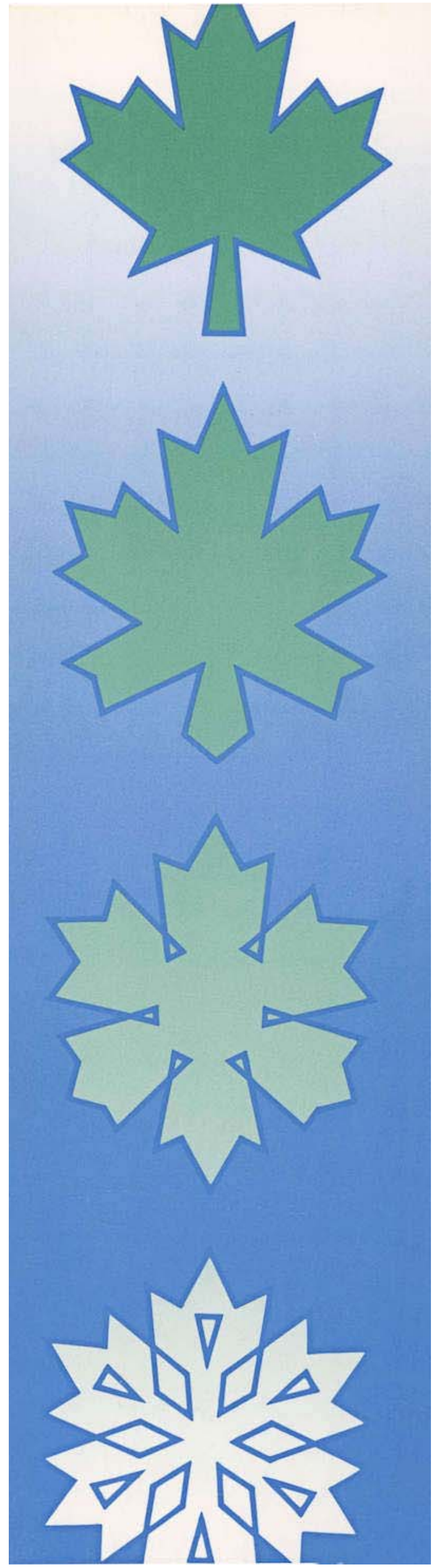
Environment Canada Environnement Canada

CLIMATE CHANGE DIGEST

Adaptation to Climate Change and Variability in Canadian Water Resources

CCD 93-02



Canada

CLIMATE CHANGE DIGEST

CCD 88-05 Implications of Climatic Change for Tourism and Recreation in Ontario

CCD 88-06 Estimating Effects of Climatic Change on Agriculture in Saskatchewan, Canada

CCD 88-07 Socio-Economic Assessment of the Physical and Ecological Impacts of Climate Change on the Marine Environment of the Atlantic Region of Canada - Phase I

CCD 88-08 The Implications of Climate Change for Natural Resources in Quebec

CCD 88-09 CO_2 Induced Climate Change in Ontario: Interdependencies and Resource Strategies

CCD 89-01 Climate Warming and Canada's Comparative Position in Agriculture

CCD 89-02 Exploring the Implications of Climatic Change for the Boreal Forest and Forestry Economics of Western Canada

CCD 89-03 Implications of Climatic Change for Prince Albert National Park, Saskatchewan

CCD 89-04 Implications of Climate Change on Municipal Water Use and the Golfing Industry in Quebec

CCD 89-05 The Effects of Climate and Climate Change on the Economy of Alberta

CCD 90-01 Implications of Climate Change for Small Coastal Communities in Atlantic Canada

CCD 90-02 The Implications of Long-Term Climatic Changes on Transportation in Canada

CCD 91-01 Climate Change and Canadian Impacts: The Scientific Perspective

CCD 92-01 Global Warming: Implications for Canadian Policy

CCD 92-02 Review of Models for Climate Change and Impacts on Hydrology, Coastal Currents and Fisheries in B.C.

CCD 93-01 Impacts of Climatic Change on the Beaufort Sea-Ice Regime: Implications for the Arctic Petroleum Industry

CCD 93-02 Adaptation to Climate Change and Variability in Canadian Water Resources

Environment Canada Environnement Canada

ADAPTATION TO CLIMATE CHANGE AND VARIABILITY IN CANADIAN WATER RESOURCES

summarized for

Climate Change Digest
Atmospheric Environment Service

by

William K. Nuttle
Rawson Academy of Aquatic Science

This Report Contributes to State of Environment Reporting

INTRODUCTION

The Canadian Climate Centre (CCC) has funded a number of studies to investigate the potential impacts of climate warming. A list of earlier titles in the series appears on the inside front cover.

DISCLAIMER

This publication contains the summary results of a study conducted by Dr. William K. Nuttle, of the Rawson Academy of Aquatic Science. The views and opinions expressed herein are those of the authors and do not necessarily state or reflect those of the Government of Canada or any agency thereof.

Single copies of this publication may be obtained, free of charge, by writing to the:

Climate Products and Publications Division
Canadian Climate Centre
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
(416) 739-4331/4328

To purchase copies of the complete report,
Nuttle, W.K. 1993, Adaptation to Climate Change and Variability in Canadian Water Resources, Rawson Academy Occasional Paper No. 7,
write to:

The Rawson Academy of Aquatic Science
Suite 404, 1 Nicholas Street
Ottawa, Ontario
K1N 7B7

Published by Authority of the
Minister of the Environment

Catalogue No. EN57-27/1993-02
ISBN 0-662-59789-3
ISSN 0835-3980

ADAPTATION TO CLIMATE CHANGE AND VARIABILITY IN CANADIAN WATER RESOURCES

1. STUDY HIGHLIGHTS

This paper is a survey of topics and issues related to adaptation to climate change in Canadian water resources. The principal findings are as follows:

- Growing concerns for the environment and adoption of the goal of sustainable resource development act to emphasize the climatic limits to water resources. Water resources are especially sensitive to changes in variability in climate and hydrology.

