CCME

Canadian Council of Ministers of the Environment

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SELECTED TOOLS TO EVALUATE WATER MONITORING NETWORKS FOR CLIMATE CHANGE ADAPTATION

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EXECUTIVE SUMMARY

The impacts of a changing climate are evident in every region of Canada. Planned adaptation to climate change (the result of deliberate policy decisions based on an awareness of changing conditions) requires decision-makers to understand the degree to which a system is susceptible to and able to cope with adverse effects of climate change.

Governments and water managers can use existing water monitoring networks to gather information needed to plan for and assess possible adaptations to a changing climate. However, because of resource constraints, it is usually not possible for jurisdictions to enhance all monitoring networks in all watersheds to provide information for assessing and adapting to climate change impacts.

Selected Tools to Evaluate Water Monitoring Networks for Climate Change Adaptation is a reference document for non-specialist water managers and climate change adaptation planners. The document was developed to help Canadian federal, provincial and territorial governments determine the suitability of their water monitoring networks to provide the data needed to plan for and to adapt to a changing climate. It describes proven and practical ways for jurisdictions to set priorities for water monitoring networks for climate change adaptation, and then evaluate the ability of these networks to provide the data needed to support climate change adaptation needs. However as the impacts of climate change vary by location, the priorities and evaluations will, by necessity, be jurisdiction- and region-specific. Prioritisation and evaluation will help jurisdictions decide whether (and how) to add or reduce stations, add hydrologic parameters, or change the frequency and timing of sampling and ultimately better support climate change adaptation planning.

Establishing Priorities: Setting priorities for water monitoring networks for climate change adaption can be done in a number of ways, ranging from qualitative approaches, such as workshops, to rigorous quantitative analyses or modelling. In a review of possible methods for setting priorities for water monitoring networks to support climate change adaptation, three methods were identified as requiring only a limited amount of data that are readily available, have the greatest flexibility in terms of scale of applicability and do not require a high level of expertise:

1) Basic Valuation Methods for Ecosystem Services
2) Ombrothermic Analysis
3) Water Resources Vulnerability Indicators Analysis

Appendix A of the document describes these three methods for setting priorities for water monitoring networks for climate change adaptation.

Evaluating Existing Monitoring Networks: Evaluating water monitoring networks for climate change adaptation considers the capacity and suitability of existing monitoring networks to provide the data required for a jurisdiction's climate change adaptation management objectives. A review identified three evaluation methods based on the following attributes: applicability at

different scales; relatively moderate expertise and data requirements; and ability to produce results that are commensurate with the monitoring objectives in terms of scope and level of detail. The three methods are:

1) Audit Approach
2) Monte Carlo Network Degradation Approach
3) Multivariate Methods

Appendix B of the document describes these three methods for evaluating existing water monitoring networks for climate change adaptation information needs.

Appendices A and B provide a detailed description of each of the six methods, background information on the concepts and terms used in the method, and notes on the resources required and on the method's applicability and limitations. Illustrated examples from studies that have used the method are included as well as references to additional information.

Appendix C of the document contains a glossary, information sources and a subject index. The information sources are presented as an annotated list which is organised thematically.

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PREFACE

The Canadian Council of Ministers of the Environment (CCME) is the major intergovernmental forum in Canada for discussion and joint action on environmental issues of national concern. The 14 member governments work as partners in developing nationally consistent environmental standards and practices.

This document is intended to assist water managers and decision-makers as they evaluate their water monitoring networks for climate change adaptation. The methods described can help decision-makers identify current and future investment needs for water monitoring while maximizing limited resources. In this way, the document can be used across Canada's jurisdictions in the on-going effort to conduct the water monitoring needed for climate change adaptation.

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1. INTRODUCTION

For more than two decades governments across Canada and around the globe have engaged in actions to understand the phenomenon of climate change and mitigate its effects. More recently, understanding that climate change will continue for many decades regardless of the success of efforts to reduce greenhouse gas emissions, governments have also begun to address climate change adaptation.

Adaptation to climate change has been defined as “making adjustments in our decisions, activities and thinking because of observed or expected changes in climate, in order to moderate harm or take advantage of new opportunities”.[1] Changes in temperature regimes and the patterns of precipitation from climate change may lead to reduced snow cover, shrunken glaciers, degraded ground ice and permafrost, reduced ice cover on rivers and lakes, changes in levels and flows of streams and rivers and other impacts. These changes have dramatic effects on Canada’s hydrologic systems and on the ecosystems and human settlements they sustain. Adapting to these changes means first of all, observing changes to the hydrologic systems, and then implementing adaptation strategies to reduce the risks to ecosystems, communities and the economy.

This document is about improving our ability to adapt to climate change impacts on our water resources. A key tool for this is our water monitoring networks – the thousands of stations, sites and surveys across the country that are used to measure parameters such as precipitation, snowpack, stream flows, water levels, water quality, and ground and water temperature. There are scores of water monitoring networks in Canada, mainly hydrologic and climatologic networks, some of which have been in place for decades. Few if any of these, however, were designed primarily to monitor the impacts of climate change, or to help us in adapting to those impacts.

This document tackles the question, “How can we adjust and refine our water monitoring networks so that we can better support climate change adaptation planning, and therefore reduce the risks associated with climate change impacts?”

1.1 PURPOSE OF THE DOCUMENT

Selected Tools to Evaluate Water Monitoring Networks for Climate Change Adaptation is intended to be a reference document for non-specialist water managers and climate change adaptation planners. The document was developed to help Canadian provinces and territories determine the suitability of their water monitoring networks to provide the data needed to plan for and to develop possible adaptations to a changing climate.

The document is intended to provide the reader with accessible and clear information on:

- the likely impacts of climate change on Canada’s water resources
- an overview of climate change adaptation

- the role and value of water monitoring networks in climate change adaptation
- one approach to climate change adaptation planning
- methods that can be used to help set priorities for water monitoring for climate change adaptation
- methods that can be used to evaluate the capacity of existing monitoring networks to provide the data needed for climate change adaptation
- information sources that may be of use.

The document is intended to be useful in all Canada's provinces and territories. Accordingly it draws from a variety of perspectives and respects the diversity found across the country. This document is not a comprehensive compilation of all methods that can be used to prioritize or evaluate water monitoring networks. It is recognised that to meet the challenges posed by climate change, new methodologies to address issues such as integrated water monitoring will have to be developed.

The integration of water monitoring at a single site to include water quantity and quality and meteorological parameters will lead to an understanding of the relationships between the various components of the hydrologic cycle. Examples include linkages between water quality and quantity, groundwater – surface water interactions, and impacts on ecosystems. In addition, monitoring of land use changes would be helpful in the assessment of any changes or trends of the monitoring data.

There is also a linkage between water monitoring for climate change adaptation and for climate change detection. The detection of climate change impacts on water resources can occur in undisturbed or undeveloped areas where trends can be more easily attributed to climate change. The magnitude and direction of these trends are important for the development of climate change adaptation planning.

1.2 DEFINITIONS

Climate Change

There are several definitions for 'climate change'. In this document, we use the term 'climate change' to refer to any change in climate over time, whether it is the product of natural factors (i.e., is due to climate variability), whether it is due to human activity or whether it is due to both. This definition is the same adopted by Natural Resources Canada (NRCan) in *From Impacts to Adaptation: Canada in a Changing Climate,*[2] the national-scale assessment of the current and future risks and opportunities that climate change presents and that used by the Intergovernmental Panel on Climate Change (IPCC). The definition used in this document differs from that used in the United Nations Framework Convention on Climate Change, which restricts the term to climate changes that can be directly or indirectly related to human activity and are additional to natural climate variability.[3] Natural climate variability refers to natural changes in climate that fall within the normal range of extremes for a particular region.

Water Monitoring Networks

Given Canada's size and its diversity of landscapes, ecoregions and resources, water monitoring networks may need to address a broad range of water issues. Monitoring is carried out for fresh and saltwater, surface and groundwater quality and quantity, coastal zones, riverine systems, snow covered areas, frozen tundra and permafrost, glaciers and lakes.

For the purposes of this document, it is accepted that water monitoring networks – while primarily focusing on hydrologic and climatologic parameters – may address a wider range of parameters. Depending on the region and the adaptation issues, monitoring parameters could include:

- surface water flows, levels and quality
- groundwater levels and quality
- lake and river dynamics
- ocean dynamics and levels
- coastal zone impacts
- snow coverage
- ice coverage
- soil moisture
- air temperature
- ground temperature and permafrost
- soil moisture
- precipitation.

The monitoring of parts of the cryosphere – sea ice, snow caps, glaciers, permafrost, ice caps and ice sheets – is beyond the scope of this document.

1.3 ORGANISATION OF THE DOCUMENT

The document is organised to provide:

1) a broad overview and examples of the impacts of climate change on Canada's water resources
2) an explanation of what is meant by climate change adaptation and adaptation strategies
3) a description of the role and value of water monitoring in climate change adaptation
4) an outline of the overall process for climate change adaptation planning and how the priority setting and evaluation methods described in the document fit into this process, and
5) overviews of priority-setting and evaluation methods for water monitoring networks. The final section presents conclusions and recommendations for further actions.

Three appendices provide supporting information:

Appendix A describes three methods that can be used to set priorities for water monitoring networks for climate change adaptation. A summary is provided for each method, along with a detailed description of the method, background information on the concepts and terms used in the method, and notes on the resources required and on the method's applicability and limitations. Illustrated examples from studies that have used the method are included as well as references to additional information.

Appendix B describes three methods that can be used to evaluate how effectively existing water monitoring networks address climate change adaptation. Each method section provides the same type of information as outlined above for the Appendix A sections.

Appendix C contains a glossary, an annotated list of information sources and descriptions of other methods.

2. THE IMPACTS OF CLIMATE CHANGE ON CANADA'S WATER RESOURCES

> *Water is the primary medium through which climate change influences Earth's ecosystem and thus the livelihood and well-being of societies. Higher temperatures and changes in extreme weather conditions are projected to affect availability and distribution of rainfall, snowmelt, river flows and groundwater, and further deteriorate water quality.*
>
> *UN Water Policy Brief 2010* [4]

In the future, climate change will exacerbate many current climate risks. It will also present new risks and new opportunities, and will have significant implications for Canadian communities, infrastructure and ecosystems. As noted in the 2007 NRCan report, *From Impacts to Adaptation: Canada in a Changing Climate*, the impacts of changing climate are already evident in every region of Canada.[5] The impacts of recent extreme weather events including those of summer 2011 – tropical storms on the east coast, a July heat wave in Montréal, heavy rains and floods in Alberta and Saskatchewan in contrast to the droughts of 2009, and forest fires in Québec and British Columbia – highlight the potential exposure of Canadian communities and infrastructure to climate change. The editor of *Degrees of Change – A summary of the impacts of climate change expected in Canada over the 21st century* cautioned that "it would be naive to suggest that any such specific event was directly caused by climate change but wise to be concerned that climate change has set the stage for it".[6]

Climate scientists predict widespread impacts on water resources across Canada as climate change brings increasing temperatures, changes in patterns of precipitation and changing moisture levels. For ice, snow and sea conditions the impacts include: a decline in the extent of summer Arctic sea ice; earlier spring snow melt in much of Canada; and shrinking of western mountain glaciers. In western Canada, changes in runoff and stream flow will occur due to variations in snowpack accumulations and melting mountain glaciers. In the prairies, risk of desertification will increase[7], as will the frequency of droughts. In northern and eastern Canada runoff will increase. In some regions of the country, water quality will be compromised due to the reduced quantity of water.[8]

Of the long list of potential climate change impacts identified for Canada's water resources, climate change experts have been able to identify three major sets of impacts with a high degree of confidence. Those impacts are:

- Increased water scarcity, particularly in the summer months, is expected to affect the prairies, southern Ontario, Québec and Nova Scotia.
- Increased frequency of flooding events is expected to affect most provinces due to the impacts of rising sea levels, an increased frequency of ice jam floods, extreme weather events, and rain-on-snow events, and increased winter precipitation.

- Increased ground temperature will result in a wide range of impacts in northern areas including the melting of ground ice that currently stabilizes natural and built structures and the release of substances retained in ground ice such as methane gas.

The majority of climate change impacts on water resources that have been identified are related to changes in the quantity of water. Often in climate change impact assessments changes in water quality must be related to changes in water quantity. For example water quality may become degraded due to reduced flows or to greater loading because of increased surface runoff due to more frequent and intense storms.

