has implemented a *Land Acquisition Program*, a *Watershed Regulatory Program*, and a *Watershed Protection and Partnership Program*. Additionally, it is helping upstate municipalities to upgrade their wastewater treatment works. Based on these initiatives, the USEPA issued a five year Filtration Avoidance Determination in 1998, renewal of which depends on the success of these measures in protecting source waters.

Source: CRNYCWMS 2000; USEPA 2005.

- Source protection plans will be developed locally for *source protection areas*, which are defined as the area over which a conservation authority has jurisdiction. In each source protection area, the conservation authority's board will act as the *source protection authority*. The Minister of the Environment has the power to designate source protection areas and authorities for areas not falling within a conservation authority. Two or more source protection areas can be consolidated into a *source protection region* by the Minister of the Environment. One of the source protection authorities in a source protection region will be designated the lead source protection authority.
- Each source protection authority will be required to create a multi-stakeholder *source protection committee* with a maximum of 16 members. Most of the planning activities in each source protection area will be carried out by a source protection committee. The committees will prepare terms of reference for two key planning tools: the *assessment report* and the *source protection plan*.
- While numerous groups and organizations will play key roles in source protection planning, municipalities will be especially important because of their responsibilities for land use planning. Under the Act, planning tasks relating to the assessment report and the source protection plan may be assigned to municipalities. Recognizing that source protection will be an ongoing process, the Act permits municipalities to pass resolutions to include existing or planned drinking water systems in the source protection planning process. In this way, threats associated with this systems can be included in the plans.
- The Province will approve plans, and will retain the authority to develop plans in regions where local stakeholders fail to do so. The Province also could require changes to a plan, but only in relation to specific considerations (for instance, if plans fail to address water risks identified in assessment reports prepared for the source protection region).
- The Act recognizes that source protection planning has far reaching implications. For instance, source protection planning in some parts of the province will affect the Great Lakes. Thus, the Act requires that in any source protection area where water flows into the Great Lakes, consideration has to be given to the Great Lakes Water Quality Agreement, the Great Lakes Charter and the Canada-Ontario Agreement Respecting the Great Lakes Basin Ecosystem. At the same time, in recognition of the importance of land use planning decisions for source water protection, the Act puts in place provisions to ensure that municipal official plans are compatible with approved source protection plans.
- While source protection will be implemented primarily at the local level, the designers of the Act also recognized that the provincial government's own activities can affect drinking water safety. Thus, the Act also requires that provincial instruments, such as certificates of approval for wastewater discharges and water taking permits, must be consistent with source protection plans.

3.3 Climate Change and Source Protection Planning

In Part II of his report on the contamination of the water supply in Walkerton, Justice O'Connor emphasized the importance of climate change for source protection planning in Ontario. He argued that source protection plans should require water budgets designed to permit identification of connections between surface water and groundwater, areas that were vulnerable to water takings, and limits on extractions. Furthermore, he suggested that contingency plans should be developed to deal with extreme climatic events (O'Connor 2002). Beyond these comments, climate change did not receive a lot of additional attention in Justice O'Connor's report because, he argued, concern for climate change was implicit in his recommendations. In other words, he assumed that people involved in source protection planning would recognize the ways in which climate change threatens drinking water, and would address them in source protection plans. This approach to dealing with climate change is appropriate because it recognizes that climate change is not a distinct concern that can be dealt with separately from other water management concerns, or left to future generations to deal with. Rather, as was argued in Section 2, climate change is a basic

Sidebar 13: Assessment Reports

Under section 13(2) of Bill 43, the *Clean Water Act*, assessment reports must do the following:

- identify all watersheds in the source protection area;
- characterize the quantity and quality of water in each of the watersheds identified;
- create a water budget for each watershed;
- identify all vulnerable areas in each watershed;
- describe drinking water issues relating to water quality and water quantity in each vulnerable area;
- identify existing and future threats to drinking water in vulnerable areas;
- after performing a risk assessment, identify *significant* threats to drinking water quality and quantity in vulnerable areas; and,
- contain other information required by the regulations.

Vulnerability is a central concern in assessment reports. Vulnerable areas under the *Clean Water Act* include the following:

- wellhead protection areas around municipal drinking water supply wells;
- surface water intake protection zones around municipal drinking water supply intakes in lakes and rivers;
- groundwater recharge areas where water seeps into aquifers through porous and permeable soil or rock below the ground's surface; and,
- aquifers that are highly vulnerable to contamination from the surface.

Technical guidance modules have been prepared (in draft form as of March 31, 2006) that provide assistance for teams preparing assessment reports. These modules include instructions for characterizing threats, issues and concerns, and for assessing vulnerability.

consideration that should be mainstreamed now in the day-to-day water management activities of all stakeholders.

In stating at the outset that "The purpose of this Act is to protect *existing and future* sources of drinking water", the *Clean Water Act* appears to strongly reflect Justice O'Connor's perspective on climate change. While the Act does not specifically mention climate change as a threat to drinking water, it is difficult to imagine how source protection planning could ignore climate change and still be successful. For example, expected reductions in streamflows, lake levels and groundwater recharge unquestionably are a future threat to drinking water supplies. Similarly, future development, combined with climate change, will reshape all four kinds of vulnerable areas that must be considered in source protection planning (see Sidebar 13).

Fortunately, there are numerous points in the source protection planning process defined by the proposed *Clean Water Act* where climate change can receive appropriate consideration. The aim of this section is to discuss two important opportunities that exist in the early stage of source protection planning. Other opportunities exist in later stages of the process, for example, during plan development, and during the actual implementation of measures for source protection. These are not addressed here, but they should emerge from initial work.

Source protection planning begins with the assessment report (Sidebar 13), which establishes the foundation for all that follows. Within the assessment report, two components are particularly important in the context of climate change: watershed characterizations and water budgets. Therefore, opportunities to incorporate climate change into these parts of the assessment report are emphasized in this section.

Mainstreaming Climate Change in Watershed Characterizations

In their assessment reports, Source Protection Committees are required to prepare *watershed characterizations* (see Sidebar 14). Watershed characterizations are meant to be comprehensive overviews of hydrological conditions, land uses and economic activities, and other considerations that are important for source protection planning.

Watershed characterizations are critical parts of the assessment report because they define topics that will receive further consideration in assessment reports, and thus in source protection plans. For example, teams preparing assessment reports must undertake detailed analyses of surface and groundwater vulnerability. Watershed characterizations will be the departure point for these analyses, because they will identify vulnerable areas. Similarly, detailed water budgets (ideally in the form of quantitative models) will be prepared for the assessment report; however, the watershed characterization will be used to define the features of the hydrologic cycle that are considered important for source protection planning in each watershed. Detailed information regarding the contents of the watershed characterization portion of the assessment report can be found in guidance modules prepared by the Ontario Ministry of the Environment (see Sidebar 14 for a summary).

It is expected that watershed characterizations will be based on existing information. For example, in the OMOE's draft guidance materials, Source Protection Committees have been instructed to draw on work completed through Municipal Groundwater Studies, and to make use of data from sources such as the provincial government's Permit to Take Water database. As a result, watershed characterizations will focus primarily on past and current conditions. Nonetheless, Source Protection Committees can — and should — address future trends in their watershed characterizations. For instance, the OMOE's draft guidance material indicates that teams preparing watershed characterizations should describe trends in water quality, water use, and future land uses and activities. Doing so satisfactorily will create numerous opportunities to consider climate change. This is illustrated in the following examples.

Ontario has experienced relatively rapid urban growth during past decades. Population forecasts prepared by the Ministry of Finance suggest that by 2031, Ontario's population will have increased to

Sidebar 14: Watershed Characterizations

The Ontario Ministry of the Environment has prepared several Guidance Modules to assist people involved in the preparation of assessment reports. These provide detailed instructions that amplify the *Clean Water Act*'s requirements. According to drafts of the guidance modules that were available in early 2006, *watershed characterizations* should include the following:

- a description of the watershed, including the boundaries of the source protection region, geology and major landforms in the watershed, hydrology, vegetative areas, aquatic ecology, human settlement and economic activity, and water uses;
- an overview of water quality, including indicators used, surface and groundwater quality, raw water quality, and microbial characteristics of source waters;
- water uses in the watershed;
- a description of vulnerable areas;
- an inventory of threats to groundwater quality and surface water quality; and,
- a summary of issues and concerns.

In some cases, assessment reports will contain text descriptions for these considerations. However, in most cases teams preparing assessment reports are expected to produce maps that show spatial patterns and trends.

Climate change is briefly addressed in draft guidance modules relating to watershed characterization. For instance, teams preparing watershed characterizations are instructed to collect continuous climate records for precipitation, evaporation and temperature, and to describe the way in which these affect hydrology. In recognition of the possible impacts of climate change, teams also are expected to consult "appropriate" climate change models (although these are not identified). Nonetheless, the focus in watershed characterizations is very much expected to be on current conditions, with some attention to future trends.

Sources: *Clean Water Act* (Bill 43); OMOE (2005a) between 16.4 and 17.95 million people (depending on levels of immigration and fertility rates) from the current population of 12.55 million people. Municipalities already are expected to incorporate these kinds of projections in their plans for future growth (see Sidebar 15), and, when they are responsible for providing drinking water supplies to their residents, in long-term water supply plans. At the provincial level, the *Places to Grow Act* also incorporates assumptions about future growth, and directs growth to certain parts of the province. For example, the Greater Golden Horseshoe has been identified as the first place in the province for which a growth plan will be prepared under this act.

Drawing on provincial policies and local plans that address future population growth and urban development, Source Protection Committees should be able to identify areas where urban growth will occur within their source protection regions. In the same way, they should be able to identify areas where industrial or commercial development is expected, or where intensification of agricultural production is likely to occur. Recent studies of agricultural water use in Ontario point towards intensification of agricultural water use around urban areas because of increased demand for the sod and horticultural crops (see Sidebar 15). At the same time, intensification of livestock production has occurred in certain parts of Ontario during the past decade; the trend towards intensification of agricultural production is expected to continue into the future (MMM, *et al.* 2002). In all of these sectors, growth or intensification not only leads to increased water use, but also may affect the vulnerability of drinking water sources. By combining knowledge of future growth in human uses of water with knowledge about water resources, vulnerable areas, and the anticipated impacts of climate change on water resources, Source Protection Committees should be able to address climate change effectively in watershed characterizations.