- Based on what we now know about global warming, significant changes in climate and hydrology are plausible within a time period that matters for managers of water resources. Global warming will tend to exacerbate existing water resources problems in the southern Prairies and the Great Lakes. The Prairies can expect increased drought during the summer growing season, and the Great Lakes can expect a decline in mean lake levels to historic low levels.

- Measures for adapting to climate change can be categorized as traditional (supply) management, non-traditional (demand) management, and non-management. Traditional practices stress system reliability. They provide some adaptation to climate change, but they are limited in their ability to respond to rapid change. Non-traditional and non-management measures stress flexibility and resilience. These measures have the advantage that they also address other, more pressing concerns of water resources managers, and thus they can be implemented immediately, before the effects of climatic change are evident.

- Water resources managers require methods of assessing the vulnerability of water resources systems to climate change to help identify when and where adaptive measures should be applied.

- Adaptation to climate change requires ongoing observation and interpretation of climate, hydrology and related environmental processes. Ways must be found to detect the onset of climate change, and we must continue to improve our understanding of climate, hydrology and the links between them.

2. VARIABILITY, CHANGE AND ADAPTATION

Water is intrinsic to climate and an essential resource for society. Evaporation of water from the oceans and the continents, condensation into clouds and precipitation are the engine that drives the weather, which determines climate. Water in its terrestrial forms, as rivers, lakes and groundwater, is used in agriculture, energy production, transportation and recreation. The prospect of global warming caused by an enhanced "greenhouse" effect has focussed attention on the impacts of climate change on society and the natural environment. Society is faced with the need to adapt to a changing climate. Even if current initiatives to control emissions of carbon dioxide are successful, a certain amount of climate change is now inevitable. Water resources is one area where the impacts of climate change are likely to be large and adaptation measures will be necessary.

2.1 ADAPTATION IN WATER RESOURCES

How well are Canadians adapted to their climate? What can be done to adapt better to a changing climate? Water resources are, by their nature, sensitive to variations in climate and hydrology. Water resources systems are well adapted to the variations in climate and hydrology that occur on seasonal, interannual and decadal time scales. However, climate change and its consequences have been implicitly ignored in the planning and design of most water resources systems. For the most part, it has been thought sufficient by hydrologists and water resources managers to characterize climate and hydrologic processes as random variation superimposed on an unchanging mean climate, the assumption of stationarity. This has been justified by the argument that interannual and interdecadal variability in the recorded data of precipitation, stream flow and the like, combined with the uncertainties introduced by errors in measuring these processes, overwhelm the changes during these periods that are associated with climate change.

Predictions of imminent, rapid global warming raise the issue of the long term variability and changeability of climate and motivate us to reexamine the assumptions underlying design and practice in water 'resources. The purpose of this paper is to provide a survey of topics and issues related to climate change and adaptation in water resources in Canada. Therefore, the emphasis is on what can be done to improve our adaptation to climate change. Three questions guided this study. What types of climate change are possible in the next 30 to 50 years, the time frame relevant in planning large water resources projects? What will be the effect of these changes on water resources? How can managers and water resources institutions respond to a changing climate?

2.2 CLIMATE VARIABILITY AND CHANGE

The distinction between climate variation and climate change is largely arbitrary. The "mean" climate is often defined in terms of 30 year averages of climate parameters, also known as the climate normals. Deviations in daily, seasonal and annual mean quantities from the climate normals are taken as measures of the daily, seasonal and interannual variability of climate. Variation in the climate normals themselves can be taken as evidence of change in the mean climate, although a certain amount of "noise" in the climate normals is still expected. Climate change refers to both changes in "mean" climate and changes in the deviations from the mean. Changes in the frequency and magnitude of flood and drought are especially important to water resources.

Long term changes in Canada's climate are apparent as trends in climate and hydrologic parameters over the last 100 years or so for which records have been collected. Whether these trends are evidence for a permanent change in mean climate or whether they are manifestations of long term, quasi-periodic variations in climate is a distinction with little practical meaning in terms of our adaptation to climate. For most people, and for society at large, change is measured as the difference between what is being experienced and what is expected based on past experience. Therefore, the definition ofclimate change depends on the length of human memory and on the underlying rate of change taking place in society at large.

3. WATER RESOURCES AND CLIMATE

The field of water resources is also changing in response to society's evolving concerns and objectives for resource management.Traditionally,water has been viewed narrowly in terms of its ability to satisfy the needs of domestic, municipal, agricultural and industrial users. The main objective of water resources management has been to "meet the demand for reliable water supply and flood protection no matter how that demand changes" (Riebsame 1988).Often, water resources development has been used to stimulate industrial and agricultural development. Traditional practice has concentrated on intervention in the hydrologic cycle by constructing facilities (storage reservoirs, diversion canals) to overcome flood hazards and the natural hydrologic constraints on the reliable supply of water.

In recent years, environmental concerns have become widespread in society. With regard to water, these manifest themselves as a concern for the effects of pollution and a growing recognition for the important roles water plays in natural ecosystems.Future management of water resources must beconsistent with the objective of sustainable development, that is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). In addition, society is less inclined to bear the cost of ever expanding facilities required by strict adherence to a supply based strategy for managing water resources, and interest is increasing in ways to manage the demand for water by society (Tate 1990). Taken together, these factors contribute to a broadening view of water resources, one which emphasizes the natural limits on water use by society, including those posed by climate change.

3.1 WATER USE BY SOCIETY

Water is used for municipal and industrial supply, irrigation, waste disposal, hydro-electric power generation, navigation, fish and wildlife production and recreation. In general, water use by society can be divided into two classes; withdrawal uses and non-withdrawal uses (also called in-stream uses). Withdrawal uses are characterized by the removal of water from a water body (river, stream, lake or reservoir) for use elsewhere, and these include municipal and industrial supply, irrigation, and water used in thermal power plants for cooling. Water withdrawn from a water body is either consumed, usually lost by evaporation, or discharged back into the water body. Nonwithdrawal uses employ water as it exists in lakes, rivers and streams, and these include both traditional uses (such as shipping, hydro-electric power production, disposal of wastes and recreation), and "uses" associated with water's role in the environment at large, such as fish and wildlife production.