Although the methods in the document focus on water quantity, there are methods that can address water quality monitoring. The prioritisation method that can address water quality is the Water Resources Vulnerability Indicators Analysis (Section 5.3). The network evaluation method that can address water quality is the Audit Approach (Section 6.1).

Examples of climate change impacts on the water resources within Canada's regions and 13 jurisdictions are noted in Table 1.1. These examples are sourced from recent national-scale studies of the climate change impacts, including:

- *From Impacts to Adaptation: Canada in a Changing Climate 2007* [9] and the

- *Degrees of Change – A summary of the impacts of climate change expected in Canada over the 21st century*.[10]

Table 1.1: Predicted and Existing Climate Change Impacts in Canada

LOCATION	IMPACTS
Atlantic Canada	• More storm events, increasing storm intensity, rising sea level, and more coastal erosion and flooding are predicted. This will affect coastal communities, their infrastructure and industries. • Variations in precipitation, seasonal and yearly, combined with higher evapotranspiration that will induce drier summer conditions are predicted, especially in the maritimes. • Increased stream flows in Labrador are predicted but a decrease through the rest of Atlantic Canada. • Increasing pressures on water resources are predicted as conditions shift and demands change in response to both climatic and non-climatic factors.

LOCATION	IMPACTS
New Brunswick	• During the 21st century the New Brunswick coast could experience a sea level rise in the order of 50 to 70 cm which will accelerate coastal erosion. In southern New Brunswick reduced or no ice cover will also result in an increase in coastal erosion. • Warmer water temperatures are expected in the freshwater and marine environments. • Coastal erosion accelerated by rising sea levels has already occurred in eastern New Brunswick, parts of which are especially susceptible to storm surges. Significantly warmer water temperatures have already been recorded in some rivers, such as the Miramichi.
Nova Scotia	• Sea level rise is expected to accelerate coastal erosion. Other potential impacts include earlier snowmelt, changes in freeze-up and break-up dates for water bodies, changes in temporal precipitation patterns and increases salt water intrusion. • Sea level rise is already evident in Nova Scotia. Research scientists have found that sea water levels in Halifax have risen approximately 0.3 m in the past 100 years.[11] Relative sea level along the east coast is affected both by rising water and by coastal land mass sinking due to changes triggered by isostatic rebound (post glaciation). Coastal erosion accelerated by these rising sea-levels has occurred along the southern coast of Nova Scotia.
Newfoundland and Labrador	• Key areas of concern relating to climate change include water quality, flows, ice stability and sea level rise; more frequent flooding in Newfoundland; greater frequency of storms; reduced river ice thickness; later freeze up date; higher frequency of ice jam flooding, and increased surface water temperature. • Some climate change models predict some parts of the province will become cooler for a period of time, as a result of melting snow and ice migrating from the north.
Prince Edward Island	• The anticipated sea level rise poses a concern for the island's two larger cities, Charlottetown and Summerside, which are coastal cities located at relatively low elevations. Reduced sea ice cover will also result in enhanced coastal erosion in northern and eastern PEI. • Prince Edward Island relies almost entirely on groundwater for its

LOCATION	IMPACTS
	freshwater water supply. Reductions in the water tables would result from decreased influx of seasonal precipitation, due to a combination of reduced summer rainfall and enhanced surface runoff of winter rain. The increased potential of salt water intrusion is of concern. • Accelerated coastal erosion is already evident along the island's northern coast.
Québec	• Sea level rise could affect coastal areas in the province where groundwater is the main source of drinking water (e.g. Iles-de-la-Madeleine). With this sea level rise, an increase in shoreline erosion is expected in Québec's maritime region along the Gulf of St. Lawrence and the St. Lawrence River estuary. • An increase in the frequency and intensity or duration of extreme weather conditions is expected to occur in southern Québec. Also expected are earlier, and possibly reduced, spring peak flows and more frequent and sudden summer and fall peak flow events. • Other anticipated impacts for the province are: increased seasonal precipitation amounts, coupled with drier periods; increased peak summer and fall stream flow and more severe low-water-level periods in the summer and longer periods of low summer stream flow; increased snow precipitation in the north of the province and a decreased snowpack where winter is milder.
Ontario	• Water shortages in southern regions of the province are projected to become more frequent as summer temperatures and evaporation rates increase. • Other significant impacts include: shifting precipitation patterns (frequency and intensity); more intense precipitation events that will take place at more regular frequencies; earlier and decreased magnitude of the spring freshet (as a result of increased frequency of freeze-thaw events); decreased soil moisture content; and increased evaporation and evapotranspiration. • Water shortages have already occurred in southern regions of the Ontario.
Prairies	• Increases in water scarcity and particularly water scarcity in the summer months, represent the most serious challenges that the prairies are expected to face as a result of climate change. Both more frequent

LOCATION	IMPACTS
	droughts and an increased frequency of severe floods are projected. • Stressed aquatic habitats will affect prairie ecosystems.
Manitoba	• Climate change studies predict the following potential impacts in Manitoba: earlier lake and river break-up date; various changes in mean annual, winter, summer and fall precipitation totals; changes in annual stream flow; and earlier spring peak flow.
Saskatchewan	• As with the other prairie provinces, the most challenging climate change impact facing Saskatchewan is expected to be water scarcity in the summer months. Most climate change models agree with predictions of increased annual precipitation, increased winter and spring precipitation and decreased summer precipitation. • Earlier spring runoff is already being experienced and can be considered, with certainty, to be a climate change impact that is being experienced and will be in the future.
Alberta	• Anticipated changes in the climate of Alberta include declining/retreating glaciers; increased temperature; increased variability in temperature and precipitation; lower groundwater table and recharge; reduced stream flows and lake levels; and decreased summer precipitation. An increase in winter precipitation is also anticipated, with a higher fraction of precipitation falling as rain, declining winter snowpack, earlier snowmelt and spring freshet, decreased summer moisture and increased evapotranspiration, and decreased runoff in the plains.
British Columbia	• Many regions and sectors of British Columbia are expected to experience increasing water shortages and increasing competition among water uses, (for example, among hydroelectricity generation, irrigation, community supplies, recreation and in-stream flow needs). More frequent and sustained droughts are expected. • Increased sea level and increased storm intensity, frequency and/or severity of storm events are considered to be among the most significant impacts anticipated. Extreme weather and related natural hazards will continue to impact critical infrastructure, affecting communities, industries and the environment. • The cryosphere – glaciers, permafrost, ice and snow – is already changing rapidly, but there is little understanding of how it is changing.

LOCATION	IMPACTS
	As in Alberta, glacier melting is cited as an underlying factor in many of the anticipated climate change impacts. Increased runoff coupled with increased precipitation and a higher fraction of precipitation falling as rain could result in increased floods and pose flood protection challenges in this province. Rain precipitation is known to maximize energy transfer to the snow thus leading to faster snow melt and the increased runoff and stream flows.
Northern Canada	• The timing and magnitude of precipitation, stream flow and runoff are expected to change north of the 60th parallel. • The projected climate-induced changes in permafrost, sea ice, lake ice and snow cover have large implications for infrastructure maintenance and design.
Northwest Territories	• Climate change impacts on water resources are expected to be regionally and seasonally variable. In particular the magnitude and timing of precipitation, stream flow and runoff are expected to change north of 60th parallel. • As is the case for the other two territories, the Northwest Territories is currently experiencing very rapidly changing climate. The territories have been experiencing average annual temperature increases varying between +2 and +3°C during the last 70 years.12 In addition to increases in average annual temperature, the most significant impacts that have been observed are: increased precipitation, earlier spring melt, reduced sea ice thickness and area, later freeze-up date, increased storm surge elevation and increased spring runoff.
Nunavut	• Nunavut is expected to continue to experience severe and rapid warming leading to a number of significant impacts on its water resources. These impacts include: later freeze-up and earlier break-up of lake, river and sea surfaces; increased mean annual precipitation; increased annual runoff; and increased evaporation and evapotranspiration.
Yukon	• Projected impacts include: increased peak flows in glacial areas; decreased peak flows in permafrost areas; greater frequency of ice jams; and earlier ice break-ups. • These projected impacts are already being observed. The most significant impact of climate change noted by a local expert is that winter low flows are increasing in magnitude throughout the territory as a result of permafrost warming and thawing.

3. AN OVERVIEW OF CLIMATE CHANGE ADAPTATION

> *"We have options, but the past is not one of them."*
>
> *From Impacts to Adaptation: Canada in a Changing Climate* [13]

As noted earlier in this document, human adaptation to climate change has been defined as "making adjustments in our decisions, activities and thinking because of observed or expected changes in climate, in order to moderate harm or take advantage of new opportunities".[14] (Natural systems can also adapt, such as when the range of a species expands as a consequence of warming temperatures; however that is not the focus of this document).

The IPCC has categorised human adaptation to climate change in three ways:

- **Anticipatory adaptation** is proactive adaptation that takes place before impacts of climate change are observed. An example of this would be municipalities encouraging or requiring increased water efficiency before drought is experienced.

- **Autonomous (or spontaneous) adaptation** happens without our conscious response to climatic stimuli. It is triggered by ecological changes in natural systems and by market or welfare changes in human systems. An example of this is a farmer changing the timing of his planting or the selection of crops based on changes in the pattern of precipitation.

- **Planned adaptation** is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state. An example of this would be the development of new standards for the sizing of stormwater management systems, given the likelihood of increased stream flows in a region.[15]

As climate change takes place over the coming decades, governments, communities, businesses and individuals will need to adapt to changing temperature and precipitation regimes, and the cascade of impacts that arise from these changes. The nature and intensity of these impacts will differ in nature and magnitude in different regions across the country. Planned adaptation requires decision-makers to understand the degree to which a system, either human or natural, is susceptible to and able to cope with adverse effects of climate change including climate variability and extremes. The degree of this susceptibility is referred to as the vulnerability of a system to climate change. Vulnerability is a function of **exposure** to climate change effects, the system's **sensitivity** and its **adaptive capacity**.

Vulnerability

The concept of vulnerability can be useful in setting priorities for water monitoring networks. Managers may assign a higher monitoring priority to areas or systems that are more vulnerable to the adverse impacts of climate change. Levels of exposure and sensitivity to climate related changes, as well as limitations in adaptive capacity, can make some systems and populations **vulnerable** to impacts of climate change.

It is not the purpose of this document to provide guidance on conducting vulnerability assessments. It is recognised however, that vulnerability assessment can provide vulnerable areas where the evaluation of water monitoring networks for climate change can be conducted.

Exposure, one of the components of vulnerability, can also be useful in setting priorities for climate change adaptation. This can be done by developing region-specific projections of future exposures to key climate change impacts. Such projections may suggest different spatial or temporal patterns of exposure than are found today. Predicting future exposure to climate change impacts requires downscaling global climate models to a regional scale. There is a high level of uncertainty, however, associated with this. For southern Ontario, for example, while there is confidence that overall air temperatures will rise with climate change, we do not know whether the future will be hotter and drier or hotter and wetter. It will take time to improve regional projections of climate change impacts.

Sensitivity, another component of vulnerability, is the degree to which a system may be affected, either adversely or beneficially, by climate variability or change. The effects of climate change can be direct, such as a change in crop yield in response to a change in the mean, range or variability of temperature. The effects can also be indirect such as damages that are caused by an increased frequency of coastal flooding due to sea-level rise.[16] The concept of sensitivity is useful in setting priorities for water monitoring. For example, river systems that are sensitive to climate change will have responses that are more likely to be detected by a monitoring network. The responses may be early warning indicators and may provide insights into an ecosystem's response to the climate changes. Detecting these responses can help inform adaptation and/or mitigation efforts.

Adaptive capacity is the ability of ecological or human systems to adapt to a changing environment. Coldwater fish communities, for example, have only a limited ability to adapt to increased stream temperatures; other more "generalist" species may have a greater capacity to adapt to warmer stream temperatures. The adaptive capacity of human systems is a function of having the right tools (information, technology, resources and planning capability) to meet the challenges ahead. Water monitoring networks that provide useful information for climate change adaptation increase our societal adaptive capacity.

Uncertainty

Because of the high level of uncertainty associated with regional climate change projections, some climate change experts suggest that projections of future conditions ought not to be the primary basis for making adaptation decisions. The projections can give us an idea of the consequences to water resources of climate change, but the probability of these consequences actually occurring is not known. Risk is defined as probability multiplied by consequence and although the assessment of risk does have a role to play in climate change adaptation, its application should depend on a defensible approach. The uncertainty of climate change projections is another reason why monitoring is so important.