Vulnerability is not a static consideration. Therefore, areas currently considered vulnerable may become more vulnerable in future due to changes in land use, population growth, and climate. By the same token, areas not considered vulnerable now may become vulnerable in future for the same reasons. Source Protection Committees already are expected to consider the ways in which future changes to land use may affect the vulnerability of wellhead protection areas, surface water intake protection zones, and other vulnerable areas. They also should consider ways in which alterations to the hydrologic cycle resulting from climate change may influence vulnerability. For example, anticipated changes in recharge due to climate change could elevate a currently low or moderate risk to groundwater quality to a significant risk.

Maps of potential future drinking water sources must be included in watershed characterizations. The aim is to ensure that future drinking water sources are not compromised by current land uses and activities, or by future development. Climate change also may affect the vulnerability of future drinking water sources, and should be considered. For example, some future surface water sources may become less reliable because of greater seasonal and annual variability in flow due to climate change. Historical analogues, such as flow conditions during previous low flow periods, do not necessarily represent future conditions. However, they can offer insight to Source Protection Committees into the kinds of problems that may be experienced due to climate change.

In communities with water supply systems, planners already are expected to consider the ability of those systems to meet future demands due to population growth. In drawing on existing long-term water supply plans, teams preparing watershed characterizations should be aware that climate change may affect the timetable. To illustrate, municipalities that assume that water resource availability in future will reflect past hydrologic conditions may discover that a new water supply planned for several decades in the future may be required much sooner — even if appropriate water conservation and other adaptive measures are used. As noted in Section 2, climate change is expected to produce not only reduced water supplies in some parts of Ontario, but also greater demand for water as temperatures and the frequency of drought-like conditions increases.

Sidebar 15: Drivers

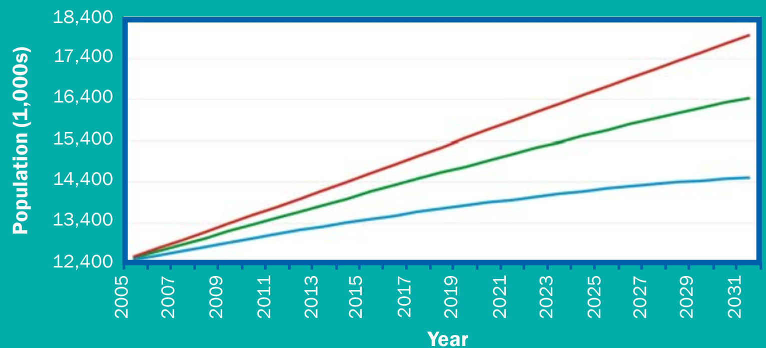
While it is not possible to know the future, it certainly is possible to identify major drivers of growth and change in population, industrial and economic development, and agricultural production — all of which are pertinent to source water protection. Two examples are discussed here: population growth and intensification of agricultural production.

Population Growth

Municipalities and other organizations are required to prepare long-term plans that incorporate assumptions about future population growth in Ontario. For example, the planning horizon for municipal drinking water systems is usually 50 years.

The Ontario Ministry of Finance publishes population projections for Ontario using different scenarios of population growth. The Ministry's projections suggest that by 2030 Ontario's population will be between 14.47 million people and 17.75 million people. These projections (which are available for each of Ontario's Census Divisions) can be used to create different scenarios for infrastructure and service planning.

Scenarios of Population Growth in Ontario



Reference Scenario: Total fertility rate increases slightly to 1.53 by 2011. Immigration is assumed to be 125,000 annually.

Low Scenario: Total fertility rate declines gradually to 1.3 by 2031. Immigration is assumed to be 90,000 annually.

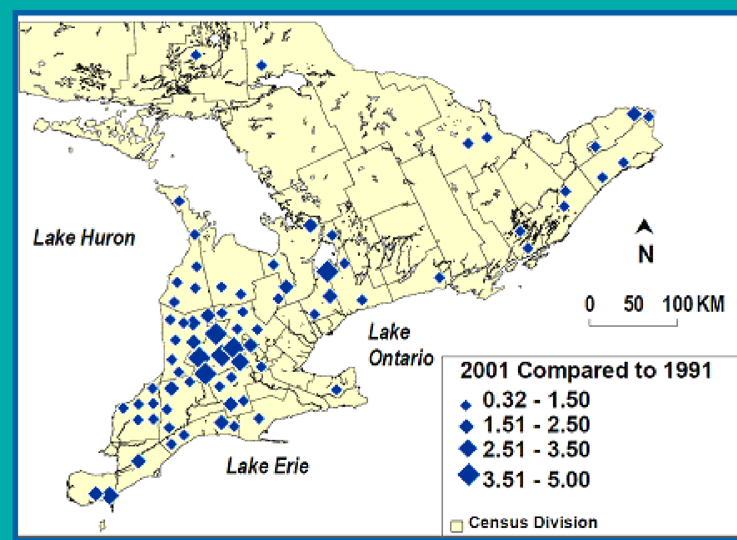
High Scenario: Total fertility rate increases gradually to 1.75 by 2031. Immigration is assumed to be 150,000 annually.

Source: Ontario Ministry of Finance (2005).

Agricultural Water Use

Agricultural water use in Ontario makes up an important portion of total water use in the Province, particularly from the perspective of consumption (the amount of water that is not returned to the source from which it is taken). Between 1991 and 2001, estimated *total* agricultural water use in Ontario has remained roughly the same. However, a noticeable trend towards intensification of water use is occurring. For example, in the map shown below, the blue diamonds represent areas where water use has increased between 1991 and 2001.

Intensification of Agricultural Water Use



Source: Map redrawn from data presented in de Loë (2005).

Clusters of diamonds highlight areas where agricultural water use is intensifying. For example, the cluster of large diamonds in Perth and Huron counties represents intensification of the livestock industry, and corresponding growth in livestock water use. The large diamonds south of Lake Simcoe represent growth in water use in the sod and horticulture industries. Intensification of agricultural water use is a potential source of stress that should be addressed in source protection plans, especially in regions where reductions in water supplies due to climate change are anticipated.

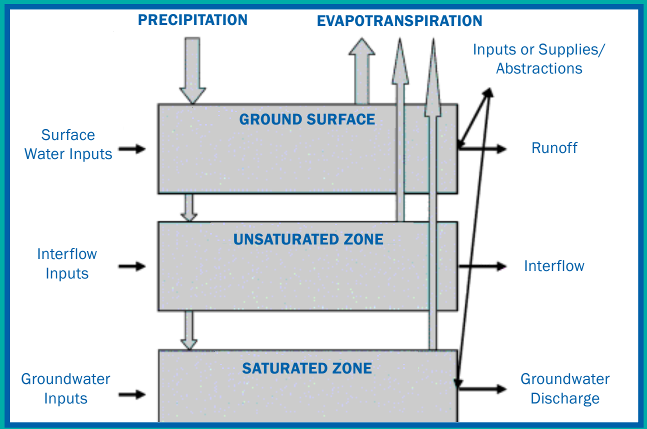
Sidebar 16: Water Budgets

Water budgets are models of water inputs, outputs and changes in storage for a particular area, such as a watershed. Spatial flows of water, and temporal patterns (seasonal and annual changes), should be captured.

- Water *inputs* include precipitation, groundwater or surface water inflows, and sources of water from human activities, for example, wastewater effluents.
- Water *outputs* include evapotranspiration, surface water or groundwater outflows, and abstractions (water removed from surface water or groundwater sources by humans).
- Water is stored in surface water bodies, the soil (as soil moisture) and in aquifers. Thus, changes in storage in these "reservoirs" also must be captured.

In a water budget, inputs must equal outputs plus changes in storage. These concepts can be represented as follows:

Conceptual Diagram of a Water Budget



Source: Ontario Ministry of the Environment (2005b)

At a conceptual level, water budgets are straightforward. Unfortunately, implementing them is technically challenging. Not only are data requirements high, but also numerical modelling associated with the development of quantitative water budgets requires a high level of technical expertise. Technical issues relating to water budgets are discussed in resource materials listed in Appendix A.

Studies of the impacts of climate change on water resources have shown that water quality also will be affected by climate change. For example, as discussed in Section 2.3, water quality is likely to be negatively affected by increased water temperature, reduced streamflows and lake levels, and increased contamination from land surfaces due to extreme rainfall events. The potential implications of these kinds of changes for drinking water sources should be highlighted in watershed characterizations.

Finally, in their watershed characterizations, teams are expected to identify *data gaps*. Numerous data gaps are likely to exist at the local scale in relation to climate change and its impacts on water use and water resources. For example, Source Protection Committees are expected to address water use patterns in their assessment reports. Currently, Ontario's water use database is generally poor. It is likely to improve dramatically as monitoring data are collected under Ontario Regulation 387/04, the *Water Taking and Transfer* regulation. Nonetheless, Source Protection Committees are expected to complete watershed characterizations using whatever data and resources are available. The anticipated impacts of climate change add urgency to the need to improve the water use database, and suggest that teams preparing watershed characterizations should identify strengthening understanding of future trends in water use as a priority rather than as a side issue.

Importantly, the fact that it may not be possible to address climate change satisfactorily in initial watershed characterizations does not mean that the opportunity has been missed. Source protection planning should be an ongoing, long-term undertaking. Plans will have to be updated continually because *everything else* is changing. Therefore, climate change can be mainstreamed in subsequent plans as data gaps are closed, skills are developed and experience is gained.

Mainstreaming Climate Change in Water Budgets

Water is a challenging resource to manage because it is continually in motion through the hydrologic cycle (Sidebar 2). Furthermore, interconnections between surface water and groundwater, and relationships between land cover and the amount of runoff and infiltration, mean that human activities can have profound — and often far-reaching — impacts on the hydrologic cycle. Climate change is expected to alter the hydrologic cycle in Ontario in ways that will not necessarily be beneficial for humans or ecosystems (see Section 2). Watershed characterizations are expected to include a conceptual overview of the hydrologic cycle in each source protection region. This conceptual overview is meant to provide guidance for the preparation of much more detailed — ideally quantitative — water budgets in the assessment report.