3.2 LINKS TO CLIMATE

Hydrology forms the primary link between water resources and climate (Figure 3.1). The atmospheric components of the hydrological cycle overlap with climate processes, these include evaporation, atmospheric transport of water vapor and precipitation. The link with water resources occurs through the terrestrial components of the hydrological cycle such as runoff, stream flow and groundwater, i.e. the components not directly involved in climate processes. Similarly, elements of water resources fall both inside and outside of society. Elements inside of society include institutions, political constituencies, and patterns of water use. Elements external to society include the facilities, such as reservoirs, canals, and dykes, that are used to manipulate the hydrologic cycle and tame flood waters.

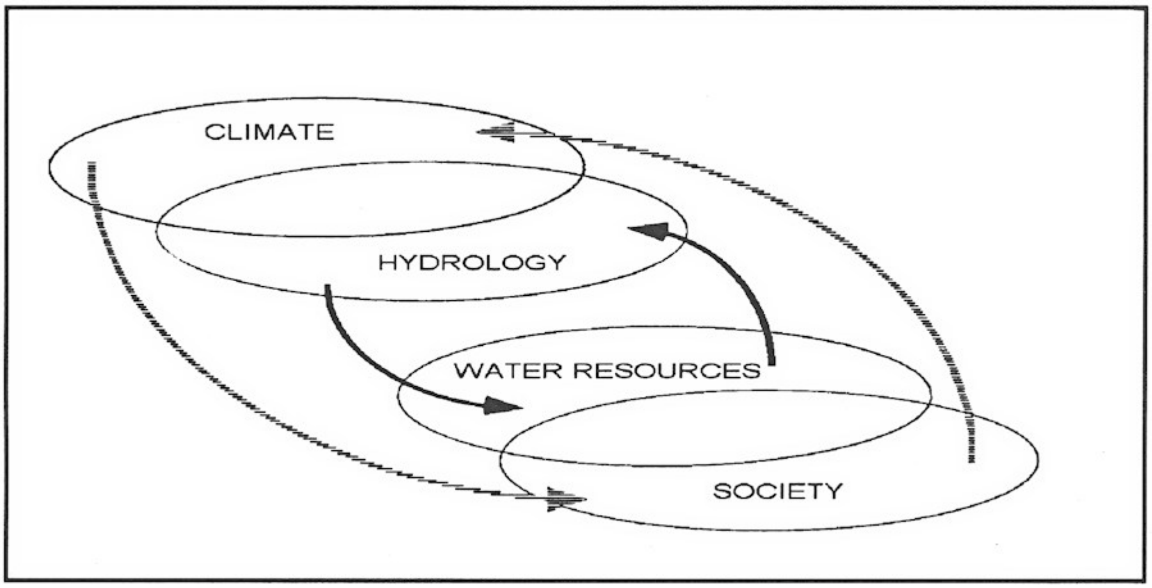


Figure 1. Linkages Between Climate and Water Resources**.**

The interface between hydrology and water resources can be defined in terms of water flow, water storage, and the state of water (Table 3.1). Flow, storage and state of water are determined by hydrologic processes that may be modified through the intervention of water resources systems.The resultsdetermine the quantity and quality of water available for use by society. The effects of climate change on hydrology propagate through the hydrology/water resources interface and affect the availability of water for use by society. Climate change can affect water use indirectly through other links between climate and society. For example temperature may affect the demand for water; however only the effects of climate on hydrology and water supply will be discussed below.

Table 3.1. Interface Between Hydrology and Water Resources.

Flow	Storage	State
Stream flow	Lake/Reservoir Levels	Water Quality
Groundwater	Soil Moisture	Snow and Ice

3.3 FLOW VARIABILITY AND SYSTEM RELIABILITY

Management of water resources is sensitive to variation in hydrologic processes occurring on all time scales.Municipal, industrial, andagricultural water uses are most sensitive to variation in flows occurring on seasonal, interannual and decadal time scales. For this reason, it has been easy to ignore the effects of climate change in designing these facilities. Larger facilities, such as reservoirs or systems of reservoirs providing multi-year storage capacity in drought prone areas, are more sensitive to variation occurring over longer time scales. Because climate change includes both changes in the mean climate over periods of several decades, or longer, as well as changes in the nature of seasonal and interannual climate variations that may occur within this period, all aspects of water resources can be affected by climate change.

Water resources facilities designed to prevent the impacts of flood and drought are very sensitive to the extremes of variation in precipitation, stream flow and soil moisture. Designs for flood protection are usually based on estimated flood levels with a frequency of recurrence of 100 to 200 years. A great deal of uncertainty is inherent in these estimates given the relatively short records of stream flow that are available. Estimating the magnitude of flood and drought for use in the design and operation of water resources facilities is further complicated by the fact that the sources of variability in precipitation and stream flow are not known.The largestfloods arise from large, short term departures from the normal range of variation in stream flow, known as the Noah effect. The severity of drought depends on the length of time experiencing precipitation or stream flow below a threshold, a characteristic of flow variability, also known as persistence. The occurrence of persistent periods of above average or below average flow is known as the Joseph effect. The Noah and Joseph effects are observable in records of a number of different geophysical parameters (Mandelbrot 1977).

3.4 REGIONAL DIFFERENCES

Canada can be divided into four regions in order to capture some of the geographic variation in climate, hydrology and the impacts of climate change; Western Canada (British Columbia, Alberta, Saskatchewan and Manitoba); Central Canada (Ontario and western Quebec); Atlantic Canada (eastern Quebec, New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland and Labrador); and Northern Canada (Yukon and Northwest Territories, and the northern most parts of British Columbia, Alberta, Saskatchewan, Manitoba, and Quebec). Each of these regions encompasses a large range of climate and hydrologic conditions. However, each region is unique in the challenges presented to managers of water resources and the difficulties in assessing the possible impacts of climate change.