The uncertainty about future regional impacts leads to the concept of “no regrets” initiatives. The “no regrets” approach to climate change adaptation promotes adaptation actions that have net benefits whether the “uncertain” climate change projections come to pass or not.[17] Examples of “no regrets” actions include the enhancement of monitoring networks to improve forecasting of extreme events such as floods and protecting or restoring systems that are already at risk. “No regrets” initiatives can be useful for decision-makers in the process of evaluating or enhancing water monitoring networks and for developing and implementing climate change adaptation strategies.

Communities and societies have a long record of adapting to the impacts of weather and climate through a range of practices that include water management. According to climate change researchers the number of adaptation opportunities for the water sector is vast.[18] For each of the many ways in which water is important, there exists a range of approaches for adapting to existing climate variability, as well as many options for adapting to anticipated climate changes.

In most cases adaptations to climate change have been implemented as part of consequence management, resource planning and initiatives linked to sustainable development (see Table 3.1). However climate change could bring consequences that are beyond the range of our past experience[19]. Are groundwater reserves decreasing? Is stream water quality being affected? Is flooding becoming more frequent or more intense? Are sea level rises causing salt intrusion in coastal aquifers? Is spring breakup happening sooner than twenty years ago? Effective adaptation planning will require a solid base of information such as that provided by water monitoring networks.

Dealing with adaptation in isolation from other water monitoring concerns is an option of the past. For the present and the future, climate change needs to be integrated or “mainstreamed” into on-going water monitoring planning, assessment and decision-making. “Mainstreaming” alone may not meet the challenge since it is not just a matter of integrating climate change adaptation into water monitoring, but also of using water monitoring to assist us in effectively planning for climate change adaptation.

Table 3.1: Selected examples of water related adaptation initiatives undertaken by individuals, community groups, industry and governments in Canada.[20]

ADAPTATION EXAMPLE
Individuals
• Homes and cottages are being built farther back from the coast.
Community groups and organisations

- Yukoners participated in the formation of their territory's Climate Change Action Plan. A key priority of the Action Plan is to enable effective adaptation to climate change in Yukon.
- Residents of Pointe-du-Chêne, NB organised an emergency shelter in response to increasing flooding risk, and lobbied elected officials for less vulnerable road access.
- A community group in Annapolis Royal NS undertook mapping of potential storm surges that has resulted in revision of emergency measures.

Industry

- Thermosyphons have been used in the construction of several major infrastructure projects in the North to induce artificial cooling of permafrost under warming conditions.
- Hydro Québec has modified its forecasts of electricity demands based on new climate scenarios.
- Some forestry companies have started using high-flotation tires on their vehicles to help navigate wet or washed-out conditions, allowing them to work in a wider range of weather conditions.

Governments

- In reconstructing a portion of the Yellowknife Highway in NWT, changes were made to the design and construction that would minimize future effects from permafrost degradation.
- In response to the effects of permafrost melt the NWT Housing Corporation (NWTHC) has repaired and replaced pile foundations damaged by ground movement or water accumulation under buildings. Where there are less stable ground conditions, the NWTHC now uses foundation systems that absorb the stress normally imposed on a building through ground movement.
- The municipality of Sept-Iles has regulated new residential construction along the shoreline to prevent damages due to shoreline erosion.
- Regional Municipality of Waterloo and the City of Guelph, ON have put in place water supply demand management programmes to make water use, storage, and distribution more efficient in anticipation of diminished water supply.
- Westbank, BC, has included climate change in the Trepanier Landscape Unit Water Management Plan.
- Water meters have been installed in the Southeast Kelowna Irrigation District and several

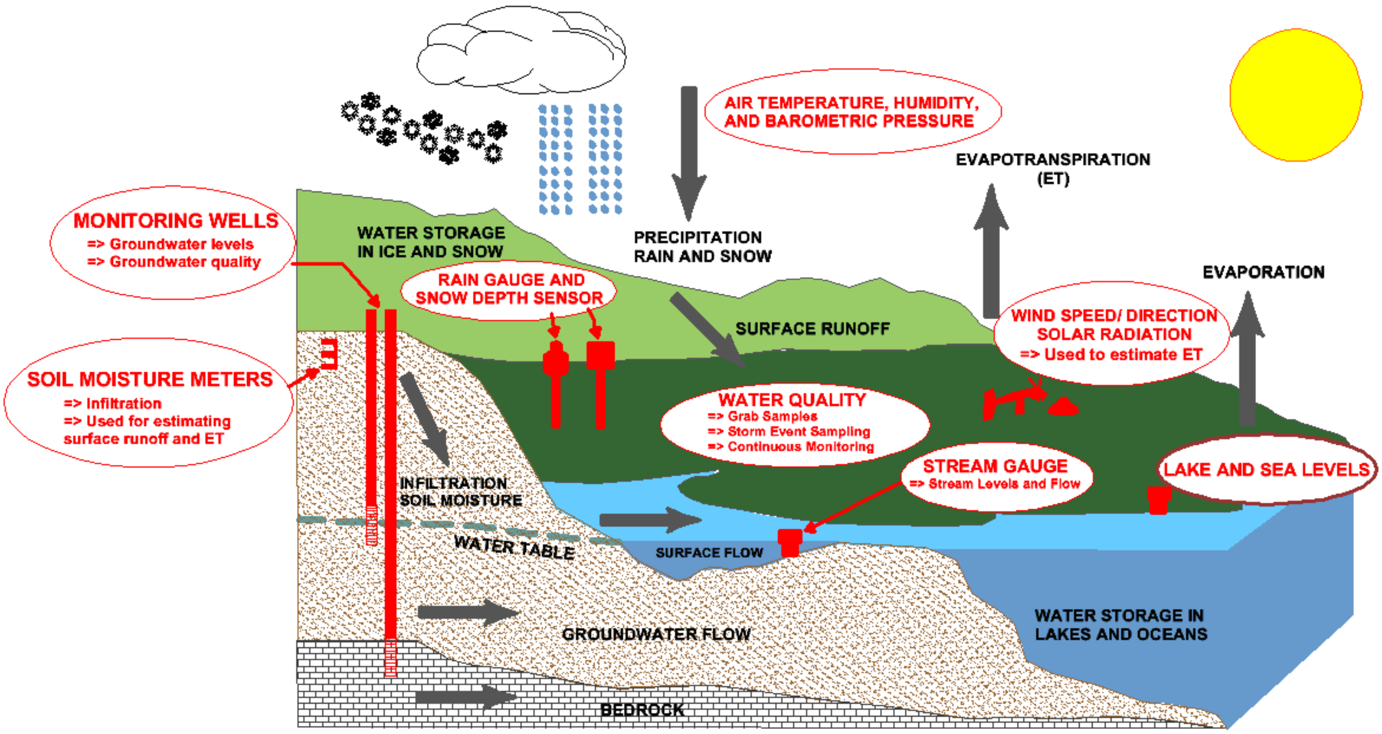
Canadian cities (e.g. Kelowna, BC; Sudbury, ON; and Moncton, NB) to reduce water consumption.

- Regina, SK has increased urban water conservation efforts.
- Greater Vancouver Regional District is considering the impact of smaller snowpack on city water supplies in planning storage capacity management and upgrades.
- New Brunswick's Coastal Areas Protection Policy establishes set-backs for permanent structures and could facilitate planned retreat.
- Halifax is creating a new green strategy for dealing with storm water via alternate landscaping patterns. The city has also formed a committee spanning police, fire and other municipal departments to plan how to keep core services operating using extreme weather events.
- NWT Department of Municipal and Community Affairs has conducted public infrastructure assessments in all 33 NWT communities for maintenance planning. The assessments provide baseline information on the state of Infrastructure which will enable measurements of the impacts of climate change over time.
- Alberta's Water for Life Strategy addresses climate change impacts in areas that are currently water-stressed.
- Construction of bridges at stream crossings along the Mackenzie Valley Winter Road was initiated ten years ago by NWT Department of Transportation because of the shorter length of the winter road season. Permanent bridges reduce the amount of time required to construct the winter road, protect stream crossings from early spring melt and extend the road’s operational season.
- Climate change and rising temperatures may provide new agricultural opportunities in Yukon. As part of the Yukon Government Climate Change Action Plan, local production and sale of agricultural products has been identified as a means to reduce food transportation costs and increase local sustainability for residents.

4. THE ROLE AND VALUE OF WATER MONITORING IN CLIMATE CHANGE ADAPTATION

Governments and water managers can use water monitoring networks to gather the information needed to plan for and assess possible adaptations to a changing climate. The nature and scale of monitoring programs will vary from region to region to reflect variations in ecosystems and climate conditions, differing management objectives, and preferred adaptation approaches. A list of the parameter types that could be monitored, depending on the region and the adaptation issues, is provided in section 1 of this document. Figure 4.1 illustrates the relationships between the water cycle and water monitoring networks.

Figure 4.1: Monitoring water and climate within the water cycle



While some aspects of water monitoring will be jurisdiction-specific, some monitoring needs are common across all Canadian jurisdictions. This is because monitoring for adaptation focuses on common water and resource issues such as:

- resource use and supply (including ground and surface water)

- consequence management (Is there sufficient data to assess flood risk, health risks from wastewater disposal, winter transportation safety, or loss of services provide by hydrologic systems?)

- the conservation of threatened or endangered species and the continued provision of ecosystem functionality.

Whatever the approach used to plan for climate change adaptation, having access to accurate, sufficient and relevant hydrological data is vital. We need monitoring data to reduce the uncertainties related to the hydrologic impacts of climate change and to calibrate and validate climate and hydrologic models. We need monitoring data to identify vulnerable water resource systems and for the "no regrets" approach to adaptation. We need monitoring as well for understanding the effectiveness of adaptation actions that are implemented.

For monitoring climate change and its impacts, water monitoring network data is required for the following important management activities:

- predictive modelling to establish initial and boundary conditions, calibrate and validate hydrologic models and develop models for downscaling climate change scenarios;

- ground-truthing to estimate accuracy and uncertainty of remote sensing data;

- risk assessment to describe recurrence intervals, design criteria, intensity-duration-frequency (IDF) curves, etc.;

- early detection to identify new trends and for explanatory purposes;

- early warning to protect against possible hydrologic events (i.e., monitoring stream flows upstream of flood-prone communities);

- trend assessment (e.g., water availability indicators);

- attribution to understand cause and effect (e.g., are decreased lake levels due to decreased precipitation, increased evapotranspiration or both?); and

- resource management to inventory assessments in a changing regime.

Also to be considered are specific needs for climate change adaptation planning:

- provide the data for the development of climate change adaptation plans;

- assess the effectiveness or impacts of implementing adaptation measures;

- provide data for improvement and calibration of climate – hydrology models.

Underlying the decision whether to monitor a particular hydrologic parameter (or set of parameters) for climate change adaptation is the question, "How critical are the potential impacts resulting from the changes in the value of a particular hydrologic parameter?"

To monitor the hydrologic impacts of climate change, Canadian jurisdictions can identify and prioritize both the parameters to be measured and the areas in which the measurement will take place. Because of resource constraints, it may not be possible to enhance all monitoring networks in all watersheds to provide information relating to climate change impacts. Decision-makers may choose to place a priority on monitoring in specific areas or watersheds that will be most vulnerable to climate change impacts.

An alternative approach is to ensure that monitoring takes place in representative types of watersheds within the jurisdiction. Still another approach might be to prioritize monitoring in areas where populations are greatest (and therefore sensitivity may be greatest) or to prioritize monitoring in key resource areas (such as cottage communities or agricultural areas). Possible methods for establishing priorities for water monitoring networks are introduced in section 5 of this document and covered in detail in Appendix A.