In simple terms, water budgets balance inputs and outputs of water in a watershed, and account for any changes in storage (see Sidebar 16). Ideally, water budgets should be quantitative (numerical) models that capture land use changes, shifts in demand, and alterations to inputs (e.g., precipitation) and outputs (e.g., evapotranspiration).

The *Clean Water Act* requires that water budgets be prepared for each watershed within a source protection area in Ontario. The Act specifies that water budgets must accomplish the following:

- identify the different ways in which water enters and leaves the water-shed, and quantify amounts of water that enter and leave in each way;
- describe groundwater and surface water flows in the watershed;
- quantify existing and anticipated amounts of water taken from the watershed, including takings that require and do not require a Permit to Take Water under the *Ontario Water Resources Act*; and
- describe existing or anticipated water shortages in the watershed.

Sound technical guidance in support of the Act's legal requirement is necessary because experience with the development of water budgets in Ontario has been limited. As of 2004, the Grand River and Credit Valley conservation authorities had developed and tested quantitative, watershed-scale water budgets. To provide needed guidance, the Province's Source Water Implementation Group has developed technical resources that build on the experiences of these conservation authorities, and on earlier resource documents prepared for the Watershed Management Committee, in 2000, and the Oak Ridges Moraine Conservation Plan, in 2005 (Cumming Cockburn Limited 2000; Ontario Ministry of the Environment 2005b).

In light of the limited experience that exists in Ontario with water budgets, and given the significant technical challenges confronting local organizations that have been assigned the task of developing these tools, the Province's technical guidance document for water budgets suggests that they should be developed in three phases:

- In Phase I, conceptual water budgets will be developed. These provide a descriptive overview of the factors that define the water budget in each source protection area. Conceptual water budgets should reveal where water is located, how it moves between the surface and the subsurface, sources and locations of stresses on water, and expected trends in development and water use.
- In Phase II, conceptual water budgets will be translated into quantitative, watershed-scale models. This involves use of numerical models of surface water and groundwater flow, and the integration of these models with each other, where appropriate.
- In Phase III, site-specific numerical models may be developed to better capture local hydrogeological conditions. These tools will be sufficiently detailed and refined to be useful for site planning decisions.

At a minimum, assessment reports must include conceptual water budgets (Phase I). Whether or not source protection committees include Phase II and III water budgets in the terms of reference for their assessment reports will depend on local needs, circumstances, capabilities and resources.

Sidebar 17: Considering Climate Change in Water Budget Development

In draft guidance material prepared by the Province of Ontario's Source Water Implementation Group, four generic steps are proposed for water budget development (Ontario Ministry of the Environment 2005c). Climate change should be considered at each one of these steps. In the following table, selected examples are provided to illustrate how this could be accomplished. Appendix A provides additional information.

Generic Step	Example Ways of Considering Climate Change at Each Step
Define objectives and spatial boundaries	• Ensure that objectives of the water budget study specifically include investigating potential impacts of climate change on the hydrologic cycle, and on human and natural systems
Collect and synthesize data	• Acquire watershed-specific data on climatological variables important to climate change (e.g., at a minimum, seasonal data on temperature, precipitation, evaporation) • Gather data that permit consideration of long-term climatic trends and calibration of models against observed data; ensure that periods of low and high water availability are captured • Collect data necessary to predict changes in hydrologic variables likely to be affected by climate change (e.g., impacts of snowmelt volumes on streamflow) • Strengthen water use database, and account for activities that may increase dramatically due to climate change (e.g., increases in irrigation where previously farmers relied on precipitation)
Develop a conceptual model (Phase I water budget)	• Recognize climate change as a "stress" in conceptual models • Draw attention to expected climate change impacts on *inputs*, *outputs* and *storage*
Develop numerical models (Phase II and III water budget)	• Ensure that suitability for predicting climate change impacts on key hydrologic variables is a model selection criterion • Multiple models may be necessary to incorporate all likely effects of climate change

Water budgets prepared for the assessment reports can serve many purposes. The Province's interim technical guidance document identifies the following major ways in which water budgets can support source protection planning:

1. Setting quantitative hydrological targets for considerations such as water allocation and expected recharge rates in the context of watershed and subwatershed plans.
2. Evaluating, relative to established targets, the implications of existing and proposed land and water uses within watersheds and subwatersheds.
3. Evaluating the cumulative effects of land and water uses.
4. Providing a framework within which site-specific studies can be undertaken, for example, plans for sewage treatment or water supply systems.
5. Guiding decision making regarding environmental monitoring programs.
6. Providing assistance for setting water conservation targets.
7. Helping to establish long-term water supply plans.

This list reinforces the fact that assessment reports prepared for source protection planning are not meant simply to be descriptions of existing conditions. Instead, they should help people involved in source protection planning to anticipate future climatic and hydrologic conditions, future vulnerabilities and the sources of those vulnerabilities.

Whether or not a water budget will be useful for the purposes listed above will depend on many factors, including the quantity and quality of available data, the appropriateness of the models used, and the extent to which the water budget is updated as new information becomes available and conditions change. Of course, given the future-oriented perspective underlying assessment reports and source protection planning, the true value of a water budget also will be determined by the extent to which it addresses climate change. Opportunities for considering climate change exist at all four generic steps associated with water budget development that have been proposed in the Province's technical guidance document (see Sidebar 17).

> "Hydrologic modeling can provide watershed planning groups the opportunity to analyze the potential impact of planning decisions and other changes, including climate variability and climate change, on water resources before those changes occur. A model's ability to provide these projections will depend on the construction of the model and availability of quality data."
>
> Whitely Binder (2002).

Appendix A offers detailed technical advice for addressing climate change in water budgets, including insights into data needs and appropriate models (see Sidebar 18 for an overview). Importantly, Appendix A assumes that water budgets are of the Phase II type, in other words, they are *numerical* rather than conceptual models. As illustrated above, climate change can be considered in conceptual (Phase I) water budgets. However, in order to *predict* the impacts of climate change on hydrological characteristics such as mean streamflow, mean groundwater recharge, streamflow variability, and return periods of droughts and floods, numerical models must be used to create water budgets.

Sidebar 18: Determining Climate Change Impacts on Hydrology

Conservation authorities, municipalities, consultants and researchers in Ontario already use models such as GAWSER and HSPF to model surface water hydrology and MODFLOW and FEFLOW to model groundwater systems. For example, both the Grand River Conservation Authority and Credit Valley Conservation have used integrated surface-groundwater modelling to create water budgets and to simulate future conditions at the watershed and subwatershed scales. These kinds of models also can be used to evaluate the impacts of climate change on the hydrologic cycle in Ontario. However, before hydrologists can build climate change into their models they have to translate projections made at the coarse scale of GCMs to local scales.

GCMs typically have grid cells that cover tens of thousands of square kilometres. Therefore, they do not provide useful insights into the ways in which changes in temperature, precipitation, and evaporation will affect the hydrologic cycle at the local scale. Even the increased resolution of new GCMs currently being developed in modelling centres around the world will not solve this problem.

Climate scientists and hydrologists have developed a number of approaches to projecting the impacts of climate change on local hydrology. These approaches, along with their strengths and weaknesses, are discussed in Appendix A. Briefly, GCM data can be translated to the local or regional scale using the following kinds of approaches:

- Many previous studies have applied GCM-derived change fields to observed baseline data (for instance, 1961–1990 climate data). Monthly change fields, for example, are derived from the GCMs by comparing the model baseline climate to projected future climate from a GCM.
- Numerous statistical and empirical methods have been developed for "downscaling" GCM climate data to local and regional scales. These typically involve three techniques: weather generators, transfer functions and weather typing schemes.
- Regional Climate Models (RCMs) are being developed to project climate using models similar to GCMs. Typically, RCMs are climate models nested within GCMs, with resolutions in the neighbourhood of 45 km. Using initial conditions derived from a GCM, RCMs can account for hydrologic variability within smaller areas.

As demonstrated by the examples in Sidebar 9, the skills and data needed to use these tools are comparable to the ones needed to use hydrologic models such as the ones listed above. Therefore, organizations that are using these models may find it feasible to study the impacts of climate change on their watersheds.

3.4 Summary

Source protection planning under the *Clean Water Act* has created an outstanding opportunity to mainstream climate change. The focus in source protection planning is necessarily on threats to drinking water safety. However, under the *Clean Water Act* these threats are characterized broadly to include both those that pertain to water quality and water quantity. The Act also requires unprecedented attention to concerns such as the relationship between land and water, and between water uses and water supplies. Climate change must be a central consideration when these relationships are explored through watershed characterizations and water budgets.

In some source protection areas, it may be possible to explore these relationships through quantitative modelling — using the kinds of tools and approaches discussed in Appendix A. In others, stakeholders may only be able to highlight potential concerns relating to future climate change using historical analogues (e.g., records and evidence of impacts from previous low flows), with quantitative modelling deferred until data become available. In either circumstance, attention to climate change not only is possible — it is necessary. In either case, it is essential to recognize that source protection planning is an ongoing, long-term undertaking. Therefore, in source protection areas where climate change has not received adequate attention in initial activities under the *Clean Water Act*, countless opportunities exist to strengthen this deficiency in future work.

Chapter 4: Conclusion

Climate change is real, and is already happening. In the Great Lakes Basin, a region where numerous studies have been completed in the past decade, noticeable trends have been observed in the following:

- Mean annual air temperature has increased across the basin
- Annual precipitation has increased, but more is falling as rain and less as snow, and there is a greater frequency of extreme events
- Snow depth has been reduced
- Both wet and dry periods have increased.

Projected warming is expected to produce many more changes like these, with significant implications for the hydrologic cycle.

Because of the way it affects the hydrologic cycle, *global* climate change is a *local* problem with which conservation authorities, municipalities, the Province and water users will have to deal. Consequently, water management, land use planning, and infrastructure decisions being made today should account for the ways in which climate change will affect water resources. The challenge is to build climate change into day-to-day activities, in other words, to *mainstream* it in water management and land use planning.