Hydrology in Western Canada is characterized by two distinct hydrologic regimes; runoff from water rich, snow fed, mountainous catchments in the Rocky Mountains, and the Interior Mountains of British Columbia, supplies water to a few large rivers draining through arid regions, the Prairies of Alberta, Saskatchewan and Manitoba and the Interior Plateau of British Columbia. These rivers supply water for irrigation, municipal supply, hydro-electric generation, as well as supporting valuable fisheries.

Water resources issues in Central Canada are dominated by the Great Lakes and the St. Lawrence River.Together, the five Great Lakes are theprimary source of water for large populations in Canada and the United States as well as providing a vital transportation link between world markets and industrial areas in both countries.Managing water quality and extremefluctuations in lake levels and the flow of the St. Lawrence River are ongoing concerns. Groundwater is used extensively for municipal supply in southern Ontario, and issues of sustainable supply and groundwater quality are gaining attention.

Hydrology in Atlantic Canada is characterized by a large number of relatively small river basins, each draining directly to the sea.Waterresources development tends to be small in scale, confined to small hydro-electric development and water supply reservoirs.Groundwater is animportant source of water in the region, and it is the sole source of fresh water on Prince Edward Island.

The distinctive characteristics of hydrology in Northern Canada derive from the presence of permafrost and the low, annual supply of water from precipitation. Northern Canada is defined here as the area with extensive permafrost coverage, often taken as the area north of the -1 degree Celsius isotherm (Prowse 1990). This corresponds roughly to the area north of 55degrees latitude, 60 degrees near the west coast.

4. IMPACTS OF GLOBAL WARMING

Canada's climate has changed in the past, and there is no reason to believe that the present climate will continue unchanged in the future (Hengeveld 1991). The question for managers of water resources is whether the impacts of climate change will be large enough and rapid enough to require measures undertaken specifically to counter its effects. Alternatively, gradual change may be accommodated as water resource systems aré modified to accommodate changes in society, e.g. economic growth. It is not now possible to reliably predict all aspects of future climate change. However, it ispossible to review some changes that are considered possible within the next 50 years and their impacts on hydrology and water resources. While a number of factors have been implicated as causes of climate change, here we consider the only the changes in climate anticipated as a result of global warming related to an enhancement of the "greenhouse effect".

4.1 PREDICTING CLIMATE CHANGE

How can we predict the climate 20, 50 or 100 years in the future when we can't reliably predict the weather for the day after tomorrow? The answer to this lies in the difference between "climate" and "weather". The phenomena that make up weather are the result of the short term, small scale fluxes of heat and water driven by turbulent transport in the atmosphere. This close association with atmospheric turbulence is responsible for the inherent unpredictability of weather systems.By contrast, "climate" carries thenotion of averaging in time and/or space. Therefore, climate reflects less the turbulent variability of weather and more the constraints on atmospheric processes posed by the conservation of mass, momentum and energy.Theseconstraints provide the basis for forecasting mean climate conditions (Somerville 1987).

Confidence in the predictability of mean climate does not extend to the prediction of how the variability of climate may change. Model simulations of climate have shown only limited success in replicating the observed variability in the present climate (Smith and Tirpac 1989).This isdiscouraging given the sensitivity of water resources to variability in the hydrologic cycle.

4.2 CLIMATE SCENARIOS

A "climate scenario" represents a possible, rather than probable, future climate. Possible climates for the purpose of investigating impacts onhydrology and water resources have been constructed from 1) observed conditions in the region of interest during warmer periods or periods of drought, 2) current climate conditions in another region experiencing a warmer climate, 3) ad hoc scenarios formulated to assess the sensitivity to climate change in a region, and 4) scenarios based on output from general circulation models of climate (GCMs). In recognition of the considerable uncertaintyinherent in these techniques, the results are referred to as climate scenarios rather than predictions.

Most GCM scenarios are designed to simulate climate conditions in equilibrium with an atmosphere containing double the pre-industrial concentration of carbon dioxide, the "2xCO_2 scenario". These scenarios are generally considered to represent possible climates for the middle of the next century (Houghton *et al.* 1990). The Canadian Climate Centre (CCC) has developed one of the most advanced GCMs. Because the results of the CCC model have been available only since the end of 1989, most existing studies of the impacts of global warming on water resources that have used GCM scenarios are based the results of four other GCMs; the Geophysical Fluid DynamicsLaboratory model (GFDL), the Goddard Institute for Space Sciences model (GISS), the United Kingdom Meteorological Office model (UKMO), and the Oregon State University model (OSU).

4.3 IMPACTS OF GLOBAL WARMING ON HYDROLOGY

Projected effects of global warming on mean annual runoff in Canada are summarized in Table 4.1. Little is known about the effect that global warming will have on groundwater recharge. The effects of climate variability ongroundwater are not well understood, but in general changes in regional groundwater recharge should follow changes in mean annual runoff.

In spite of their problems, the impact studies provide an indication of the type and direction of changes to expect. Global warming will tend to exacerbate existing water resources problems in the southern Prairies and the Great Lakes basin.The Prairies can expect increased drought during thesummer growing season, which has implications for the future of irrigated agriculture there. The Great Lakes can expect a decline in water levels and river discharge to historic low levels, which has implications for shipping, recreational water use and hydro-electric power generation. In other regions the picture is less clear. In Atlantic Canada and in Western Canada west of the Rocky Mountains, the smaller scale of hydrological units limits our ability to infer regional effects from GCM scenarios. Assessment of hydrological impacts in Northern Canada is further complicated by lack of understanding of hydrological processes, especially the response of permafrost to climate change.

Table 4.1. Projected Changes in Climate and Hydrology Based on 2x CO_2 Scenario.