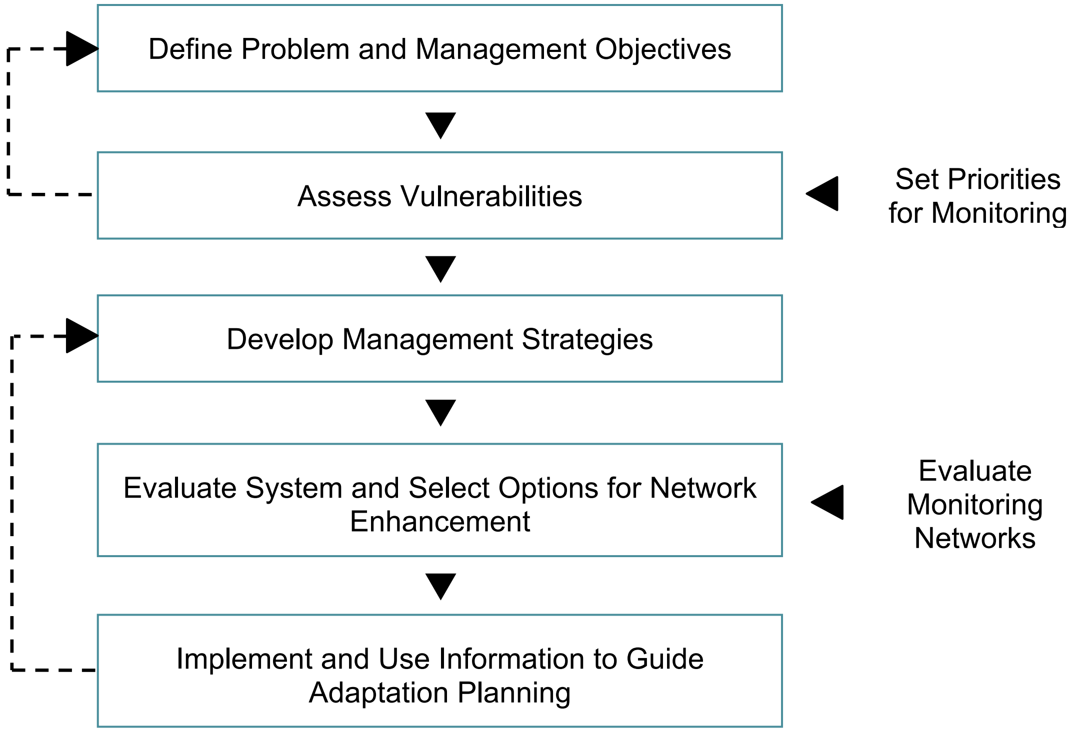
Once the priorities for water monitoring networks have been set, the next step is to evaluate existing water monitoring networks for climate change adaption. Possible ways of carrying out this evaluation are introduced in section 6 of the document and covered in detail in Appendix B.

First however, we consider the overall process used for climate adaptation planning and how prioritisation and evaluation of water monitoring networks might fit into the process.

4.1 INTEGRATING MONITORING NETWORK PRIORITISATION AND EVALUATION INTO A CLIMATE CHANGE ADAPTATION PLANNING PROCESS

This section of the document describes how prioritisation and evaluation of water monitoring networks might fit into a potential climate change adaptation planning process. Making decisions about climate change adaptation – deciding who needs to do what and when – is a complex undertaking and there is no one way to do it. One example of how to do this using a "structured decision-making process" is illustrated in Figure 4.2.

Figure 4.2: An Example of a Framework for Climate Change Adaptation Planning



The planning process can take place in a number of stages. It is often an iterative process, with potential “feedback” loops between stages. Here is a brief description of what these stages might contain.

Definition of the problem and management objectives: For decision-makers the first stage of adaptation planning involves defining the problem(s) and developing management objectives to address those problems. Adaptation planning decisions are driven not only by climate change impacts, but also by technical, management, and socioeconomic concerns. Adaptation planning could be part of a larger climate change adaptation strategy that draws on a wide range of information sources including projections from downscaled climate change models. Typically, this stage of the planning process involves on-going collaboration among scientists, managers, and decision makers, and incorporation of public and stakeholder concerns.

Assessment of current and future system vulnerabilities: This stage provides the rationale for setting priorities for adaptation planning. Managers can assess system vulnerabilities based on responses defined by historic data, current conditions, and/ or projected future vulnerabilities. As conditions change over time, regional priorities and management objectives may need to be adjusted (and the first stage repeated).

► **The prioritisation methods in described in Section 5 and Appendix A of the document can help inform this stage of the decision-making process**.

Development of management strategies: For any one system vulnerability, there are typically a number of different adaptation strategies or actions that could be taken to reduce the risk of adverse impacts. In an area that is vulnerable to increased riverine flooding, potential adaptation strategies could include removal of houses in the floodplain, construction of flood protection works, or the development of new building standards that lessen the risk associated with the flooding. In this stage of adaptation planning, potential strategies are evaluated against criteria such as cost, effectiveness and social impact. The result is a suite of management strategies that can be used to adapt to key climate change impacts and reduce vulnerability.

Evaluating system and selecting options for network enhancement: Once adaptation management strategies are adopted, managers may need to ensure that water monitoring networks will provide the data needed to detect change, monitor trends and evaluate the effectiveness of the adaptation strategies. Are the networks monitoring the right parameters, at the right density and frequency, using the right methodology and in the right places to support climate change adaptation? After evaluating existing water monitoring networks, managers in a jurisdiction may recommend adding parameters to be measured, increasing the frequency of measurement, adding new monitoring stations or re-locating some stations.

► **The results of water management evaluation methods such as those described in Section 6 and Appendix B of the document will help inform this stage of the decision-making process.**

Implement and use information to guide adaptation planning: The culmination of the adaptation planning process is the implementation of adaptation strategies or actions that are supported by a robust information system. Using the principles of adaptive management, implementation includes on-going monitoring, adjustment of management actions as monitoring information is fed into the process, and the periodic review of management objectives to ensure that they are still relevant.

5. SETTING PRIORITIES FOR MONITORING NETWORKS

Setting priorities for water monitoring for climate change adaptation begin with the identification of potential climate change impacts and the development of management objectives. What do we value? What are we trying to protect? In setting management objectives, jurisdictions may take into account the potential impacts in combination with a variety of factors including rarity of a particular ecosystem, representativeness of particular ecosystem types, vulnerability to climate change effects, the value of natural resources, the value of the ecosystem function or services provides by certain natural systems, the sensitivity of water resources to climate change impacts (e.g., alteration or loss), and/or the cost-benefits and probability of success of pursuing adaptation strategies in an area.

Setting priorities for water monitoring networks for climate change adaption can be done in a number of ways, ranging from qualitative approaches, such as workshops, to rigorous quantitative analyses or modelling. CCME reviewed possible methods for setting priorities for water monitoring networks to support climate change adaptation. The review examined methods that could be used at different scales and which would provide dependable and documentable outcomes. The applicability at different scales is important because Canadian provinces and territories have such a wide range of size, complexity, and availability of monitoring resources.

Three methods were identified as methods that require only a limited amount of data and use data that are readily available, have the greatest flexibility in terms of scale of applicability and do not require a high level of expertise. The three methods are:

1) Basic Valuation Methods for Ecosystem Services
2) Ombrothermic Analysis
3) Water Resources Vulnerability Indicators Analysis

All three of these methods are also able to produce results that are understandable to the public. They are briefly described here and in more detail in Appendix A. References for and brief descriptions of other prioritisation methods are provided in Appendix C.

5.1 BASIC VALUATION METHODS FOR ECOSYSTEM SERVICES

Ecosystem services are the goods and services that natural systems provide, such as nutrient cycling, water supply, waste assimilation and flood protection. The basic valuation method (BVM) for ecosystem services is used to differentiate areas, such as large watersheds or ecoregions, based on relative differences in the ecosystem services provided. BVM determines the value of the average types and amounts of services provided by a land use, such as a wetland, in a specific area (e.g., in the United States). In a process known as “benefits transfer”, these values are then applied to all similar land use types (wetlands in this case) in a different area (e.g., southern Québec or Alberta). The value of the ecosystem services provided by different land uses can be measured in terms of their spatial distribution and economic value ($ per hectare). For setting priorities for water monitoring networks, the relevant ecosystem services are those that are related to hydrologic systems.

In the basic valuation approach, land use cover is mapped in the region of interest. This is done using generally readily available land use cover data (wetlands, forests, grasslands, agricultural lands, barren grounds, developed lands, etc.). Then the ecosystem services of those land uses are evaluated and mapped. The resulting maps visually show the relative combined values of the hydrologic services provided and their spatial distribution. Knowing which areas provide which certain types of hydrologic services and their relative value can help set priorities for water monitoring networks for climate change adaptation.

A possible additional application for the results of the BVM is to use the economic values assigned to various land use types as weighting factors for other prioritisation methods such as the Water Resources Vulnerability Indicator Analysis. In such an application, a wetland area might be weighted more than a forest which might be weighted more than a cropland or pasture.

5.2 OMBROTHERMIC ANALYSIS

Water balance is one of the main environmental conditions that influence the vulnerability of a region to climate change. Ombrothermic analysis uses two indicators – precipitation (*ombro = rainfall*) and temperature (*thermic*) – to assess the spatial extent of vulnerability of a region to climate change. Ombrothermic analysis uses humidity/aridity indices and graphics to integrate temperature and precipitation data over time. Using readily available temperature and precipitation data, the method produces graphics and maps that can identify vulnerable areas that may be prone to humidity (excessive rainfall) or aridity (drought). Knowing if a region has such vulnerable areas and where these vulnerable areas are can help managers set priorities for water monitoring networks to address climate change adaptation. The ombrothermic method is often used when evaporation cannot be easily computed in the evaluation of water balance of an ecosystem.

Ombrothermic analysis can be done in two ways:

- Generation of ombrothermic diagrams for specific locations
- Mapping of vulnerability, as determined by the ombrothermic index which measures critical humidity (excessive rainfall) and aridity (drought) periods.

5.3 WATER RESOURCES VULNERABILITY INDICATORS ANALYSIS

Regional Water Resources Vulnerability Indicators Analysis (WRVIA) can be used to evaluate the vulnerability of regional water resources and water dependent resources to climate change impacts. The analysis uses indicators to assess key aspects of water supply and use (such as stream flow, evapotranspiration losses, water quality, water withdrawals and settlement in the floodplain) to identify watersheds where water uses are currently most vulnerable to increased stress and where current vulnerability could be exacerbated or relieved by changes in mean climate and extreme events. WRVIA is based on the concept that water resources that are currently stressed are more likely to be vulnerable to future climate change than those that are not currently stressed The identification of watersheds that are potentially vulnerable to the adverse impacts of climate change helps anticipate where climate change impacts might be greatest.

This relatively simple method uses available water resources data to produce maps in a GIS environment. The maps of watershed vulnerabilities can help set priorities for water monitoring networks to address climate change adaptation.

6. EVALUATING WATER MONITORING NETWORKS FOR CLIMATE CHANGE ADAPTATION

Evaluating water monitoring networks for climate change adaptation is essentially an evaluation of the capacity and suitability of the monitoring networks. Can the network or network(s) provide the required data? Is the data accurate, spatially and temporally representative, and relevant to the climate change adaptation management objectives and purposes established by the jurisdiction?

When evaluating monitoring networks to support climate change adaptation, it may be useful to note that:

- The maintenance of a dense network of stations does not necessarily improve the quality of information available for trend assessments, adaptation planning, extreme event projections, or for hydrologic or climate models.

- Arbitrary deletion of stations does not assure that the remaining locations are meaningfully sited in relation to other stations within an existing network.

- Long-term, consistently collected data is highly valuable, and critical for detection of long-term trends. This is vitally important given the need to account for climate change effects in the context of on-going water resource and adaptation planning.

CCME carried out a review of water monitoring network evaluation methods. The review focused on fixed installation monitoring networks and identified a range of evaluation options that ranged from fairly simple qualitative audits to sophisticated statistical or modelling methods. CCME's review identified three methods based on the following attributes: applicability at different scales; relatively moderate expertise and data requirements; and ability to produce results that are commensurate with the monitoring objectives in terms of scope and level of detail. The three methods are:

1) Audit Approach
2) Monte Carlo Network Degradation Approach
3) Multivariate Methods

The relative simplicity of these methods, particularly the first two methods, was a key reason for their selection. The three methods are described below in brief and in detail in Appendix B. References for and brief descriptions of other monitoring network evaluation methods are provided in Appendix C.

Where priorities have been set for monitoring for climate change adaptation, any of the above methods can be used to evaluate the adequacy of networks within high priority regions. If prioritisation has not been done, jurisdictions may consider applying the audit method as a first step in network evaluation. This is because the audit method can be used to identify under-sampled areas and stations which are providing inadequate data or data considered to be unrepresentative. Rectification of inadequate sampling at one or more monitoring stations may be completed based on these results.

If the audit results show there are systemic problems in the network(s), such as under-representation in some areas and/or redundancy in other areas, knowing which stations to eliminate and/or remove may require more analysis. In such cases, quantitative assessment can be applied to get the required information. For both climate and hydrological networks, the Network Degradation Analysis approach can be relatively easy to use and requires the least investment of time, resource, or expertise. This network degradation method will serve most purposes for evaluating the adequacy of existing network density in generally well sampled areas. However the network degradation method does not give direct inputs on optimal locations for gauges to be removed or added.