Source protection planning in Ontario, under the forthcoming *Clean Water Act*, provides an outstanding opportunity to mainstream climate change. Under the proposed *Clean Water Act*, local stakeholders will develop source protection plans at the watershed-scale. Plans will build on detailed assessment reports. Among the many topics covered in these reports, *watershed characterization* and *water budgets* are especially pertinent for climate change.

In watershed characterizations, teams involved in source protection planning will develop watershed-wide overviews of land uses and activities, water resources, and threats to drinking water safety. In water budgets, relationships between inputs of water, withdrawals of water, and storage in watershed will be represented — at first, conceptually, but then quantitatively.

While preparing watershed characterizations, Source Protection Committees should consider how climate change will influence vulnerable areas; the need for, and vulnerability of, future drinking water sources; and the quality of water sources that supply drinking water. Because watershed characterizations are the foundation of the assessment report, and because assessment reports will guide source protection plans and resulting activities, building climate change into watershed characterizations is critical.

In creating detailed, quantitative water budgets, Source Protection Committees should be able to provide the detailed local understanding of the impacts of climate change on hydrology that has been difficult to incorporate in regional studies of climate impacts completed to date. Technical challenges exist relating to incorporating climate change in water budgets. However, Appendix A demonstrates that these are resolvable. Indeed, several conservation authorities in Ontario already have been building climate change into their hydrologic and water quality models.

Many other opportunities exist for addressing climate change in the source protection planning process. Nonetheless, being able to address climate change in watershed characterizations and water budgets would represent significant progress towards mainstreaming climate change into water management.

At the outset of source protection planning, it may not be possible to address climate change satisfactorily in initial watershed characterizations and water budgets in all source protection areas. However, this does not mean that the opportunity has been missed. Source protection planning must be an ongoing, long-term undertaking. Plans will have to be updated continually anyway because *everything else* is changing. Therefore, climate change can be mainstreamed in subsequent plans as data gaps are closed, skills are developed and experience is gained.

Appendix A: Integrating Climate Change into Hydrologic Models[1]

Numerous modelling centres around the globe have developed Global Climate Models (GCMs) to estimate the trajectory of future climate change. Projections from the numerous GCMs share a common result: rising concentrations of greenhouse gases will result in significant changes to climate at global and regional scales. Therefore, to be robust, drinking water source protection plans should consider the potential impacts of anticipated climate change. This appendix outlines how GCM data are transferred between the coarse resolutions in GCMs to the local and regional scales of interest to watershed planners and hydrologic modellers.

- Section A.1 outlines the current state of climate change models at the global scales.
- Section A.2 explains how the results from these global models have been, or could be, translated to the local and watershed scales.
- Section A.3 addresses ways in which models and scenarios apply to Ontario, focusing on the Great Lakes basin.
- Recommendations for incorporating climate change into hydrologic models during source protection planning are provided in Section A.4.

Selected web resources for those seeking additional information are presented in Appendix B.

[1] Appendix A was prepared by Dr. Aaron Berg, Department of Geography, University of Guelph.

A.1 Overview of the Current State of Climate Change Models

Uncertainty is an inherent component of future climate prediction. In particular, considerable uncertainty exists regarding the prediction of future emissions of greenhouse gases, aerosols and their combined effects. Confidence in GCM output decreases as the spatial scale shifts from global to regional, and as the temporal scale changes from seasonal to daily. Therefore, in impact studies researchers have found it necessary to use a range of possible future scenarios of climate change. Specifically, researchers should choose between different models (summarized below) and among different scenarios of future population growth and greenhouse gas emissions. Under this approach, the reporting of results, and thus the plans that are adopted, should be based on more than one anticipated outcome of climate change. This allows planners to acknowledge the potential uncertainties of climate change and to explore the range of plausible scenarios of future climate change (Mortsch, *et al.* 2005).

Unfortunately, given the large number of modelling centres, scenarios and simulations, considerable (and sometimes conflicting) information is available. Therefore, in this section a general overview is presented that outlines how uncertainty in projections of future climate change can be addressed through the analysis of multiple scenario and modelling results. Three main topics are addressed:

- Modelling centres and the uncertainties inherent in modelling climate change.
- Scenarios used to predict what the world will be like over the next century in terms of population, technological development and emissions of greenhouse gases.
- Suggestions for how uncertainty can be addressed when climate change information from GCMs is incorporated into the decision making process.

GCMs: Modelling Frameworks and Uncertainty

Given an estimated trajectory of future greenhouse gas emissions, the numerous modelling centres around the world have produced several scenarios of future climate change. Among modelling centres, each of the GCMs differs in terms of the parameterization of the dynamical equations that control atmospheric circulation and feedbacks of the coupled Earth system. For adequate simulation of climate, the important components of the coupled climate system must be represented in sub-models (ocean, land, atmosphere, cryosphere, and biosphere) along with the important feedbacks and processes that interlink them. Currently, the spatial resolution of the atmospheric sub-models of GCMs is approximately 250 km in the horizontal and 1 km in the vertical; the ocean models typically require finer resolution. Equations are solved for transport of heat and moisture typically at every half hour of a model integration. The different modelling centres have used numerous scenarios of greenhouse gas and aerosol emissions to drive the GCMs to explore the sensitivity of the climate system to these emissions. Given their current temporal and spatial resolution, GCMs present a generalized view of the climate system; numerous processes will occur at scales (temporal or spatial) not resolved explicitly by the models.

Climate model experiments typically follow a common strategy. When a model is updated or developed, a long-term control climate simulation is carried out. The control climate simulation typically considers an atmosphere with greenhouse gas composition resembling that of the 1961–1990 time period. Then, a climate change experiment is completed by adjusting CO_2 levels of the atmosphere to reflect the trajectory of increasing greenhouse gases possible over the next century. Differences between the control simulation and the experiment reflect possible changes due to changes in greenhouse gas concentrations in the atmosphere. In other experiments, modelers use historical greenhouse gas concentrations for driving the GCMs until 1990 and then greenhouse gas concentrations based on different economic scenarios are used.

Comparing the results across several models allows researchers to characterize the current level of scientific understanding and uncertainty of the trajectory of future climate change. Therefore, it is increasingly recognized that comprehensive impact studies should be based on multiple GCM outputs (Wilby, *et al*. 2004), selected from among the more recent versions of the available GCMs. The results of these experiments are typically archived at the web sites of the individual modelling centres and at the Intergovernmental Panel on Climate Change (IPCC). Appendix B provides suggested web site addresses.

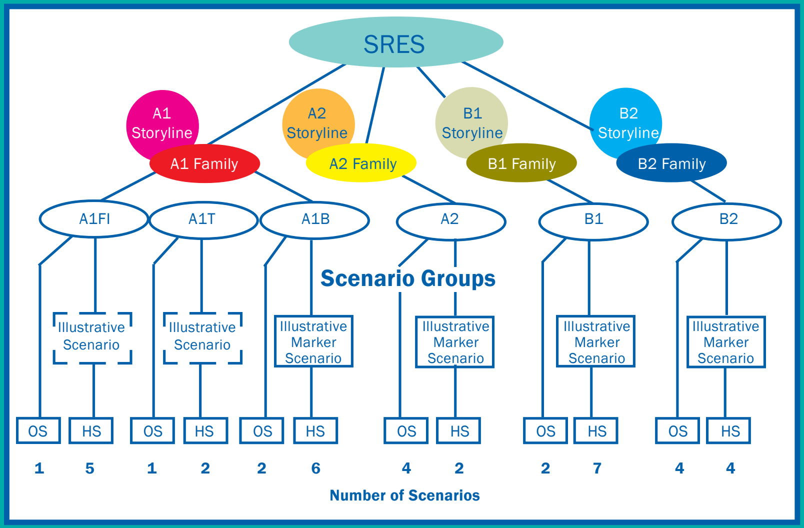
Scenarios of Future Climate Change

Just as it was difficult for futurists in 1900 to imagine our current world, we do not know how the global economy, population, technological development and fossil fuel use will change over the next century. Given different levels of global co-operation, technological development, and dependence on fossil fuel use, a wide range of plausible scenarios for future greenhouse gas emissions to the atmosphere is imaginable. In the climate change literature, these scenarios are known as “storylines”. Impact studies dealing with climate change must reflect some of this uncertainty. The IPCC Special Report on Emission Scenarios (SRES) outlines four main scenarios that project the future growth of greenhouse gas emissions. The SRES replace the scenarios released by the IPCC in 1992. The most widely used of these scenarios was IS92a, commonly known as the “business as usual” scenario, which had the effective CO_2 concentration increasing at 1% per year from 1990 to 2100. CO_2 is only one of several greenhouse gases important for climate change, therefore the rise in greenhouse gases often is treated as the CO_2 equivalence of other greenhouse gases. Currently, most modelling centres use the SRES scenarios. However, numerous simulations driven by the IS92 forcing scenarios are still available; although it is recommended that the updated SRES be used in climate change studies. A summary of the SRES scenarios and storylines from the IPCC Special Report on Emission Scenarios (IPCC 2000) is presented in Sidebar A1.

Sidebar A1: Special Report on Emission Scenarios (SRES)

The Special Report on Emission Scenarios includes four sets of scenarios based on qualitative "storylines".