Region	Temp (°C)	Precip (%)	Runoff (5)	GCM	Study
	+2.0 to 3.0	+23	+20	UKMO/83	Ripley (1987) Pacific Drainage
	+2.5 to 3.0	+23	+235	UKMO/83	Ripley (1987);Gulf of Mexico drainage
Western	+2.5	+18	-20	GFDL/80	Haas and Marta (1988);
Canada	+4.4	+19	+28	GISS/84	S. Saskatchewan R.
	+2.8	+48	+83	GFDL/80	Zaltsburg (1990);
	+4.5	+10	- 5	GISS/84	Wilson Creek, Manitoba
	+2.2	+18	-58	GFDL/80	Cohen (1991);
	+4.4	+19	+38	GISS/84	Saskatchewan R.
	+3.0	+ 8	+ 8	OSU/88	
	+6.7	+ 7.5	-15	GFDL/87	
	+4.6	+19	+34	GISS/87	
	+3.1 to 3.7	+0.8	- 8.2-10.9	GFDL/80	Cohen (1986,1987);
	+4.3 to 4.8	+6.5		GISS/84	Great Lakes
	+3.2 to 7.2	0-6	-11 to -25	GISS GFDL OSU	Hartmann (1990); Great Lakes
Central Canada	+4.7	+0.03	-16	GISS	Sanderson and Smith (1990); Grand River
	+3.5	+17.5	+10.9 +15.7	GFDL/80	Singh (1988);
	+4.7	+15		GISS/84	James Bay
Atlantic	+4.0	-2 to -3	+20		Saulesleja (1989);
Canada	+4.0 to 4.7	+5.9 to +7.5	+35		MaritimesNFLD/Labrador
	+4.5 to +5	+15 to +20	-5	CCC	Morin and Slivitsky (1992) Moisie River
Northern Canada	+2 to +3.5	+54	+95	UKMO/83	Ripley (1987)

table adapted and updated from original provided by T. Marta

There is considerable room for improving our understanding of the links between climate and regional hydrology. Further improvements in our capacity to predict climate change are also needed and should be pursued. However, more research in these areas will not change the message of relevance here: Significant climate change is plausible within a period of time that matters to managers of water resources. Until our ability to predict these changes improves, we must assume the worst. Klemes [1] has summarized the possible impacts on water resources as:

- less water available
- greater extremes and fluctuations in general
- less advantageous seasonal distribution of precipitation and/or runoff.

5. ADAPTING TO CLIMATE CHANGE

Managers of water resources are faced with the certainty that climate will change, and the distinct possibility that climate will change quickly in the near future. What can be done to better adapt the management of water resources to a changing climate? Where should measures be taken to reduce sensitivity of water resources systems to climate change? Will adaptation to climate change be difficult? In addressing the above questions, it is convenient to borrow a conceptual framework proposed by Kates (1985) for describing how societies cope with hazards of climate.

Kates organizes adaptive measures into three categories based on the type of action taken in response to a hazard to society; change use, reduce loss, and accept loss. Further, adaptive measures can be categorized aseither incidental or purposeful. Incidental adaptation to climate variability occurs when an action motivated for another purpose, for example in response to changes in the demand for water, has the additional effect of reducing the effect of climate change on a water resources system. Purposeful adaptation refers to measures Undertaken explicitly to address the effects of climate change.

5.1 INCIDENTAL ADAPTATION

Incidental adaptation already occurs as the result of good practice in water resources management. Even assuming that climatic and hydrologicprocesses are stationary, errors of observation and interpretation introduce considerable uncertainty into what can be known about these processes. Managers account for this uncertainty by 1) designing for robustness, resilience and adjustability as well as reliability in water resources systems, 2) monitoring climate and hydrology and adjusting systems to maintain desired performance, and 3) maintaining "excess capacity" as a buffer against the unexpected.

Robustness refers to the insensitivity of a system to errors and uncertainties in the information used in the design of the system. Resilience refers to both the ability of a system to operate under conditions different from those it was designed for (Matalas and Fiering 1977), and

---

1 V. Klemes, Implications of possible climate change for water management and development. Canadian Water Resources Association Newsletter, April 1992.

the ability of a system to recover quickly from failure (Riebsame 1988). Adjustability refers to the ability of managers to change the system in response to evolving conditions at minimal cost.

Riebsame (1988) describes how the normal practice of modifying the operating rules for an existing reservoir as data on precipitation and stream flow accumulates from monitoring can also serve as adaptation to a changing climate. In general, this approach is limited in its ability to deal with rapid change, and there may be limits on the adjustability of a system. For example, changes in the operating rules can degrade the performance of a reservoir meant to serve multiple, possibly conflicting purposes, such as flood control and water supply.

Excess capacity refers to the ability of a system to perform beyond normal requirements, at least for short periods of time. Traditionally, excess capacity has been built in to systems by constructing facilities larger than needed as a buffer against increases in water use and uncertainties in estimated natural supply or hazard of flood and drought. One objective of the water conservation programs, in which there is a growing interest, is to maintain excess capacity in the face of growing demand without the expense of constructing larger facilities.

5.2 PURPOSEFUL ADAPTATION

Management options for accommodating climate change can be broadly organized into three categories; traditional management options (supply management), non-traditional management options (demand management), and non-management options. These roughly correspond to Kates' categories of societal response; reduce loss, change use, and accept loss. Some specific adaptations to the effects of climate change on flow, storage and state of water are summarized in Table 5.1.

Options that fall under the traditional approach to managing water resources (reduce loss) involve manipulating the hydrology of a basin through construction of reservoirs or modifications to natural channels in order to maintain the reliability of water supplies and provide protection from flood and drought. The primary effect of climate change is that it increases the uncertainty about future flows, storage and state of water. The unpredictability of climate change is a barrier to responding through traditional management, in part, because there is no way to quantify the benefit to society of undertaking the cost of constructing larger dams and levees required to maintain system reliability in face of growing uncertainty. As a result, many managers have the opinion that nothing should be done to respond to climate change until there is clear, compelling evidence that change has already begun, e.g. a catastrophic drought or flood.