Multivariate analysis methods can be used to identify groups of stations with similar behaviour (i.e., stations that record similar data over time). They can also be used to identify regions of low representation (i.e., where there are fewer stations compared to the temporal and spatial variations in the data set) and regions with high representation and potentially redundant stations.

6.1 AUDIT APPROACH

The audit approach is a relatively simple, qualitative way to evaluate water monitoring networks for climate change adaption purposes. It incorporates expert knowledge of existing networks in a methodical and detailed review of existing and proposed stations against pre-set criteria. A number of network scenarios are then evaluated against their ability to meet overall network objectives and cost.

The audit method described in detail in Appendix B of the document was used in New Brunswick to evaluate and rank the stream flow gauging stations in the provincial hydrometric network in order to create a more cost-effective network.[21] The approach is easily transferable to evaluating water monitoring networks for climate change adaptation planning. To do this, criteria are developed for the evaluation. The criteria would reflect factors that are relevant to regional climate change adaptation priorities. These might include the "suitability" of the station site, representation of the regional hydrology, usefulness for estimation purposes (e.g., for ungauged sites), and servicing of client needs for climate change adaptation actions and strategies. Each station is then audited in a roundtable session that involves the operators and managers responsible for the networks and climate change specialists involved in water monitoring. Existing and proposed stations are scored against the evaluation criteria and ranked using the sum of points accumulated for each priority consideration. The results of the evaluation and ranking of the stations are used to construct alternate network scenarios and sets of network objectives for use in making network design decisions. A cost benefit analysis can be conducted by comparing the benefits of each scenario (total station audit points) and increase or decrease in operating costs that would be incurred by the implementation of the scenario.

6.2 NETWORK DEGRADATION ANALYSIS - MONTE CARLO

Network Degradation Analysis (NDA) is used to evaluate existing meteorological or hydrometric monitoring networks and to determine the network density required to meet a particular monitoring goal or goals. The NDA simulates a systematic decrease or "degradation" of a network's sampling station density and determines how well each successive degraded network performs compared to the full network. Monte Carlo sampling, the random selection of stations from the entire network of existing stations, is used to create the simulated degraded networks. The degraded networks created are subsets of the full network, with less spatial and/or temporal data densities than the full network.

This NDA method has been used in numerous applications. For the U.S. Climate Reference Network (CRN), the National Oceanic and Atmospheric Administration (NOAA) has used it to determine the spatial density and total number of monitoring stations required to improve the capacity to observe climate change and temporal variability across the U.S. The goal of the CRN is "to provide homogeneous observations of temperature and precipitation from benchmark stations that can be coupled with historical observations for adequate detection and attribution of climate change".[22] The analysis conducted for the CRN divided the 48 conterminous states into 115 grid cells and within each grid cell created hypothetical networks from representative subsamples of stations, selected by Monte Carlo sampling, from an existing higher-density baseline network. The adequate number of CRN stations was defined as the number of stations required to reproduce, within certain predetermined error limits, observed annual temperature and precipitation trends across the U.S. Although the study concentrated on a definition of climatic behaviour that emphasized trends, the researchers assert that their technique can be applied to other measures of climate behaviour.[23]

The NDA method has also been used in cost-benefit analysis of monitoring networks and in the determination of the relationship between station density and network performance.

This evaluation method assumes that the existing full monitoring network, or other sampling data, generally provides reasonable representation of the true values of the parameters measured. Although NDA can be used to evaluate the adequacy of existing network density in areas that are generally well sampled, it does not give direct inputs on optimal locations for gauges to be removed or added. To achieve this, a variance reduction/error minimization or modelling method may be required. These are more complex and the feasibility of using them would be considered on a case-by-case basis. (See Appendix C*:* Information Sources – Evaluation Methods: Variance Reduction/Information Gain Approaches, and Geostatistical Methods and Minimization of Error).

6.3 MULTIVARIATE METHODS

Multivariate analysis methods are statistical techniques that are used to assess the statistical relationship between variables. In the case of monitoring networks the variables could be meteorological and/or hydrometric parameters. Multivariate analyses can identify stations with similar behaviour (i.e., stations that record similar data over time). This similarity is referred to as the "homogeneity" of stations and is of interest in network rationalisation since data interpolation between stations is best done between homogenous stations. Multivariate analysis methods can also identify regions of low representation (fewer stations compared to temporal and spatial variations in data set) and regions with high representation and potentially redundant stations. Two multivariate approaches are briefly described here and in more detail in Appendix B:

1) **Principal Component Analysis (PCA):** This method identifies groups of stations that have similar spatial and temporal properties. For example, PCA would be able to identify within the same subwatershed homogeneous stations that measure statistically similar mean annual precipitation over time. The results of the analysis are expressed as correlation coefficients between the stations and principal components. The coefficients are presented in tables and graphs for ease of comparison. The PCA can also be used to identify relatively homogeneous and redundant stations. This method has been applied to precipitation data in the Appalachian Region of Québec in order to identify homogeneous stations and therefore redundant stations that could be closed.[24]

2) **Clustering-based Analysis (CBA):** This method identifies groups of stations that have similar spatial and temporal properties using cluster tree diagrams (or dendrograms). For example, the CBA method would be able to identify two homogeneous hydrometric stations located 5 km from each other on a river segment without incoming tributaries, which measure similar annual peak flow over time. CBA has been used to rationalise a stream flow monitoring network in and near the Pembina River basin in southern Manitoba. Although this method can be used to identify redundant stations, it does not differentiate between them. Accordingly external criteria are required to select the most representative station(s)). However, the CBA could be used in combination with other statistical methods, such as the variance reduction or error minimization methods, to identify the station(s) that provide the most information. The CBA method has been applied to stream flow data from the Pembina River watershed in the Manitoba, Canada – North Dakota, U.S., in a rationalisation process to reduce the number of hydrometric stations.[25]

While evaluating water monitoring networks it is important to recognise that some of the existing monitoring stations exist to address special needs or have long-term records which are important for both climate change detection and adaptation.

7. CONCLUSIONS AND NEXT STEPS

Experts generally agree on the nature of projected hydrologic impacts of climate change and that some of those impacts are already occurring and can be measured. Because it is generally understood that climate change will continue for many decades to come, regardless of the success of efforts to reduce greenhouse gas emissions, governments are addressing climate change adaptation. Adaptation to climate change means making adjustments in our decisions, activities and thinking because of observed or expected changes in climate in order to moderate harm or take advantage of new opportunities presented by impacts of the changing climate.

A key tool for climate change adaptation is our water monitoring networks – the thousands of stations, sites and surveys across the country that are used to measure important hydrologic parameters. However, few if any of these were designed primarily to monitor the impacts of climate change, or to help us in adapting to those impacts. This document provides advice on how we can adjust and refine our water monitoring networks to better support climate change adaptation planning and reduce the risks associated with climate change impacts.

One approach to determining the suitability of water monitoring networks for climate change adaptation – the approach described in this document – is to set priorities for water monitoring networks for climate change adaptation, and then evaluate the ability of these networks to provide the data needed to support climate change adaptation needs. The document describes proven and practical ways to carry out this priority-setting and evaluation, methods that are intended to be useful in all Canada's provinces and territories. However as the impacts of climate change vary by location, the priorities and evaluations will, by necessity, be jurisdiction- and region-specific. Prioritization and evaluation will help jurisdictions decide whether (and how) to add or reduce stations, add hydrologic parameters, or change the frequency and timing of sampling.

The following ideas for next steps are offered for consideration as advances are made in the evaluation of hydrologic monitoring networks:

- Although there is considerable diversity in jurisdiction-specific parameter needs, there are common monitoring needs across all Canadian jurisdictions for certain parameters. This suggests that there may be valuable and significant opportunities to share data, information, experiences, ideas and solutions.

- Across all jurisdictions, decision-makers require high quality long-term data to plan for climate change. There is a need for data to be comparable between stations, for data quality to be verified, and for data to be archived allowing long term access for decision making.

- The usefulness of the methods for prioritisation and evaluation of water monitoring networks described in the document can be increased with Canadian case study examples and the sharing of experience among jurisdictions. When available, Canadian examples have been included in the document.

- Reviewers have identified the need for methods and information that specifically address monitoring of the cryosphere. This could include: snow coverage, glacier mass balance, glacier area, lake, river and sea ice cover, and permafrost temperature, area and depth. Jurisdictions whose river-lake systems rely on glaciers or ground ice as water sources will need to consider fully the need for monitoring ice degradation. Some of the methods described in the document could potentially be adapted for use in setting priorities and evaluating cryospheric monitoring networks.

- The contribution of reviewers from jurisdictions across Canada and from academia was extremely valuable in the development of this document. Contributors not only suggested improvements to the document but also identified needs related to assessing climate change impacts and to developing climate change strategies and plans. For example,
    - a framework that integrates monitoring, modelling and management would be useful to facilitate the development and implementation of climate change adaptation strategies and plans;
    - integrated water resources management could have a major role in climate change adaptation;
    - the evaluation of water monitoring networks may result after a climate change vulnerability assessment has been conducted and vulnerable or priority areas have been identified in that way.

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APPENDIX A

METHODS FOR SETTING PRIORITIES FOR WATER MONITORING NETWORKS

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APPENDIX A: METHODS FOR SETTING PRIORITIES FOR WATER MONITORING NETWORKS

Three methods were identified as methods that require only a limited amount of data that are readily available, have the greatest flexibility in terms of scale of applicability and do not require a high level of expertise. The three methods are:

1) Basic Valuation Methods for Ecosystem Services
2) Ombrothermic Analysis
3) Water Resources Vulnerability Indicators Analysis

All three of these methods are also able to produce results that are understandable to the public. References for and brief descriptions of other prioritization methods are provided in Appendix C.

Each of the methods have been applied at different scales. The Basic Valuation Methods for Ecosystem Services is often applied at a regional or watershed scale. The Omborthermic Analysis has been applied to areas where there are significant differences in the basic climatic parameters of temperature and precipitation. This is more likely to occur at regional or national scales. The Water Resources Vulnerability Indicators Analysis has been applied at all scales from a national scale to a watershed scale.

Depending on the scope of the evaluation of water monitoring networks, different prioritization methods may be used in conjunction. For example, the Ombrothermic Method may be used to identify priority areas within a regional or national scale. Then one of the other methods may be used to further evaluate those priority areas.

A.1. BASIC VALUATION METHOD FOR ECOSYSTEM SERVICES

This section provides detailed information on how to apply the Basic Valuation Method for ecosystem services to set priorities for water monitoring networks for climate change adaptation. The Basic Valuation Method (BVM) for ecosystem services is used to differentiate areas, such as large or multiple watersheds or ecoregions, based on relative differences in the ecosystem services provided.

Ecosystem services are the goods and services that natural systems provide, such as nutrient cycling, water supply, waste assimilation and flood protection. The BVM determines the value of the average types and amounts of services provided by a land use, such as a wetland, in a specific area (e.g., in a region in the U.S.) In a process known as “benefits transfer”, these values are then applied to all similar land use types (wetlands for example) in a different area (e.g., southern Québec). The value of the ecosystem services provided by different land uses can be measured in terms of their spatial distribution and economic value ($ per hectare). For setting priorities for water monitoring networks, the relevant ecosystem services are those that are related to hydrologic systems.

In the basic valuation approach, land use is mapped in the region of interest. This is done using generally readily available land use data (wetlands, forests, grasslands, agricultural lands, barren grounds, developed lands, etc.). Then the ecosystem services of those land uses are evaluated and mapped. The resulting maps show the relative combined values of the hydrologic services[1] provided and their spatial distribution. Knowing which areas provide which types of hydrologic services and their relative value can help set priorities for water monitoring networks for climate change adaptation.

1.1 BACKGROUND INFORMATION

As noted above, the term "ecosystem services" is used to describe the goods and services that natural systems provide. These are often referred to as "natural capital".[2] Ecosystem services are provided at many scales from global to regional to local. Table A1.1 presents categories and examples of different types of ecosystem services.

Some of these ecosystem services provided by natural systems are direct services to humans, such as the provision of drinking water, timber and food. These types of services are relatively easy to value. However, other ecosystem services, such as nutrient cycling and flood protection, are less tangible and harder to value.

Hydrological services (such as water supply, flood protection, waste assimilation and water purification) are critical to our environment, communities and economy. These ecosystem services are highly valuable and often highly sensitive to climate change.