SRES Storylines and Scenario Families



The A1 storyline and scenario

- Rapid economic growth
- Population peaks in 2050 and declines thereafter
- Rapid technology growth and adoption
- Reduction in regional prosperity differences
- Subdivided into three sub-scenarios based on technological emphasis: (I) Fossil fuel intensive (A1FI); (2) Non-Fossil Fuels (A1T); (3) Balance across all sources (A1B)
- Of all of the scenarios the A1FI represents the highest range of CO_2 emissions

The A2 storyline and scenario

- A very heterogeneous world with great regional diversity
- Self-reliance and preservation of local identity is an underlying theme
- Continuously increasing global population
- Per capita economic growth and technological change are regionally fragmented and slower
- Upper-middle range of CO_2 emissions

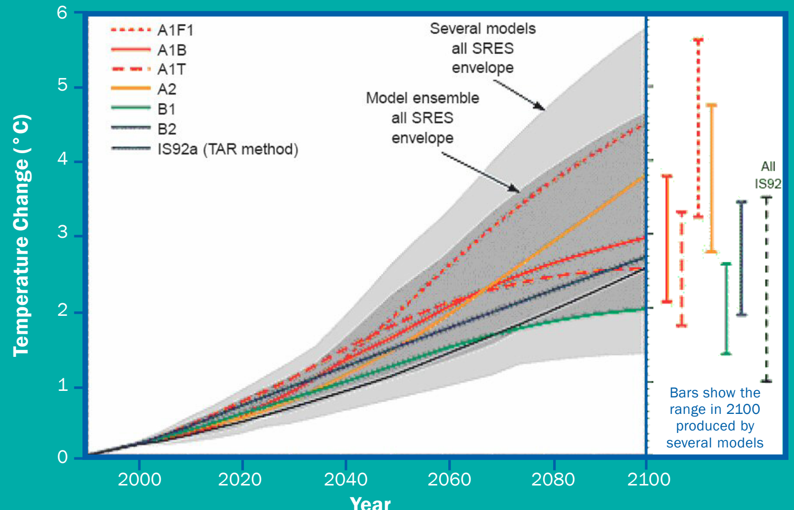
The B1 storyline and scenario

- Population peaks in 2050 and declines thereafter
- Rapid changes in economic structures toward a service and information economy
- Reductions in material intensity
- Rapid introduction of clean and resource-efficient technologies
- Emphasis is on global solutions to economic, social, and environmental sustainability
- Low end of range in CO_2 emissions

The B2 storyline and scenario

- Emphasis is on local solutions to economic, social, and environmental sustainability
- Continuously increasing global population although lower than A2
- Intermediate levels of economic development
- Less rapid and more diverse technological change than in B1 and A1 storylines
- Environmental protection and social equity at local and regional levels Lower mid-range of CO_2 emissions

The global temperature response to these six scenarios as predicted across several GCMs is illustrated below.



Source: Cusbach, *et al.* (2001)

Choosing Among Climate Models and Scenarios of Future Climate Change

The IPCC recommends that "users should design and apply multiple scenarios in impacts assessments, where these scenarios span a range of possible future climates, rather than designing and applying a single 'best guess' scenario". This is not always a simple matter as there are numerous scenarios available from several modelling centres. To aid in the selection of scenarios, the Canadian Climate Change Scenarios Network (CCSN) has online tools designed to help researchers evaluate changes to temperature, precipitation, and other climate variables across multiple GCMs over an area of interest (see Sidebar A2). Mortsch, *et al.* (2005) provide further insight for selecting among possible scenarios over the Great Lakes basin. In their analysis they demonstrate that the following models and scenarios are representative of the range of uncertainty among 28 SRES-based emission scenario experiments from six different GCMs:

- Warm and Wet: HadCM3 A1FI
- Warm and Dry: CGCM2 A21
- Not as Warm and Wet: HadCM3 B22
- Not as Warm and Dry: CGCM2 B23

A.2 Downscaling Climate Model Output to Regional and Local Scales

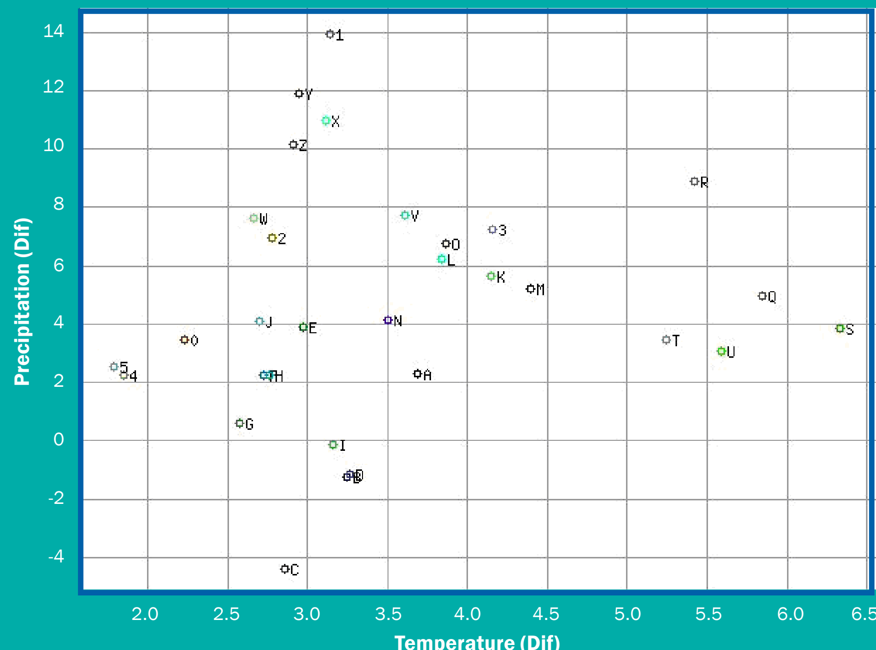
Climate change scenarios generated from GCMs are applicable at resolutions of several tens of thousands of square kilometres and for showing changes to monthly and to seasonal climate. This spatial and temporal resolution is typically not useful for planning at local and regional scales. In cases where fine resolution forces (e.g., rain shadow, lake effects) are important drivers of local climate a method of regionalization or "downscaling" of the climate output from GCMs is recommended. However, the added information that is provided by applying a regionalization technique must be balanced against the value added by the technique used, and therefore will depend on the spatial and temporal scales of interest, the climate statistics required, and details of the proposed study. Important questions to be

Sidebar A2: Evaluating Multiple Models

The following image illustrates how predicted changes to precipitation and temperature for a GCM grid box centred over Southern Ontario for the 2050 time period can be plotted (CCSN 2006). The numerous models and scenarios available are plotted separately with their anticipated response to changes in greenhouse forcing relative to the 1961–1990 climate. The spread among models highlights the uncertainties in both modelling future climate change and trajectories of greenhouse gases over the next half century. This research tool, which is available from the Canadian Climate Change Scenarios Network website, can be used to choose among results provided by the different modelling centres.

Following Mortsch, *et al.* (2005) it is recommended that users bound the uncertainty in their selection of scenarios by choosing from the "warmest wet", "warmest dry", "warm wet", and "warm dry" model results.

Predicted Temperature and Precipitation Change From Numerous GCMs and Scenarios for a Grid Box Centred Over Southern Ontario for the 2050 Time Period



Source: Canadian Climate Change Scenarios Network (2006) addressed before considering the use of a regionalization scheme include the following:

- Will higher resolution data significantly impact my results?
- Do changes in variability impact the result?

If the focus of the study is directed towards planning at local or regional scales (e.g., small watersheds), involves features such as steep precipitation gradients, heterogeneous land surfaces, mesoscale convective systems, or requires climate information at a high temporal scale (such as daily or extremes), then downscaled information is required (Mearns, *et al.* 2003). Researchers have employed numerous methods for downscaling GCM climate data to local and regional scales and several papers have been written to provide overviews and comparisons of the various approaches (e.g., Giorgi, *et al.* 2001, Mearns, *et al.* 2003; Wilby, *et al.* 2004). The following section provides an overview of this literature, and discusses several different methods for obtaining input from GCMs: direct output from a GCM; change factors and analogues; statistical downscaling; and regional climate models. The final section summarizes the strengths and weaknesses of the various methods.

Direct Output from a GCM

By definition GCMs are not designed to provide direct information at scales less than the modelling resolution, which typically spans several model grids (on the order of several hundred kilometres). Therefore, they cannot resolve forces generating local climate features, such as lake effects, or the impacts of topography, such as rain shadow. Of particular concern to understanding the impacts of climate change in Ontario is the lack of representation of the Great Lakes system in many GCMs.

In the direct output approach, information from the GCM grid cell overlying the region in question (or potentially averaged or interpolated over several surrounding cells) is applied directly for local modelling applications. Advantages to using direct output include a wealth of data available from long model integrations, from numerous modelling centres and scenarios. Furthermore, a wider range of climate elements is available from the direct model output that may not be available when downscaling approaches are applied. However the disadvantages to this technique are numerous. In particular, daily climate features are likely to be unrealistic, and considerable bias should be expected when data from a small region are used. Therefore, direct output from GCMs should be seen only as a starting point for generating impact assessments, particularly because the results of numerous studies have demonstrated that much better results are obtained when downscaling methods are employed. This is especially true in hydrological applications (Wilby, *et al.* 2000).

Change Factors

A method which often is employed in generating regional scenarios directly from GCM output is the use of *change factors*, also known as the delta method. Change factors can be calculated through comparison of the 1961-1990 baseline climatology and predicted future climate from the GCM output (typically 30 year averages centred on the 2020s, 2050s, and 2080s). Changes in climate are then calculated as the difference or ratio between the simulated and baseline climatology. Differences are typically applied to baseline temperature time series while ratios are often applied to precipitation, vapour pressure, and radiation (Arnell and Raynard 1996; Mearns, *et al.* 2001). When using this technique, care must be taken to ensure that realistic values are retained (e.g., no negative precipitation values). This method is particularly advantageous when climate change information is necessary across relatively large basins. For example, to complete downscaling for the larger Great Lakes basin would require climate downscaling at over 1800 stations (Mortsch, *et al* 2005).

In some cases, GCMs do not supply all of the variables necessary for hydrologic modelling. For example, Mortsch, *et al.* (2005) found that the NCAR-PCM model runs did not supply wind speed or humidity, therefore the scenarios produced from this GCM were omitted from their hydrological modelling study of the Lake Ontario and St. Laurence River. Addressing changes to variables that are not often directly output from GCMs, such as potential evapotranspiration, typically requires that the researcher use methods such as the Penman Monteith equation to evaluate changes (e.g., Diaz-Nieto and Wilby 2005).

Several weaknesses are associated with the change factor approach. Most critically, the technique makes the inappropriate assumption that a single GCM grid can be used to represent the climate of the region (Wilby, *et al.* 2004). It should also be noted that the use of simple change factors does not affect the variability of a time series while ratio changes will affect the time series' standard deviation, a situation which may not be a reasonable assumption. In a study by Arnell (2003), the relative variability from year-to-year precipitation was altered "by multiplying the difference between monthly precipitation total for a given year and the monthly mean by the proportional change in coefficient of variation, and then recalculating the annual value by applying the altered difference to the mean" (see also Mearns, *et al.* 1992). This approach changes the variability in the original time series, although it does not change the variability in climate from day to day. Therefore, the usefulness of this technique is limited in cases where the length of wet or dry spells is important. Furthermore, the spatial patterns of the climatology is assumed to remain fixed, an assumption that may not be reasonable.