Non-traditional options (change use) emphasize maintaining system reliability through increased flexibility by adjusting water use to match changes in hydrology. Rather than isolating society from the effects of climate variability, this approach seeks to minimize the impact of unexpected and catastrophic events (Holling 1978). Adaptive measures in this category include some innovative methods for demand management that are currently under development in Canada (Tate 1990).These measures offer the best opportunities to improve adaptation to climate change because many can be implemented to address other problems that face water resources managers.

Table 5.1. Adaptation to Climate Change in Water Resources.

	Change Use (Location, Use)	Reduce Loss (Prevent, Modify Effects)	Accept Loss (Share, Bear Loss)
Flood	▸ Restrict development on flood plains ▸ Change operating rules to increase flood storage in reservoirs	▸ Construct/upgrade flood storage reservoirs, dykes, river channelization ▸ Review dam safety	▸ Improved flood forecasting and flood warning ▸ Formulate evacuation plans ▸ Flood insurance, disaster relief ▸ Plan for disaster relief and emergency preparedness
Drought	▸ Reduce water requirements ▸ Abandon/expand agricultural lands	▸ Increase water stored in reservoirs ▸ Change farming practices to increase soil moisture ▸ Expand irrigation	▸ Contingency plans for allocating water during shortages ▸ Share water supplies regionally
Ground-water	▸ Increase/reduce use as sustainable yield changes	▸ Increase number/depth of wells to exploit recharge over larger area ▸ Exploit new sources of water (e.g. surface water)	▸ Institute management of groundwater withdrawals
Lake Levels	▸ Restrict lakeshore development ▸ Increase/reduce recreation and shipping as levels change	▸ Dredge harbors, raise seawalls and bulkheads ▸ Construct water level control structures ▸ Interbasin transfers to maintain levels	▸ Flood insurance ▸ Disaster relief
Soil Moisture	▸ Expand/abandon agricultural land ▸ Expand forest by planting ▸ Change crops ▸ Change tillage systems ▸ Manage wetland habitat to reduce loss/degradation by other causes	▸ Expand irrigation ▸ Construct artificial wetlands	▸ Subsidize agriculture ▸ Crop insurance, farm income supports

Table 5.1. Adaptation to Climate Change in Water Resources (continued)

	Change Use (Location, Use)	Reduce Loss (Prevent, Modify Effects)	Accept Loss (Share, Bear Loss)
Water Quality	▸ Expand/restrict use of affected water bodies ▸ Redirect fishery to exploit species that benefit from change ▸ Change land use practices to control erosion ▸ Control point and non-point discharge of wastes	▸ Increase/decrease level of water treatment Stock lakes and rivers from hatcheries ▸ Augment stream flow during low-flow events ▸ Install aeration and/or other mixing devices	▸ Subsidize fishery
Snow and Ice	▸ Increase/reduce recreational use and shipping ▸ Expand/restrict hydro-generation as ice allows	▸ Increase/decrease investment in ice breaking to maintain shipping channels ▸ Modify water intake structures to prevent ice build-up	▸ Subsidize expansion of alternative modes of bulk transport ▸ Contingency plans for interruption of service

Adjustments in the third category fall well outside of the bounds of traditional water resources management. These measures implicitly accept the fact that climate change may mean more frequent failure of water resource systems. Failure is planned for rather than trying to avoid it at all cost. These measures attempt to minimize the effects of failure on society and/or share the consequences of failure broadly within society.

5.3 VULNERABLE COMPONENTS

Adjustments to adapt to climate change should be undertaken first where the vulnerability to climate change is the greatest. The question of where to act has two aspects. The first concerns identifying those activities associated with managing water resources are most sensitive to change or at the greatest risk of failing as a result of change. The second concerns the geographic location where patterns of water use and climate coincide to maximize sensitivity to changes in climate. The work that has been done in each of these areas serves only to illustrate possible approaches to identifying areas sensitive to climate. As yet, there is no clear answer to the question of when to act.

Identifying areas of vulnerability within multi-component, and multi-sectorial water resources systems that serve most Canadians presents managers with a complex task. While studies by Klemes (1985), Rogers and Fiering (1990) and Riebsame (1988) provide a guide on how to assess the climate sensitivities of one element of water resources systems, they fall short of the goal of identifying the most sensitive component in the regional system. Break point analysis offers an approach that may be used to assess an entire, interconnected system. Under this approach, one identifies the limits in terms of climate and hydrologic parameters beyond which components or subsystems would fail to perform. These break points can then be compared both within the system to identify vulnerable components and against anticipated range of climate conditions to assess the risk of failure of the system (WMO 1987).

5.4 VULNERABLE REGIONS

Identifying geographic regions vulnerable to climate change is based on the principle that regions that are currently operating close to the limits imposed by climate on the availability of water are the most susceptible to changes in climate. Gleick (1990) suggests five indices for use to quantitatively assess the vulnerability of water resource systems to climate change. These are 1) the ratio of storage in a basin to annual supply; 2) the ratio of consumptive use to supply; 3) the ratio of hydro-electric generation to total power generation; 4) the ratio of groundwater overdraft to total groundwater withdrawal; and 5) the ratio of annual stream flow with a 5% exceedance to the stream flow with a 95% exceedance. Information is available for a preliminary assessment of the vulnerability of Canadian water resources based some of these indices.

5.4.1 RATIO OF CONSUMPTIVE USE TO SUPPLY

Regions where annual consumption of water is large relative to the reliable annual supply are especially vulnerable to interruptions to supply caused by fluctuations in annual runoff. A region is vulnerable if the ratio of consumption to runoff is greater than 0.2, allowing for water needed to satisfy in-stream uses. By this measure, the Assiniboine-Red, Missouri, and South Saskatchewan basins are vulnerable to water shortages.