Table A1.1: Ecosystem services

ECOSYSTEM SERVICE CATEGORY	EXAMPLES OF ECOSYSTEM SERVICES
Provisioning services	• Food • Drinking water supply • Timber • Fibre
Regulating ecological processes or functions on which humans rely	• Climate regulation • Waste assimilation • Flood protection • Water purification • Fire regulation
Supporting services	• Nutrient cycling • Soil formation

ECOSYSTEM SERVICE CATEGORY	EXAMPLES OF ECOSYSTEM SERVICES
Cultural services	• Well-being • Spiritual nourishment • Recreational places

Two approaches can be taken to the valuation of ecosystem services:

1) Original valuation by gathering primary, site-specific data on ecosystem services in all areas that are of concern. This type of analysis could be very costly.

2) Valuation by benefit transfer which draws on other studies to determine the economic value of hydrologic services in one kind of land use and then transfers the values to all similar land use types.

The BVM described here uses the second approach. However there are some drawbacks to the benefit transfer (valuation) method. Those are described in Appendix A1.4.

In BVM, standard sets of ecosystem services are identified for each land use type. For example, forestland could be linked to the following set of services: climate regulation, flood regulation, nutrient cycling and recreation/ecotourism services.

1.2 BASIC VALUATION ANALYSIS IN DETAIL

In BVM, the setting of priorities for monitoring networks for climate change adaptation is based on the spatial distribution and quantitative assessment of ecosystem services related to hydrologic systems. The quantitative assessment considers the (average) types and value of services provided by different types of land uses. The steps in the BVM are summarized in Figure A1.1.

Figure A1.1: Procedure for the BVM

STEPS	
Step 1	Identify regional management objectives
	▼
Step 2	Review available land use mapping data
	▼
Step 3	Combine land use maps

STEPS		
	▼	
Step 4	Identify set of hydrological services and ecosystem services related to hydrologic systems for each of the different land uses	
	▼	
Step 5	Valuation of hydrologic services	
	▼	
	Step 5a	Assign economic value to each hydrologic service provided by the different land uses
		▼
	Step 5b	Compute unit area value of each hydrologic service - land use combination
		▼
	Step 5c	Compute total unit area value of each land use
		▼
	Step 5d	Compute total unit area value of each sub-region
		▼
	Step 5e	Map total unit area value of each sub-region
		▼
Step 6	Interpret results	
	▼	
Step 7	Prioritize monitoring sites	

Step 1 - Identify regional management objectives: Jurisdictions identify regional management objectives within the context of existing plans, policy statements and environmental conditions. This is a key step in the setting of priorities for water monitoring to address climate change. Typically, the setting of regional management objectives considers environmental, technical, management and socioeconomic concerns.

Step 2 - Review available land use mapping data: Review land use mapping for the area of interest (the territory, ecological region, or large watershed). The review considers coverage (extent of available mapping), accuracy (how the mapping reflects current conditions) and precision/scale. Mapping may be available from different sources (national, provincial, regional or local sources).

Step 3 - Combine land use maps: The different land use maps are overlain onto a single map of selected land uses. The selected land uses will relate to the regional management objectives (step 1) and may include such land use cover as wetlands, forests, and urban areas. The land use mapping is done within a GIS environment.

Step 4 - Identify set of hydrological services and ecosystem services related to hydrologic systems for each of the different land uses: Identify the set of hydrological services, and ecosystem services related to hydrologic systems, that are provided in each land use type. This is done through a literature review of relevant publications. This information could be mapped to show the spatial distribution of the services provided by the land uses.

Step 5a - Assign economic value to each hydrologic service provided by the different land uses: Economic values are assigned to each hydrologic service provided in each land use. This step requires a literature review of studies that provide the economic value of activities or ecological functions that can be linked to a particular ecosystem service. It is essential that the value of the ecosystem services be derived from study sites that can be linked to a particular landscape type.

Step 5b - Compute unit area value of each hydrologic service - land use combination: The unit area value for each hydrologic service - land use combination is determined by dividing the estimated value of a particular hydrologic service by the area of the relevant land use type. This step produces a constant value for that hydrologic service–landscape type combination per unit of area (i.e., flood protection value per hectare of forest land).

Step 5c - Compute total unit area value of each land use: The total unit area value of each land use is determined by adding the unit area value of each of the hydrologic services that are present in each land use type (i.e., the value of all hydrologic services provided per hectare of forest land).

Step 5d - Compute total unit area value of each sub-region: The unit area value of sub-regions (e.g., ecoregions or watersheds) is determined by calculating a weighted average of the unit area value of each of the land uses found in that sub-region (i.e., value of combined hydrologic services per hectare of land in a sub-region).

Step 5e - Map total unit area value of each sub-region: The unit area values of the sub-regions are mapped using GIS.

Step 6 - Interpret results: The results are interpreted with respect to the regional management objectives.

Step 7 - Prioritize monitoring sites: Locations of existing monitoring sites are overlaid on top of mapped results to identify parts of the region that are covered or not covered by water monitoring networks. Areas in which the water monitoring needs to be improved are identified.

The Southern Ontario Greenbelt Example

The Southern Ontario Greenbelt surrounds an area in Southern Ontario called the "Golden Horseshoe". The Golden Horseshoe is the lands which arc around the western end of Lake Ontario. It is the most densely populated area in Canada, with approximately a quarter of the country's human population. [3] The Greenbelt is approximately 325 kilometres in length, includes 0.73 million hectares and consists of protected green spaces, farmlands, communities, forests, wetlands, and watersheds.

In 2008, the David Suzuki Foundation analysed the ecosystem services that are provided within the Southern Ontario Greenbelt. Researchers determined the types of land use within the study area using provincial land cover data. They then estimated the unit area value of a wide range of ecosystem services provided by sub-watersheds of the Greenbelt. Although the study was not intended specifically for setting priorities for monitoring networks for climate change adaptation, the authors mention that its results can be useful in helping to establish investment priorities.[4] The study identifies the importance and value of ecosystem services in land-use planning and policy decisions taken by different levels of government.

Table A1.2 provides a list of ecosystem functions and the corresponding ecosystem services that were analysed in the study. Key hydrologic services are indicated with shading. Water availability is also important for other functions such as food production.

Table A1.2: Ecosystem services in the Southern Ontario Greenbelt [5]

FUNCTIONS	ECOSYSTEM SERVICES
Gas regulation	UVb protection by ozone, maintenance of air quality
Climate regulation	Maintenance of a favourable climate, carbon regulation, cloud formation
Disturbance prevention	Storm protection, flood control, drought recovery
Water regulation	Drainage, natural irrigation, transportation
Water supply	Provision of water by watersheds, reservoirs and aquifers
Soil retention	Prevention of soil loss/damage from erosion/siltation; storage of silt in lakes and wetlands; maintenance of arable land
Soil formation	Maintenance of productivity on arable land; maintenance of natural productive soils
Nutrient cycling	Maintenance of healthy soils and productive ecosystems; nitrogen fixation

FUNCTIONS	ECOSYSTEM SERVICES
Waste treatment	Pollution control/detoxification, filtering of dust particles, abatement of noise pollution
Pollination	Pollination of wild plant species and crops
Biological control	Control of pests and diseases, reduction of herbivory (crop damage)
Habitat	Biological and genetic diversity, nurseries, refugia, habitat for migratory species
Food production	Provision of food (agriculture, range), harvest of wild species (e.g., berries, fish, mushrooms)
Raw materials	Lumber, fuels, fodder, fertilizer, ornamental resources
Genetic resources	Improve crop resistance to pathogens and crop pests, health care
Medicinal resources	Drugs and pharmaceuticals, chemical models & tools
Recreation	Ecotourism, wildlife viewing, sport fishing, swimming, boating, etc.
Education, Culture & Spirituality	Provides opportunities for cognitive development: scenery, cultural motivation, environmental education, spiritual value, scientific knowledge, aboriginal sites

The researchers identified potential ecosystem services for each land cover type. These are outlined in Table A1.3. Key hydrologic services are indicated with shading. Other services may also involve hydrologic systems.

Table A1.3: Ecosystem services by land use type in the Southern Ontario Greenbelt [6]

Ecosystem Service	Forests	Grasslands	Rivers	Wetlands	Cultivated Lands	Urban Parks
Fresh water	●		●	●		
Air quality	●					●
Erosion control	●	●		●		
Global climate regulation	●			●		
Local climate regulation	●	●				●
Storm protection				●		
Pest control	●	●			●	
Pollution control	●		●		●	
Waste processing				●		
Flood regulation	●		●	●		

Ecosystem Service	Forests	Grasslands	Rivers	Wetlands	Cultivated Lands	Urban Parks
Sediment retention	●	●	●	●		
Disease regulation			●			
Nutrient cycling	●	●	●		●	
Medicines	●					
Recreation/ ecotourism	●	●	●	●		●
Aesthetic	●	●	●		●	
Spiritual	●	●	●			
Cultural/heritage	●	●	●	●	●	●
Education	●	●	●	●	●	●

The researchers then assigning a dollar value to each ecosystem service. This can be a challenging task because of the relative lack of economic information, especially in the case of non-market values. Table A1.4 lists some of the techniques that have been developed by economists to determine economic values for non-market ecosystem services.

Table A1.4: Non-Market Ecosystem Valuation Techniques [7]

NON-MARKET ECOSYSTEM VALUATION TECHNIQUES
Avoided Cost (AC): Ecosystem services allow society to avoid costs that would have been incurred in the absence of those services. For example, flood control provided by a barrier island reduces property damage along the coast.
Replacement Cost (RC): Services could be replaced with human-made systems. For example, nutrient cycling waste treatment can be replaced with costly treatment systems.
Net Factor Income (NFI): Services provide for the enhancement of incomes. For example, water-quality improvements increase commercial fisheries catches and incomes from the fishery.
Travel Cost (TC): Service demand may require travel, the cost of which can reflect the implied value of the service. For example, recreation areas attract distant visitors whose value placed on that area must be at least what they were willing to pay to travel to it.
Hedonic Pricing (HP): Service demand may be reflected in the prices people will pay for associated goods. This method is often used to estimate property values. For example, housing prices along the coastline tend to exceed the prices of inland homes.

NON-MARKET ECOSYSTEM VALUATION TECHNIQUES
Contingent Valuation (CV): Service demand may be elicited by posing hypothetical scenarios in surveys that involve some valuation of land-use alternatives. This method is often used for less tangible services like wildlife habitat or biodiversity. For example, people would be willing to pay for increased preservation of beaches and shoreline.

Once dollar values were calculated for ecosystem services, researchers combined the unit area values of each ecosystem service for each land use type in the Greenbelt sub-watersheds.

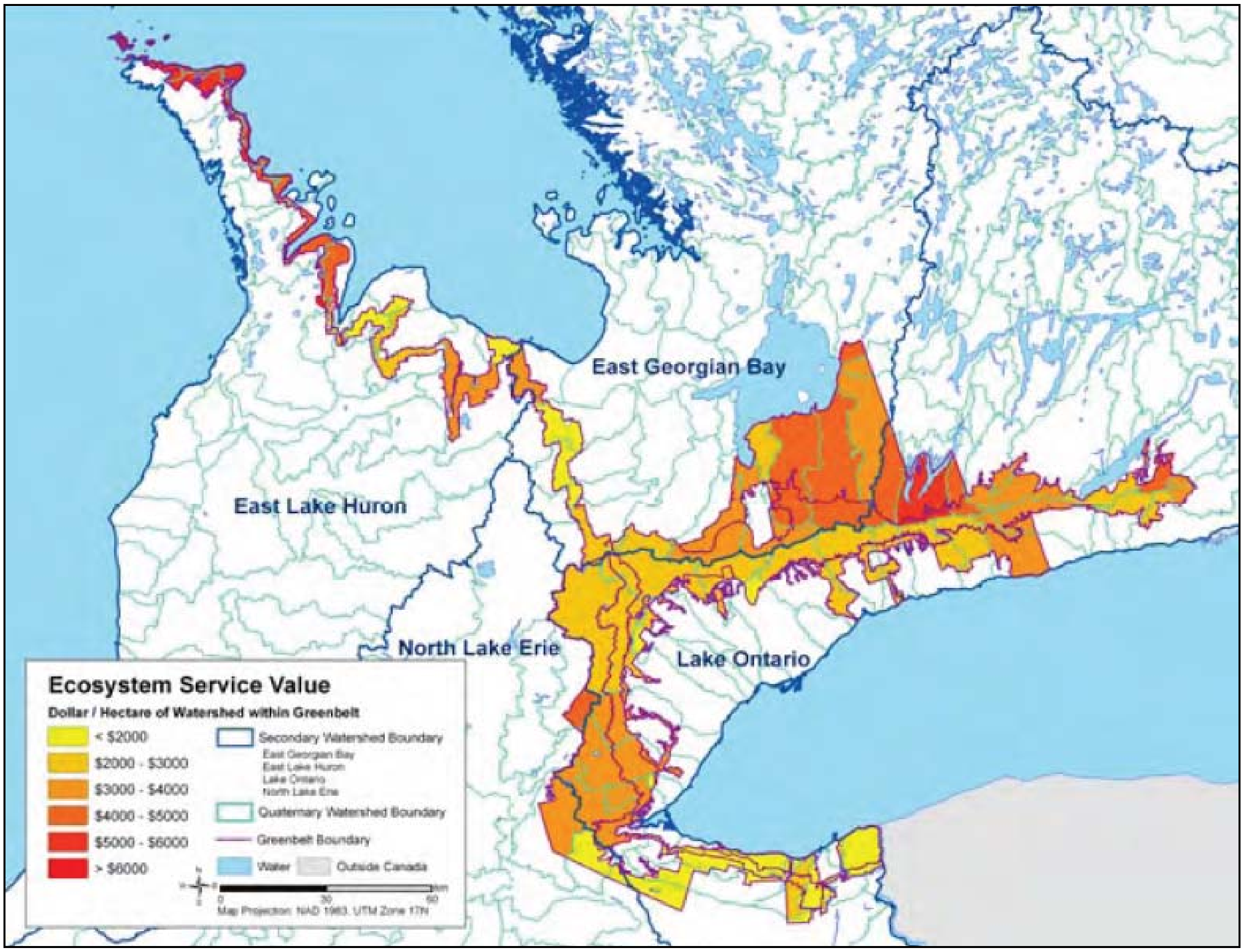
Table A1.5 shows the value of different land cover types within the Southern Ontario Greenbelt sub-watersheds.