Analogues

Several researchers have used spatial or temporal analogues for understanding the impact of climate change. In this approach, historical climate records are analysed to identify periods of record that resemble what may be expected in a climate change scenario (these could be identified using tools such as those described in Sidebar A2). The analogues are either spatial or temporal in nature. A spatial analogue may take the observed climate from another region and apply it to region of interest, while a temporal analogue will identify periods of record that may closely resemble a future scenario. For example, a spatial analogue is presented in a report by Kling, *et al.* (2003), who projected that the future summer climate of southern Ontario in 2095 may resemble that of present day Virginia. In contrast, temporal analogues will draw from previous climate events that may occur with greater frequency in the future, such as the probability of drought or floods. Temporal analogues are useful to evaluate the sensitivity of a region to extreme events as derived from historical data sets from the region (Mortsch, *et al.* 2005).

Empirical/Statistical Downscaling Methods

Statistical downscaling is based on an assumption that the regional climate is affected by large-scale climatic patterns and local to regional physiographic features, and that these relationships will persist in the future. Based on this assumption, statistical association between large-scale features (predictors) forecast from the GCM and the resultant effects on the local/regional scale climate variables are predicted. Advantages of these techniques include a low computational expense, which enables multiple scenario evaluation, and site-specific information of critical importance to regional/local scale climate change impact assessments.

Several key assumptions should be kept in mind when climate model output is downscaled to regional or local scales (Giorgi, *et al.* 2001; Wilby, *et al.* 2004):

- The predictors modeled by the GCM are realistically modeled;
- The transfer function to future climate will remain valid (an assumption which may not be verifiable); and,
- The predictors chosen fully represent the climate change signal.

Despite these assumptions, numerous studies have shown improvements to regional climate simulation when statistical downscaling methods are adopted. Many statistical downscaling methods have been developed, but, in general, these methods are based on three techniques: weather generators, transfer functions, and weather typing schemes. These techniques are discussed separately, but it should be recognized that several of the techniques represent a combination of approaches. In the following sub-sections, statistical downscaling techniques are discussed following the classification of Wilby, *et al.* (2004): weather generators, weather classification schemes and regression models.

Weather Generators: Weather generators reproduce the sequence of climatological events based on statistical probabilities from local climate variables such as the mean and variance. The models typically replicate the distribution and transition between wet and dry days. Secondary variables such as air temperature, solar radiation and humidity are modeled conditionally on the presence or absence of precipitation. Wilks and Wilby (1999) present a review of weather generation models including their use for temporal and spatial downscaling in climate change. Weather generators are typically used for modelling climate at a single point. However, researchers such as Wilks (1999) have included multiple weather generators, each driven with random numbers which are spatially correlated among modelling points, while Yates, *et al.* (2003) have developed spatially consistent resampling techniques. Cunderlik and Simonovic (2005) provide a recent application of this technique in Southern Ontario.

A weather generator which has been used for modelling climate change is the LARS-WG model (Semenov and Barrow 1997). The LARS-WG model is useful for generating a suite of climate variables for a single site at a daily time step. It is particularly valuable for generating daily data from monthly climate change scenario output. A short overview of the model and web sites to the model are available from the Canadian Climate Impacts and Scenarios project webpage (see Appendix B).

Transfer/Regression Functions: Transfer functions are typically regression-based models for identifying relationships between large-scale forcing (predictors) and local to regional scale predictands. Numerous transfer techniques have been developed and applied for downscaling climate including multiple regression (Murphy 1999), canonical correlation analysis (von Storch, *et al.* 1993), and artificial neural networks (Coulibaly, *et al.* 2004). In Coulibaly, *et al.* (2004) an artificial neural network approach for downscaling climate was applied for modelling the frequency of flooding in the Saguenay river system in Quebec. In this study, a neural network approach was found to compare better with local observations (1961-1990) than downscaling techniques such as LARS-WG (described above) and the Statistical Downscaling Model.

A widely used model for regional and local scale climate change impact assessments is the Statistical Downscaling Model (SDSM) (Wilby, *et al.* 2002). The SDSM tool statistically downscales climate using a multiple regression approach to identify the optimal downscaling predictor variables from the GCM that are correlated with local data. The model has been released as a Windows-based software tool, with data sets and tutorials available at the Canadian Climate Impacts and Scenarios project webpage (see Appendix B).

Weather Typing: Given that GCMs are more reliable at producing large-scale features such as atmospheric circulation patterns, weather typing schemes correlate groupings of synoptic scale weather patterns or atmospheric circulation patterns to local or regional climate variation. Typically, local scale weather sequences or events conditional on circulation patterns are identified and compared to potential changes in frequency of these weather classes in GCMs. Regression or other transfer techniques are then used to relate the changes observed in circulation patterns in the GCM to develop a regional climate change response (e.g., Saunders and Byrne 1999; Zorita and von Storch 1999).

Recommendations and Comparisons of Statistical Approaches: The following advice regarding statistical downscaling methods for constructing climate change scenarios is pertinent to users working at the local to regional scales (Wilby, *et al.* 2004):

- Not all climate assessments require high resolution data. Therefore, it is important to ensure that the time and resources involved in creating the downscaled climate scenarios are justified given the study objectives, and that a comparable outcome cannot be achieved using more straightforward means (e.g., change factors or interpolation from the GCM).
- Be aware of the strengths and weakness of statistical downscaling method(s) employed (see Sidebar A3 for a

summary). In general, the transfer functions and weather generator approaches are far easier for a non-climatologist to use than are the weather typing schemes due to the necessity of a detailed weather classification. Furthermore, in the case of the transfer/regression and weather generator approaches, software such as the SDSM and LARS-WG are freely available and supported with online technical manuals. At the same time, several of the described methods may be useful for understanding changes to temperature and precipitation but cannot be used to supply all of the elements necessary for hydrological modelling.

- Test the statistical downscaling model using independent data, and recognize that downscaling predictability may vary seasonally.
- If possible, apply regional climate scenarios (discussed below) together with statistical approaches to explore the uncertainty due to the downscaling method.
- If statistical downscaling is conducted for input into hydrological models one should be aware of the necessary input parameters for the model as some downscaling techniques may not produce all of the necessary variables.

Regional Climate Models

Regional climate models (RCMs) are increasingly becoming an important method for downscaling climate from GCMs. Regional climate models (RCMs) do not replace GCMs, but when used with a GCM are useful for providing fine-scale resolution climate impact assessments. The resolution of RCMs varies between models. However, they are useful at correctly representing climatic and hydrologic processes such as the formation of thunderstorms, and the simulation of soil moisture. Typically, a RCM is driven by or "nested" within a GCM; therefore, the GCM provides boundary or initial conditions so that the RCM model can account for features not resolved at the GCM resolution. The feedback is typically only one way, meaning that there is no connection from the fine resolution RCM back to the GCM.

Sidebar A3: Summary of Strengths and Weaknesses of Statistical Downscaling Approaches

Method	Strengths	Weaknesses
Weather Generators (e.g., Schnur and Lettenmaier 1998; Semenov and Barrow 1997; Wilks 1999; Yates, *et al.* 2003)	• Can produce large ensembles of data for uncertainty analysis or extreme event simulation • Can produce sub-daily information • Model parameters can be related to landscape patterns using interpolation • Off-the-shelf software available	• Adjustment of weather parameters to future can be arbitrary • When precipitation parameters are adjusted, there are unanticipated effects to secondary variables
Regression/ Transfer Function Methods (e.g., Coulibaly, *et al.* 2004;Wilby *et al.* 1998; Wilby and Wigley 1997)	• Relatively easy to apply • Off-the-shelf software available • Uses a very large range of potential predictor variables	• Observed variance is poorly represented • Assumed linearity or normality of data not valid • Extreme events are poorly simulated
Weather Typing (e.g., Lapp, *et al.* 2002; Hughes, *et al.* 1999; Zorita and von Storch 1999)	• Versatile to numerous study objectives (e.g., applied to air quality, flooding, surface climate) • Useful for analysis of extreme events • Yields physically plausible linkages to surface climate	• Requires additional task of weather classification • Circulation-based schemes can be insensitive to changes in climate forcing • May not be able to resolve weather patterns that fall between classifications

Source: Adapted from Wilby, *et al.* (2004)

Work with RCMs is a rapidly evolving and advancing area in atmospheric science. However, there are some important disadvantages currently associated with RCMs:

- Because the RCM is driven from the GCM, bias or systematic errors due to the GCM are fed into the regional simulation as well.
- Some studies have shown that RCMs exhibit their own internal variability apart from the GCM, which adds another component of uncertainty for regional climate simulation.
- Due to the computational demands of the process, there presently are few data sets available that use multiple GCMs, long time simulations, and multiple scenario runs available over Canada.

In Canada, regional climate simulations have been carried out using the Canadian Regional Climate Model (CRCM) (Caya and Laprise 1999). Researchers have used the CRCM coupled to the Canadian GCM2 to produce regional simulations over much of Canada with an approximate spatial resolution of 45-km by 45-km (Goyette, *et al.* 2000; Laprise, *et al.* 1998). The climate change scenario follows the IS92a and the time periods available include 1970–1994 and 2039–2063. The data sets produced from these simulations are available from the Canadian Centre for Climate modelling and analysis (CCCma).

In the near future, further advancements towards regional modelling improvement can be anticipated. A network for regional climate modelling has been established in Canada that will continue to update scenarios of climate change as models are updated and enhanced (see Appendix B). Furthermore, the North American Regional Climate Change Assessment Program links several Canadian and US agencies and modelling centres for the development of multiple high resolution regional climate scenarios over much of North America. When these data become available, they will be of considerable value for generating multiple downscaled climate scenarios for impact studies.