5.4.2 RATIO OF HYDROELECTRIC TO TOTAL POWER GENERATION

Regions that depend on hydro-electric generation for a significant portion of their total electric power requirements are susceptible to disruptions caused by variability in stream flow. Gleick used a threshold of 0.25 for this ratio in his assessment of climate vulnerability in the U.S. By this criteria, all of Canada is vulnerable; 65% of the total electric supply comes from hydro-electric generation, however, vulnerability varies within Canada. Some provinces have no hydro-electric generation, such as Prince Edward Island and Nova Scotia, while other provinces depend on hydroelectricity almost entirely.

The most vulnerable provinces include Quebec, Manitoba, British Columbia, and Ontario, which is vulnerable indirectly because of purchases made from other provinces. Hydro-electricity is an area where vulnerability to climate change may mean opportunity. Increased basin supply is projected for northern Quebec, meaning that more water will be available for generating electricity provided that reservoir capacity is sufficient to capture it. Increases in consumptive use of water may decrease water available for hydro-electric generation in Ontario and Manitoba; however a decline in the demand for electricity with warmer temperatures may compensate to some extent (Sanderson 1987).

5.4.3 RATIO OF GROUNDWATER OVERDRAFT TO TOTAL WITHDRAWAL

The ratio of groundwater overdraft to total groundwater withdrawals measures the degree to which groundwater currently is being over exploited as a source of water and therefore is unavailable as an alternative supply. Information on groundwater use and availability in Canada is scarce, so it is difficult to say to what extent over exploitation is occurring. Groundwater is widely used as the primary source of domestic water in rural areas, but that alone probably would not tax groundwater supplies. However, a number of large communities rely solely on groundwater for their municipal supplies (Hess 1986). These communities may be vulnerable to changes in recharge rates brought on by climate change.

5.4.4 RATIO OF 5% EXCEEDANCE FLOW TO 95% EXCEEDANCE FLOW

The ratio of high flow to low flow is a measure of the variability in the hydrologic system. Areas that experience high variability are most susceptible to flood and drought, and these areas are vulnerable to changes in the frequency of extreme events as a consequence of climate change. Gleick (1990) suggests that areas where this ratio exceeds 3 be classed as vulnerable. In Canada, the Okanagan, Missouri, Assiniboine-Red, and Churchill rivers fall into this category. Variability is also high enough in the Winnipeg and South Saskatchewan rivers to be a concern.

The indices discussed above measure vulnerability principally with respect to shortfalls of supply and risks of flood and drought. Quantitative measures of vulnerability associated with other impacts of climate change have not been identified. Vulnerability related to non-withdrawal uses of water is particularly difficult to assess. Issues of concern include the effect of higher water temperatures on thermal power generation, fish, and microbial processes and thus on assimilative capacity and water quality. Presently, low water temperatures in Arctic rivers reduce their capacity to assimilate municipal wastes relative to that in rivers in the south. Fluctuations in the levels of the Great Lakes will affect shipping, water intake and outfall structures, shoreline development, and extreme low water introduces the risk that contaminants in the sediments may be reintroduced into the water column.

5.3 DIFFICULTY OF ADAPTATION

Some adaptation to climate will be easy and relatively painless to accomplish. Managers of water resources must constantly adapt to changes in society, and this continual change can be used to improve adaptation to climate as well. For example, a recent report by the Adaptation Panel of the U.S. National Academy of Science (National Academy of Science, 1991) notes that if the national economy grows at 2 to 3 percent per year, the long term average for industrialized societies, then half of all capital stock will always be less than 30 years old. This rate of turnover of infrastructure is fast relative to the 50 to 100 year time period that it will take to realize the changes projected for the $2xCO_2$ climate scenarios. Adaptation to reduced water supplies can be accomplished by fitting all new construction with water efficient appliances. Other programs designed to reduce costs to users, such as water audits that identify areas where cost saving changes in water use can be made, also reduce our vulnerability to climate change by maintaining a buffer between the demand for water and the amount of water that climate can deliver.

Long lived components of water resources systems present challenges to better adaptation to climate. Pipelines and treatment plants are designed for a working life of 40 years and typically serve longer before being replaced. Dams and levees designed to reduce the risk of flooding are affected by the changes in variability that may occur with climate change. The future performance of these long lived elements is most vulnerable to changing conditions. Designs that anticipate change may be warranted for new facilities of this type. The questions of when and how to modify existing systems to reduce their vulnerability to climate change present new problems to hydrologists and engineers.

Finally, water resource systems operate at the interface between human society and natural systems (i.e. climate, hydrology and ecology) and our dependence on these unmanaged systems is largely unknown. The response of these systems to climate change may be drastic and unpredictable (e.g. loss of the boreal forest, changes in lake dynamics). Projections of global warming coincide with the period of general adjustment as society tries to move toward sustainable use of natural resources. In this situation one cannot be confident that adaptation to climate change will always be easy.

6. MANAGING CHANGE

Better adaptation to climate variability and change in water resources requires strategies that anticipate variability and uncertainty and accommodate them. Rather than trying to isolate society from the effects of change and variability, a better objective may be to prevent surprise and catastrophe. Adaptation measures under the categories of "change use" and "share loss" (Table 5.1) are examples of how this approach can be adopted.

Adaptation requires the ongoing observation and interpretation of climate, hydrology and related environmental processes. This is an extension of the monitoring that is currently conducted as part of managing water resources systems. Emphasis should be given to finding ways to monitor for the onset of climate change and to modifying techniques of hydrologic analysis so as not to give too much weight to the past in anticipating future climate. Water resources managers should assess the vulnerability of existing and planned systems to climate change and develop criteria for deciding how and when to modify each system to reduce its vulnerability. Finally, we should continue to improve our understanding of the fundamental processes controlling climate and hydrology.

Adaptation can be defined as bringing ourselves into harmony with changed circumstances. The traditional view of climate as variable but unchanging is giving way to the realization that climate is changeable and is changing. The traditional view of water as an unlimited, essentially free resource is increasingly questioned as society confronts the need for sustainable development that recognizes on constraints on the resource. These changes define the fundamental challenges for adaptation in water resources.