Table A1.5: Non-Market Ecosystem Services Values by Land Cover Type – Southern Ontario Greenbelt Sub-watersheds [8]

LAND COVER TYPE	AREA (Hectare)	VALUE PER HECTARES ($/Hectare/yr)	TOTAL VALUE ($Million/yr)
Wetlands	94,014	$14,153	$1,331
Forest	182,594	$5,414	$989
Grasslands	441	$1,618	$0.71
Rivers	7,821	$335	$2.60
Cropland	384,378	$477	$183
Idle land	78,889	$1,667	$132
Hedgerows	7,039	$1,678	$11.80
Orchards	5,202	$494	$2.60
Other	42	$0	$0
TOTAL	760,420	$3,487	$2,652

Figure A1.2 shows the distribution of annual ecosystem services value per hectare by watershed unit. The value of annual ecosystem services ranges from about $2,000/hectare to greater than $6,000/hectare.

Figure A1.2: Distribution of annual ecosystem services value per hectare by watershed unit



The Lake Simcoe Example

In 2008, Natural Capital Research & Consulting performed the first basic valuation analysis of a watershed in southern Ontario. The study analysed the value of ecosystem goods and services provided by Lake Simcoe's watershed, a section of which is located in the Greater Toronto Area's Greenbelt. The total area of Lake Simcoe watershed area analysed was 3,307 square kilometres. Table A1.6 shows the values determined for different the land cover types within Lake Simcoe's watershed.

Table A1.6: Non-Market Ecosystem Services Values by Land Cover Type – Lake Simcoe Watershed [9]

LAND COVER TYPE	AREA (Hectare)	VALUE PER HECTARES ($/Hectare/yr)	TOTAL VALUE ($Million/yr)
Forest	66,379	$4,798	$319
Grasslands	8,353	$2,727	$23
Wetlands	38,974	$11,172	$435
Water	72,141	$1,428	$103
Cropland	96,202	$529	$51
Hedgerows/Cultural Woodland	3,855	$1,453	$5.60
Pasture	24,447	$1,479	$36
Urban Parks	3,363	$824	$2.77
TOTAL	330,741	$2,948	$975

1.3 REQUIRED RESOURCES

The Basic Valuation Method requires the following resources:

Data and software resources required:

- Land use maps with good spatial coverage of wetlands, grasslands, forests, agricultural lands, barren ground, developed lands, etc. are required. The detail of the mapping should be sufficient for the identification of hydrologic ecosystem services.
- Literature information on the types and value of hydrologic services found in the each type of land use is required.
- GIS software capability.

Level of effort and expertise required:

- Basic GIS skills and basic analytical skills for the evaluation of the ecosystem services.

1.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

The assessment of ecosystem services provided by specific land uses is a relatively new concept and has not been widely tested. However, the method can be applied at larger scales, such as the province/territory scale, which cover multiple representative land use types and may be applicable at slightly smaller scales such as large watersheds and combined watersheds or ecoregions.

There are a number of limitations to the method.[10] BVM can lead to over- or under-estimations of values because:

- not all parcels of land that are classified in one land use type are of the same value (e.g., deciduous and softwood forests do not have the same value but may both be classified as forest lands in the land use type)
- the size of a parcel of land of a specific land use may influence its ability to provide ecosystem services (e.g., water treatment and storage services may be less efficient in a small wetland than in a larger wetland)
- the condition of a parcel of land of a specific land use may influence its ability to provide ecosystem services (e.g., erosion control services would be less efficient in a forest that has gone through clear cutting than in a mature forest, and
- the proximity of a parcel of land of a specific land use to urban areas or other areas may influence its ability to provide ecosystem services, (e.g., ecotourism services may be less valuable in a forest that is located near an urban center than in a protected undisturbed forest).

These shortcomings may not be serious for the purposes of setting priorities for water monitoring networks for climate change adaptation, as relative differences are what is important, not absolute values. In addition, when the BVM is applied on a regional scale, the spatial pattern of relative differences in the distribution of ecosystem services may minimise the drawbacks of transferring average benefits.

1.5 IN SUMMARY

The BVM is a relatively simple method which considers the value of ecosystem services attributed to different types of land uses. In this document, special attention has been given to the ecosystem services related to hydrologic systems that are provided by the different types of lands as those services are sensitive to the impacts of climate change. For the valuation of hydrologic services, the average types and amounts of services provided by certain land uses is determined, and then the value of those services is applied to all similar land use types. The value of hydrologic services can be measured in terms of spatial distribution and economic value ($ per hectare or potentially $ per hectare per unit time).

The method uses generally available land use maps that distinguish wetlands, forests, grasslands, agricultural lands, barren grounds, developed lands, etc. The method requires basic software capability, GIS software capability along with basic analytical and GIS skills. Also required are references that provide the types and value of hydrologic services associated particular land use types. The BVM may be applied to province/territories and to large watersheds or ecoregions.

Maps can illustrate the combined value of the different hydrologic services provided and their spatial distribution. Knowing the location of areas that provide high levels of hydrologic services can help set priorities for water monitoring networks for climate change adaptation. Table A1.7 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements for the BVM method.

Table A1.7: Summary of the Basic Valuation Method Characteristics

FEATURES	REQUIREMENTS
Types of criteria / parameters	Ecosystem service values based on land use distribution, using average types and relative values of hydrologic services provided by certain kinds of land uses.
Data needs	Spatial coverage of land use data (wetlands, forests, grasslands, agricultural land, barren ground, developed lands, etc.) with sufficient detail to separate types according to the types of hydrologic services typically provided. References defining the type and value of hydrologic services associated with the land use types.
Software	Data base, GIS, and basic computational software.
Expertise	Data management, basic analysis, and GIS skills. Understanding of benefit transfer technique.
Scale considerations	Evaluation of ecosystem services is relatively new, and not widely tested; however, it appears that this approach has applicability particularly at larger scales that cover multiple representative land use types. It is applicable at the province/ territory scale, and may be applicable at slightly smaller areas (e.g., large or multiple watersheds and ecoregions).

ENDNOTES

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[1] This may also include ecosystem services that are specifically hydrologic, for example “provision of food” which depends on water supply by irrigation may be a management priority. Therefore water supply and food provision services may both be used for the valuation. This would depend on the jurisdiction’s management objectives.

[2] Costanza, R. and J. Farley. 2007. Ecological economics of coastal disasters: Introduction to the special issue. Ecological Economics 63:249-253.

[3] Wilson S.J. (Natural Capital Research and Consulting). September 2008. Ontario's Wealth, Canada's Future: Appreciating the Value of the Greenbelt's Eco-Services. 61 p.

[4] Ibid.

[5] From Wilson S.J. (Natural Capital Research and Consulting). September 2008. Ontario's Wealth, Canada's Future: Appreciating the Value of the Greenbelt's Eco-Services. 61 p. -Adapted from de Groot, R.S. 2002. “A typology for the classification, description and valuation of ecosystem functions, goods and services.” Ecological Economics. 41: 393-408.

[6] From Wilson S.J. (Natural Capital Research and Consulting). September 2008. Ontario's Wealth, Canada's Future: Appreciating the Value of the Greenbelt's Eco-Services. 61 p.

[7] Ibid.

[8] Ibid.

[9] From Wilson S.J. (Natural Capital Research and Consulting). Lake Simcoe Basin’s Natural Capital: The Value of the Watershed’s Ecosystem Services. Friends of the Greenbelt Foundation Occasional Paper Serie - June 2008. 45 p.

[10] Limitations discussed by:
Koch, E.W., E.B Barbier, B.R. Silliman, D.J. Reed, G.M.E. Perillo, S.D. Hacker, E.F. Granek, J.H. Primavera, N. Muthiga, S. Polasky, B.S. Halpern, C.J. Kennedy, C.V Kappel,, and E. Wolanski. 2009. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Frontiers in Ecology and the Environment 7(1):2937.
and
Plummer, M.L. 2009. Assessing benefit transfer for the valuation of ecosystem services. Frontiers in Ecology and the Environment 7(1):38-45.

A.2. OMBROTHERMIC ANALYSIS

This section provides detailed information on how to apply Ombrothermic Analysis to set priorities for water monitoring networks for climate change adaptation. Ombrothermic analysis uses two indicators – precipitation (*ombro = rainfall*) and temperature (*thermic*) – to assess the spatial extent of the vulnerability of a region to climate change. Ombrothermic analysis uses humidity/aridity indices and graphics to integrate temperature and precipitation data over time. Using readily available temperature and precipitation data, the method produces an index that can identify vulnerable areas that may be prone to humidity (excessive rainfall) or aridity (drought). The method can also use the temperature and precipitation output from climate models to calculate a projected ombrothermic index. The differences between current and projected indices can be used to identify potentially vulnerable areas. Knowing if a region has such vulnerable areas and where these vulnerable areas are can help set priorities for water monitoring networks to address climate change adaptation.

Ombrothermic analysis can be done in two ways:

- Generation of ombrothermic diagrams for specific locations
- Mapping of vulnerability, as determined by the ombrothermic index which measures critical humidity (excessive rainfall) and aridity (drought) periods.

2.1 BACKGROUND INFORMATION

CCME's review of possible priority setting methods determined that the Ombrothermic Analysis method is an important method since it can easily accommodate the two major climatic factors that are the most reliable outputs from climate change models: temperature and precipitation. In this way current and projected climates can be easily compared. However to be most useful in the Canadian context, the method does require some modification. The reasons why are described here.

The concept of ombrothermic analysis was developed in 1953 by two famous botanists, Bagnouls and Gaussen, who pioneered the use of ombrothermic diagrams and the ombrothermic index. The method was developed for use in the Mediterranean.

The **ombrothermic index** or Bagnouls-Gaussen humidity/aridity index (BGI) can be computed from temperature and precipitation data. This index is the summation, for the twelve months of the year, of the difference between mean monthly air temperature (in ^{o}C) multiplied by 2 and the average total monthly precipitation (in mm) all of which is multiplied by the proportion of months in a year where the double of the temperature value (in ^{o}C) is greater than the precipitation value (in mm). The index can be expressed as follows:

Equation 2.1: Annual Ombrothermic Index

$$I_{annual} = \sum_{i=1}^{12} (2T_i - P_i) \times k$$

Where

I_{annual} is the annual ombrothermic humidity/aridity index
T_i is the mean air temperature in month i (in ^{o}C)
P_i is the average total precipitation in month i (in mm)
k is the proportion of months where $2T_i$ is greater than P_i
$_i$ is the month 1, 2,…12

As it was originally developed, the index summarizes hydrological stress on plant development and biomass growth. Bagnouls and Gaussen defined dry areas as those for which the monthly values of $2T_i$ are greater than P_i. This condition normally exists at only a few locations in Canada: specifically in the dryer climate of the interior plateau of British Columbia (Kamloops, Kelowna, Penticton), in southern Alberta (Medicine Hat) and possibly in southern Saskatchewan. Everywhere else in Canada, it is expected that the monthly values of $2T_i$ are less than P_i. This reflects an abundance of water in most Canadian regions in comparison to the Mediterranean region, for which the index was originally developed.