Method Intercomparisons

A number of studies have focused on the comparison of downscaling techniques (e.g., Dibike and Coulibaly 2005; Wilby, *et al.* 1998; 2000; Wilby and Wigley 1997; Wood, *et al.* 2004) and Barrow (2002) presents an informative review. In Wilby, *et al.* (1998) and Wilby and Wigley (1997), six statistical downscaling techniques are compared for multiple locations in the USA using observed GCM output (control simulations with historical greenhouse gas forcing). These studies compared the downscaling techniques for the reproduction of daily statistics including wet and dry spell length, median, wet to wet and dry to dry probabilities and several measures of the standard deviation. Rather than pointing to one method, the results of these analyses demonstrate the relative strengths and weaknesses of each of the approaches. Nevertheless, techniques similar to the SDSM, which are based on atmospheric circulation, were found to offer the best overall performance (Wilby, *et al.*1998; Wilby and Wigley 1997). Given the different precipitation scenarios predicted across the six techniques, Wilby, *et al.* (1998) also suggest the importance of using predictors such as humidity, which will capture long-term changes to atmospheric moisture, when these predictors are used for a climate change experiment.

Comparisons between RCMs and statistical downscaling techniques have been completed by several researchers (Kidson and Thomson 1998; Mearns, *et al.* 1999; Murphy 1999; 2000; Wood, *et al.* 2004; Wilby, *et al.* 2000). The consensus from a majority of intercomparison studies is that statistical and dynamical (e.g., RCMs) methods offer similar levels of skill for downscaling weather variables in the current climate setting. However, studies such as Murphy (2000) demonstrate that statistical methods can produce different precipitation scenarios than RCMs for simulations of the future climate, particularly if humidity measures are excluded from the predictors used for generating the statistical models. Given this result, it is recommended that, where possible, studies should employ both RCM scenarios and statistical methods in parallel to further explore the uncertainty due to choice of downscaling method

Sidebar A4: Summary of Different Downscaling Techniques and an Evaluation of Their Advantages and Disadvantages

Technique	Description	Advantages	Disadvantages
Direct GCM outputs	• Description of climate change over 100's of kilometres • Starting point for many studies	• Most up to date models available· Large amount of available data • Long model runs • Numerous variables available	• Poor spatial resolution results in unrealistic climate in some regions • Large bias evident in some model simulations • Extreme events are typically below the resolution of the GCM
Spatial and Instrumental Analogues	• Explores vulnerabilities and adaptive capacities from relationships	• Can be physically realistic changes • Data readily available • Can contain a mixture of well resolved variables	• Not necessarily related to greenhouse gas forcing • Magnitude of climate change is often small • No appropriate analogues may be available • May be physically implausible
RCMs	• Provide high spatial and temporal resolution	• Many variables available • Resolved from physically- based GCM models • Can represent weather extremes not captured in GCMs	• Computationally expensive and few multiple scenarios available • Depend on potentially biased output from the GCM as model input
Statistical Downscaling	• Provides high spatial and temporal resolution	• Can generate information at high resolution • Computationally inexpensive • Can be applied rapidly to multiple GCMs	• Assumes that empirical relationships will exist in future • Requires daily observational data that spans the range of observed variability • Some techniques do not provide many output variables • Depends on potentially biased output from driving GCM

Source: Mearns, *et al.* (2003)

(Wilby, *et al.* 2004). The advantages and disadvantages of various techniques for downscaling climate are summarized in Sidebar A4.

Beyond simple comparisons of the performance of techniques, several studies have examined the impact of different regionalization techniques for hydrological simulation (e.g., Dibike and Coulibaly 2005; Wilby, *et al.* 2000; Wood, *et al.* 2004). Xu (1999) and Xu and Singh (2004) present reviews of downscaling for hydrological applications. In the studies by Wood, *et al.* (2004) and Wilby, *et al.* (2000) RCMs and statistical downscaling approaches were shown to have comparable predictive capabilities. However, in the Wood, *et al.* (2004) study, it was necessary to include a bias correction step to both the RCM and to the GCM output to produce a realistic hydrologic simulation. Recently Dibike and Coulibaly (2005) demonstrated that choice in downscaling technique can influence the outcome of a hydrologic study. In their study they compare the SDSM and LARS-WG methods of downscaling climate from GCMs for hydrological prediction over a region of the Saguenay watershed of Quebec. They found that both methods approximated the observed climate data reasonably; however, scenarios of future hydrological states simulated by each of the methods would not lead researchers to identical conclusions.

A.3 Climate Change Scenarios and Application to Hydrological Models in Ontario and the Great Lakes Basin

This section outlines how climate change information has been used in hydrological models for understanding the potential impact of climate change over Ontario and the larger Great Lakes basin and identifies some of the important challenges for adequately representing climate change in hydrologic models. It should be recognized that the climate component reflects only one aspect of the many potential changes which may occur to the hydrological cycle over a given region. Other changes in a watershed, such as land use change, demographic shifts, changes to economic structure and priorities, and changes in technologies, also may have dramatic effects on the hydrology of the region of interest (Bronstert 2004; Varis, *et al.* 2004). The impacts of climate change are even less clear when estimating changes to groundwater recharge or water quality as these values will depend greatly on demand and the potential responses of water managers (Arnell, *et al.* 2001). Therefore, studies of future changes to the hydrologic functioning of a watershed should place the expected climate change within the broader context of all the potential changes which may take place in that watershed over the time span being considered. This advice is particularly important in the context of source protection planning.

Hydrological Models and Climate Change

Application of hydrological models can provide quantitative estimates of the impact of climate change on the hydrologic cycle. Uncertainty in a given estimate can be quantified (using sensitivity studies) and numerous scenarios of land use or climate change can be efficiently evaluated. Varis, *et al.* (2004) outline the hydrologic state information that may be required for water resource management:

- Changes to mean streamflow
- Impact on mean groundwater recharge
- Variation in streamflow
- Variation in groundwater discharge
- Forecast changes to percentile flow volumes (Q95)
- Changes in flow duration curves
- Impacts of snowmelt volumes on streamflow
- Changes to flood or drought probabilities (return periods).

Hydrological models can contribute to our understanding of these important features; however, it is also important to note that there are very few hydrological models available that can be used to answer all of these questions. Therefore, it is important to understand what characteristics a hydrologic model should posses to be relevant for use in assessments of hydrologic impact due to climate change.

Cunderlik (2003) reviews the relative strengths and weaknesses of 18 hydrological models for use in climate change studies for southern Ontario. Cunderlik's study reviews several factors important for selecting the appropriate modelling platform, including the spatial and temporal scale; processes simulated; cost of model; support available; and ease of use. While the choice of the appropriate model will ultimately depend on the study questions to be addressed, the report by Cunderlik (2003) provides a useful overview of the numerous factors which must be considered in model selection. Xu (1999) reviews further approaches for applying climate change information into hydrological models.

The majority of hydrologic studies addressing the effects of climate change follow the "impact approach" outlined by Carter, *et al.* (1994). In hydrological modelling, the following strategy commonly is used (Cunderlik and Simonovic 2005):

1. calibration and verification of hydrologic model using observed data;
2. application of the modified climate interpreted from the GCM; and,
3. running of the hydrologic model under the new climate conditions.

Arnell, *et al.* (2001) list more than 40 examples of impact studies to water supply, irrigation, power generation, navigation and flood risk. In addition to the steps outlined above, Bronstert (2004) suggests that hydrologic modelers must also:

1. clearly define the modelling purpose and define the important hydrological processes and relevant temporal and spatial scales;
2. identify if the chosen hydrological model represents the processes to be modeled adequately;
3. evaluate if the impact to be understood involves feedbacks among climate and land use changes, and, if so, develop appropriate scenarios; and,
4. assess the uncertainty of the modeled system (input data, process model, parameter uncertainty).

Uncertainty of the model parameters and how these may change in a climate change setting is rarely assessed despite the potential impacts of this uncertainty on trend detection (Beven 2001).

When hydrological models are used to evaluate climate change impacts in Ontario, there are several important features that the proposed hydrological models should possess. Specifically, the chosen hydrological model should allow for continuous simulation, have a physically-based evaporation scheme (particularly if water budget questions are of concern), and have explicit representation of snowmelt processes. Continuous hydrologic models are run over long periods (typically 10 years or more); thus, events are sequenced realistically with the appropriate boundary or initial conditions. In studies conducted to assess runoff-generation under extreme precipitation, to identify shifts to discharge regimes, or to assess drought severity, improperly proscribed boundary conditions will severely limit the realism of the results.

In Ontario, evapotranspiration is always the largest output in a water budget assessment (Parkin, *et al.* 1999) yet the actual volume of water loss through this pathway is also least certain. In a climate change scenario, the trajectory of changes to evapotranspiration rate is even less certain. Over Northwestern Ontario, studies by Schindler, *et al.* (1990; 1996) demonstrate that annual evaporation has increased by approximately 50 per cent over the period 1970–1990. In a warmed climate, a longer frost-free season could result in longer growing seasons and therefore increased evapotranspiration (Mortsch, *et al.* 2000). Studies that apply empirical techniques such as the Thornthwaite's method for estimating evapotranspiration based on air temperature (e.g., Sanderson and Smith 1993) will often lead to the conclusion that increases to potential evapotranspiration will outstrip increases to precipitation and therefore water deficits. Paradoxically, a study by Roderick and Farquhar (2004) demonstrate that pan-based evaporation has decreased globally despite increased global temperatures — a result that points to water budget uncertainty in the context of climate change. Based on these findings, the Canadian Climate Impacts and Adaptation Research Network (Mehdi, *et al.* 2004) highlights uncertainty of future evaporation rates as a critical knowledge gap for assessing future climate change. Given this uncertainty, use of temperature-based evaporation schemes in hydrological models for long-term assessments of mean river flow, mean groundwater recharge, mean seasonal variation in river flow or groundwater discharge should be discouraged in favor of more physically-based techniques.