7. ACKNOWLEDGEMENTS

This study was supported in part by a contract from the Climate Adaptation Branch of the Atmospheric Environment Service, Department of the Environment. The final report was improved significantly as the result of comments on a preliminary draft by R. Bocking, S. Kerr, M. Sanderson, M. Slivitsky, P. Sly and D. Thompson (Fellows of the Rawson Academy); I. Burton and A. Saulesleja (Atmospheric Environment Service); and external reviewers A. Banga and A. Kassem.

8. REFERENCES

1. Cohen, S.J. 1986. Impacts of CO_2-induced climatic change on water resources in the Great Lakes basin. *Climatic Change* 8:135-153.

2. Cohen, S.J. 1991. Possible impacts of climatic warming scenarios on water resources in the Saskatchewan River sub-basin Canada. *Climatic Change* 19:291-317.

3. Gleick, P.H. 1990. Vulnerability of water resource systems. pp 223-240 in P.E. Waggoner (ed) *Climate Change and U.S. Water Resources.* John Wiley and Sons, New York.

4. Haas, J. and T.J. Marta, 1988. Assessing the effect of climate change on the operation of a water supply reservoir. Inland Waters Directorate, Environment Canada (unpublished manuscript).

5. Hartmann, H.C. 1990. Climate Change Impacts on Great Lakes Levels and Flows: Energy and Transportation Implications. pp 239-246. *In*: G. Wall and M. Sanderson (ed) *Climate Change : Implications for Water and Ecological Resources.* Department of Geography Publication Series, Occasional Paper No. 11, University of Waterloo, Waterloo, Ontario.

6. Hengeveld, H. 1991. Understanding Atmospheric Change. SOE Report 91-2, Environment Canada, Ottawa, Ontario.

7. Hess, P.J. 1986. Ground Water Use in Canada, 1981. NHRI Paper No. 28, IWD Technical Bulletin No. 140, Inland Waters Directorate, Ottawa, Ontario.

8. Holling, C.S. 1978. *Adaptive Environmental Assessment and Management.* John Wiley and Sons, Chichester.

9. Houghton, J.T., G.J. Jenkins and J.J. Ephraums. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge University Press. Cambridge.

10. Kates, R.W. 1985. The Interaction of Climate and Society. pp 3-36 in R.W. Kates, J.H. Ausubel, and M. Berberian (eds) *Climate Impact Assessment.* John Wiley and Sons, Chichester.

11. Klemes, V. 1985.*Sensitivity of Water Resource Systems to Climate Variations.* World Meteorological Organization, WCP-98.

12. Mandelbrot, B.B. 1977.*Fractal Geometry of Nature.* W.H. Freeman andCo., New York.

13. Matalas, N.C. and M.B. Fiering 1977. Water resource systems planning. pp 999-110 in: *Climate Climatic Change and Water Supply.* National Academy of Science, Washington, DC.

14. Morin, G.M. and M. Slivitsky, 1992. Impacts de changements climatiques sur le regime hydrologique: Le cas de la rivière Moisie.Revue des Sciences de l'Eau 5:179-195.

15. National Academy of Science, 1991. Policy Implications of Greenhouse Warming: Report of the Adaptation Panel. National Academy Press, Washington, D.C. (prepublication manuscript).

16. Prowse, T.D. 1990. Northern Hydrology: An Overview. pp 1-36 in T.D. Prowse and C.S.L. Ommanney (eds) *Northern Hydrology: Canadian Perspectives.* NHRI Science Report No. 1, National Hydrology Research Institute, Saskatoon, Saskatchewan.

17. Riebsame, W.E. 1988. Adjusting water resources management to climate change. *Climatic Change* 13:69-97.

18. Ripley, E.A. 1987. Climatic Change and the Hydrological Regime. pp 137-178, *In* M.C. Healey and R.R. Wallace (ed) *Canadian Aquatic Resources.* Department of Fisheries and Oceans, Ottawa.

19. Rogers, P.P. and M.B. Fiering, 1990. From flow to storage. pp 207-222 in P.E. Waggoner (ed) Climate Change and *U.S. Water Resources.* John Wiley and Sons, New York.

20. Sanderson, M. 1987. Implications of Climatic Change for Navigation and Power Generation in the Great Lakes. *Climate Change Digest* 87-03, Atmospheric Environment Service, Environment Canada.

21. Sanderson M. and J. Smith. 1990. Climate Change and Water in the Grand River Basin, Ontario. pp 243-261. *In*: Proceedings of 43rd Conference of the Canadian Water Resources Association, Penticton, B.C.

22. Saulesleja, A. 1989. Possible Impacts of Climate Change in Eastern Canada. pp 21-22. *In*: R.G. Lawford and T.J. Marta (ed), Proceedings of a Workshop on Climate Change and Water Resources. Technical Workshop Series No. 9, National Hydrology Research Centre, Saskatoon, Saskatchewan.

23. Singh, B. 1988. The Implications of Climatic Change for Natural Resources in Quebec. *Climate Change Digest* 88-08, Atmospheric Environment Service.

24. Smith, J.P. and D. Tirpac, 1989.The Potential Effects of Global Climate Change on the United States. Hemisphere Publishing Corporation, New York.

25. Somerville, R.C.J. 1987.The predictability of weather and climate. *Climatic Change* 11:239-246.

26. Tate, D.M. 1990. Water Demand Management in Canada: A State-of-the-Art Review. Social Science Series No. 23, Inland Waters Directorate, Environment Canada, 52 pp.

27. WCED 1987. *Our Common Future.* Oxford University Press, London.

28. WMO 1987. *Water Resources and Climate Change: Sensitivity of Water - Resource Systems to Climate Change and Variability.* WorldMeteorological Office WCAP-4, WMO/TD-No. 247.

29. Zaltsberg, E. 1990. Potential changes in mean annual runoff from asmall watershed in Manitoba due to possible climate changes. *Canadian Water Resources Journal* 15:333-344.