The climate warming impact on basins dominated by snowmelt processes will be an increasing trend towards an earlier freshet (the freshet is snowmelt-dominated peak in discharge during the early to late spring). Further, the volume of discharge associated with the spring melt likely will be decreased as a greater proportion of precipitation falls in the liquid form resulting in smaller snowpacks (Mortsch, *et al.* 2000; Lapp, *et al.* 2005). Several impacts are possible for basins impacted by changes to snowmelt processes, including an increased probability of rain on snow events, multiple melts throughout the winter season, and smaller total snowpacks. To adequately represent these conditions in hydrological simulations it is necessary that a realistic snowpack model be included in the hydrological model selected. In a recent study, Cunderlik and Simonovic (2005) used the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) to examine changes to runoff in the Thames River basin of Southern Ontario under a climate warming scenario. The use of this model required that a separate snowpack accumulation model be developed and integrated into their modelling study.

Modelling the Impacts of Climate Change in Ontario

A summary of the potential impacts of climate change on the hydrology of the Great Lakes basin projected by the current suite of climate change models and scenarios is presented in documents by Kling, *et al.* (2003), Lemmen and Warren (2004), Mortsch and Quinn (1996), and Mortsch, *et al.* (2000). These impacts include increased temperature and possible precipitation increases, although it may be likely that these future periods also may experience increases to water deficits (Bootsma, *et al.* 2004). Bootsma, *et al.* (2004) point out that expected changes to temperature are of greater certainty than are changes to measures of aridity or moisture deficits. Mortsch, *et al.* (2000) and Lofgren, *et al.* (2002) use climate scenarios derived from the Hadley Centre Model 2 (HadCM2) and the Canadian Centre for Climate Modeling and Analysis (CGCM1) to demonstrate different trajectories of water availability; climate predictions using the CGCM1 point to water deficits and lowering of lake levels while the simulations using the Hadley Centre Model show a slight increase in lake water levels. This issue recently has been revisited in a study by Kutzbach, *et al.* (2005). In their study, the predicted trends in the hydrology of the Great Lakes basin are evaluated using an ensemble of 8 different GCMs and two different emission scenarios. The results of this study suggest that the likely hydrologic response of the Great Lakes region is towards increased net moisture, particularly in the emission scenario with the largest increase in CO_2 (A2 scenarios). The results of the study by Kutzbach, *et al.* (2005) highlight the importance of approaches that use multiple scenarios.

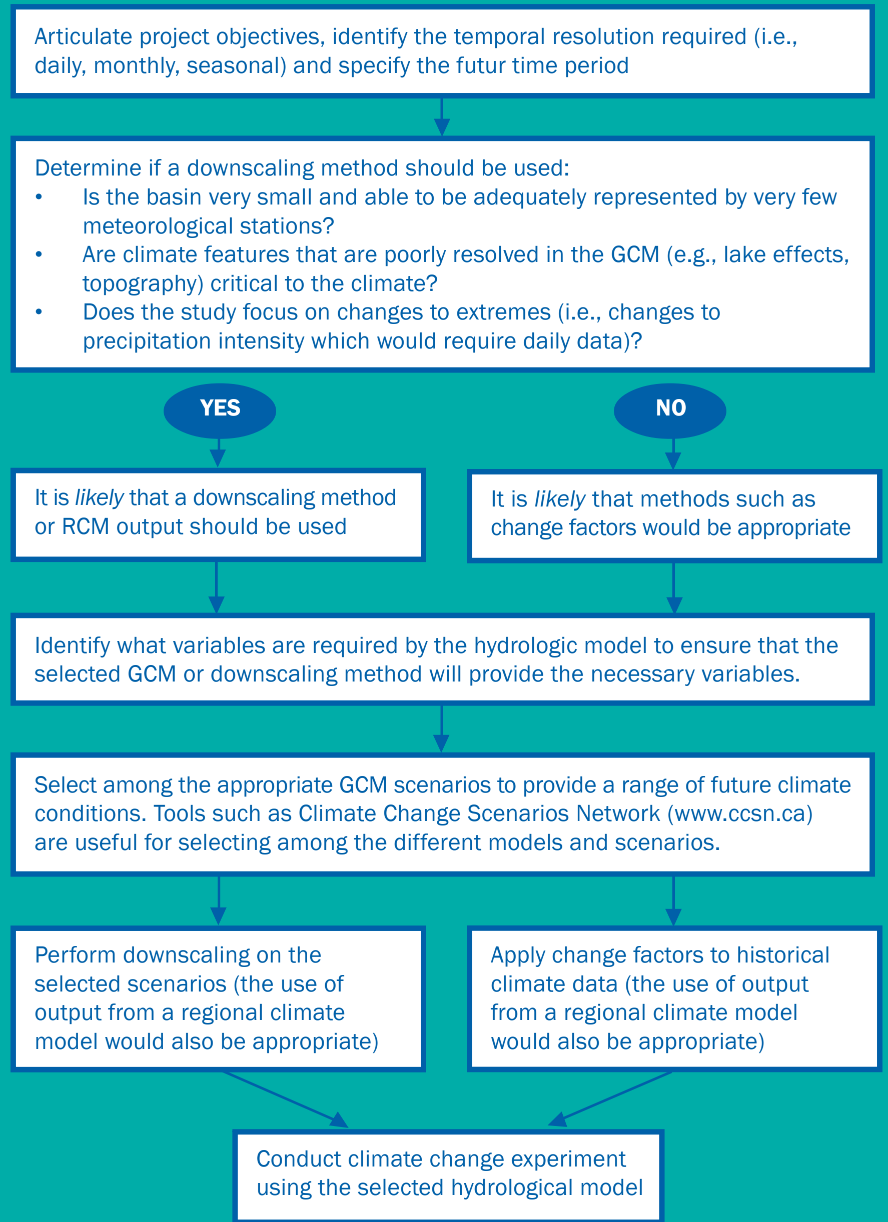
The impact of climate change at the scale of a single hydrological basin in Ontario has been the focus of several studies. In Southam, *et al.* (1999) several scenarios of future changes to climate were used as input into a water use model for the Grand River Basin of Southern Ontario. The results of this study suggest that the wastewater assimilation and water supply functions of the Grand River would be diminished during the summer and early fall given the climate change scenarios. An important feature of this work was the examination of streamflow conditions with climate change scenarios with application of numerous adaptive strategies. A second study of future climate change and hydrology in the Grand River basin was completed by the Grand River Conservation authority (Bellamy, *et al.* 2002). In this study, they used output from two GCMs (CGCM1 and HadCM2) and a hydrological model calibrated to the Grand River basin to identify future changes in runoff and groundwater recharge in the basin. The conclusions of this report demonstrate the importance of multiple scenario approach. In Bellamy, *et al.* (2002) study, yearly average precipitation was shown to increase in both climate scenarios, although net streamflow over the basin was shown to either increase or decrease depending on the GCM scenario used. Thus, an important concern identified in their study is the trajectory of changes to water budgets and particularly to evapotranspiration rates in a future climate simulation.

A.4 Summary and Recommendations

The following points summarize the findings presented above and provide overall guidance on using GCM output for impact assessments in hydrological models. Sidebar A5 presents a graphical overview.

- The current suite of different international modelling centres captures the current range of scientific uncertainty of how the atmosphere will respond to increases in greenhouse forcing. Therefore, impact assessments designed to capture the uncertainty of climate change should reflect this uncertainty by selecting across the range of the different models available. Preferably, users should select from the most recent SRES scenarios using both greenhouse gas and aerosol simulations.
- A wide range of possible scenarios for greenhouse gas and aerosol emissions to the atmosphere are imaginable over the next 50–100 years. Therefore, impact studies dealing with climate change also must reflect some of this uncertainty. Using tools available from The Canadian Climate Change Scenarios Network (www.ccsn.ca), analysts can identify the range of future possible change for the variables of interest, and can select the GCMs and scenarios representative of this range.
- The results of numerous studies demonstrate that the use of a downscaling strategy is important for understanding the impact of climate change, particularly if information is required over local to regional areas. In general, the use of statistical downscaling methods and regional climate models is very well supported in the scientific literature, and therefore their use should be examined for regional impact assessments. Fortunately, statistical downscaling tools (e.g., SDSM) and output from regional climate model simulations (including the

Sidebar A5: Summary of Potential Steps for Generating an Appropriate Climate Change Scenario for Hydrological/Water Balance Models



Canadian Regional Climate Model) are becoming increasingly accessible to develop robust impact assessments. Over larger regions, particularly where it would be necessary to apply a statistical downscaling model over numerous meteorological stations, the use of methods such as change factors or regional climate models would be preferred.
- Hydrological models are important to our understanding of the impacts of climate change. While this appendix has identified numerous studies which have applied GCM information to hydrological models, the model selection process must be closely guided by the study questions to be addressed. Some of the key questions that modelers must address in their selection of models include the following: (1) How important are impacts of land use change? (2) How realistic is the evapotranspiration formulation for use in a climate change context? (3) How well are snowmelt processes and snowpack accumulation represented? (4) Are continuous hydrological models necessary? (5) If not, does the model allow for realistic simulation of boundary conditions?

Appendix B: Useful Resources

B.1 Climate Change

Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report
www.grida.no/climate/ipcc_tar/index.htm

Canadian Climate Impacts and Scenarios project.
www.cics.uvic.ca/scenarios/index.cgi

Canadian Climate Change Scenarios Network
www.ccsn.ca/contents-e.html

Model output from the most recent GCM experiments for assessment in the Assessment Report 4 report of the IPCC.
www-pcmdi.llnl.gov/ipcc/about_ipcc.php

Climate change and variability in the Great Lakes
www.ijc.org/php/publications/html/climate/index.html

The Canadian Regional Climate Modeling Network
www.mrcc.uqam.ca/E_v/index_e.html

North American Regional Climate Change Assessment Program
www.narccap.ucar.edu/index.html

Water and Climate Change Bibliography
http://pacinst.org/topics/global_change/water_bibliography

B.2 Source Protection Planning

Ontario Ministry of the Environment Watershed-Based Source Protection Planning resources
www.ene.gov.on.ca/envision/water/spp.htm

Ontario Ministry of the Environment Clean Water Act web site
www.ene.gov.on.ca/envision/water/cwa.htm

The Waterhole: information about source protection in Ontario
www.thewaterhole.ca

Conservation Ontario Source Water Protection web site
http://conservation-ontario.on.ca/source_protection/index.html

United States Environmental Protection Agency, Groundwater and Drinking Water web site
www.epa.gov/safewater

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