To make the method applicable to Canadian conditions, a water balance approach can be taken to modify the method. Water balance is one of the basic concepts in the science of hydrology. It represents the amount of water in and out of an ecosystem and it is a function of precipitation, runoff, evapotranspiration and storage. The major input of water is from precipitation and in a natural environment, the major output is evapotranspiration[1]. Water balance analysis can be used to predict where there may be water shortages and to help manage water supply. It has also been used in agricultural applications (such as irrigation), runoff assessment and other ecosystem analyses. Water balance in a region can be estimated by comparing mean monthly precipitation to mean monthly potential of evaporation and storage.

The $2Ti$ factor used in the calculation of the ombrothermic index can be viewed as an estimation of evapotranspiration which is one of the major components of the water balance. The factor of 2 used to multiply the temperature may be applicable to Mediterranean conditions but needs to be modified for Canadian conditions. To determine a factor applicable to Canadian conditions the potential evapotranspiration was determined for 3 Canadian locations: Penticton in British Columbia; Barrie in Ontario; and St. John's in Newfoundland and Labrador.

The potential evapotranspiration was calculated for each of the 3 locations using a simple monthly water balance model that was developed by the United States Geological Survey (the

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[1] This is the case for the majority of the country where evapotranspiration "outputs" 50 to 60% of the total precipitation input. Runoff, inflows and outflows, and lake storage can also be important components of the water balance.

program is available at http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/software/thorn_s/thorn.shtml). For determining potential evapotranspiration the input to the simple water balance model consists of the average monthly temperature and precipitation for the 1971 to 2000 period and the latitude of the meteorological station (available at: http://climate.weatheroffice.gc.ca/climate_normals/index_e.html).

Ombrothermic diagrams are simple climatic graphics that show the monthly variation of average temperature multiplied by a factor and precipitation over a year. Figures A2.1, A2.2 and A2.3 show examples of ombrothermic diagrams along with calculated potential evapotranspiration for the 3 Canadian locations based on 1971-2000 data.

Figure A2.1: Ombrothermic Diagram for Penticton, British Columbia

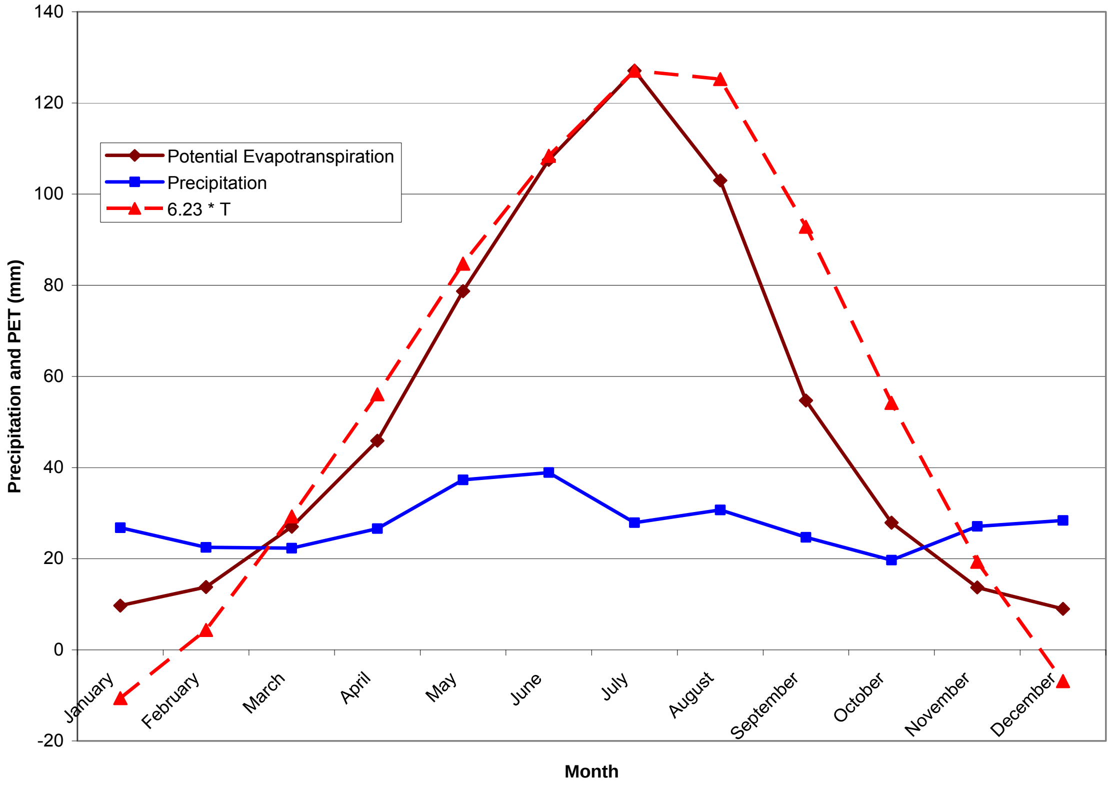


Figure A2.2: Ombrothermic Diagram for Barrie, Ontario

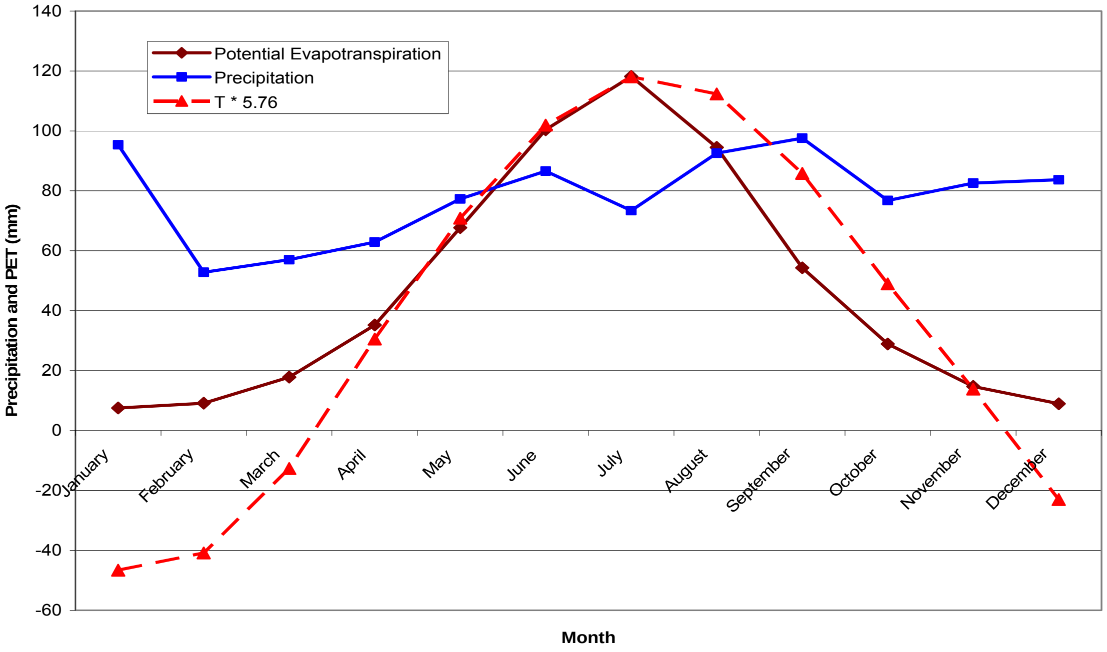
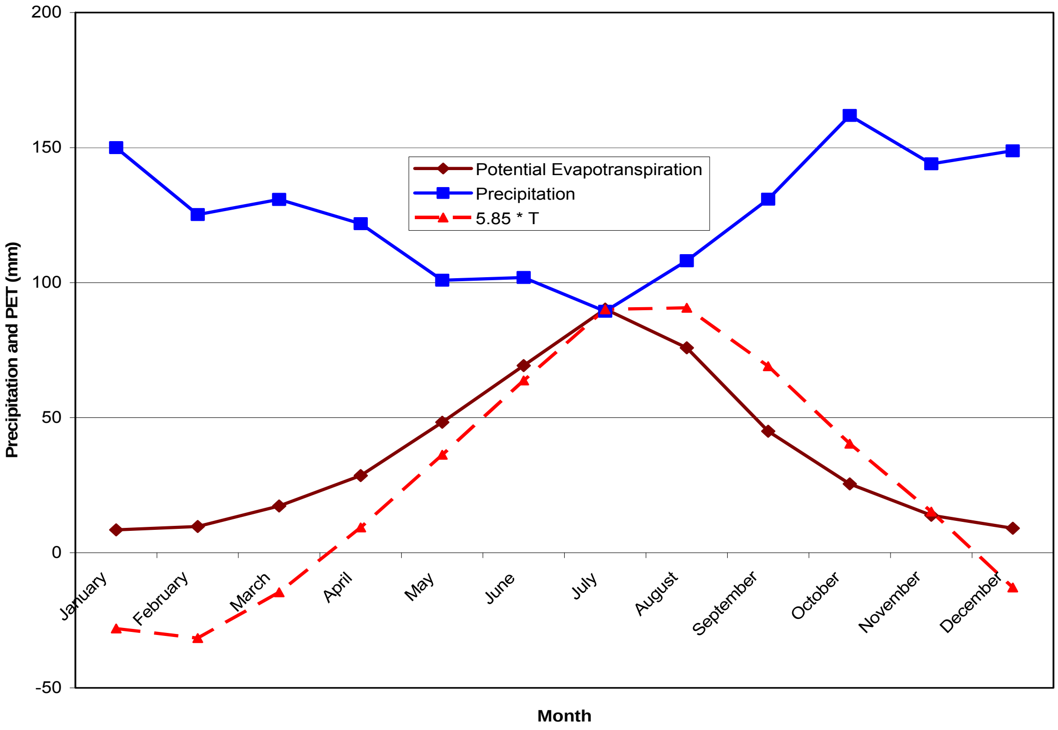


Figure A2.3: Ombrothermic Diagram for St. John's, Newfoundland and Labrador



To estimate potential evapotranspiration from temperature a multiplication factor ranging from 5.76 to 6.23 was used for the Canadian locations. Even with this larger factor, it is possible that the annual ombrothermic index as calculated by a modified Equation 2.1 will not be suitable for all Canadian locations. In some areas, such as in Newfoundland and Labrador and northern regions, the potential evapotranspiration could be less than precipitation throughout the year. This would leave the value of k in Equation 2.1 to be 0 making the calculation invalid.

For those areas the ombrothermic index can be computed on a monthly basis and does not include the factor of k as follows:

Equation 2.2: Monthly Ombrothermic Index

$$I_i = \sum_{i=1}^{12} 2T_i - P_i$$

Where

I_i is the ombrothermic humidity/aridity index computed on a monthly basis
T_i is the mean air temperature in month i (^{o}C)
P_i is the total precipitation in month i (mm)
$_i$ is the month (1, 2,… or 12)

Table A2.1 Ombrothermic Indices for Three Canadian Locations

Location	Factor (multiplied by monthly temperature)	k (number of months that Factor * Temp is greater than Precipitation)	Annual Ombrothermic Index (I_{annual})	Monthly Ombrothermic Index (I_i)
Penticton, BC.	6.23	8	3253	644
Barrie, ON	5.76	3	-522	-174
St. John’s, NFL	5.85	1	-1186	-1186

The literature indicates that drought conditions may be identified where the computed index is positive ($I_i > 0$) as shown by the indices calculated for Penticton. Similarly, excessive rainfall conditions will be associated with low monthly values of the index ($I_i < -400$). The monthly ombrothermic index can be used to obtain a range of values that can help identify zones that may be more susceptible to climate change. Higher values of the index will indicate dryer conditions (Penticton) whereas lower values of the index will represent wetter conditions (St. John’s).

2.2 OMBROTHERMIC MAPPING IN DETAIL

Figure A2.4 summarizes the steps in the ombrothermic mapping method. Additional steps may be necessary depending on the management objectives identified in step 1.

Figure A2.4: Procedure for the Ombrothermic Mapping Method

STEPS	
Step 1	Identify regional management objectives
	▼
Step 2	Review temperature and precipitation data
	▼
Step 3	(If possible) interpolated temperature and precipitation data
	▼
Step 4	(Optional) Obtain climate change projections
	▼
Step 5	Produce ombrothermic diagrams
	▼
Step 6	Calculate Ombrothermic Index
	▼
Step 7	Map Ombrothermic Index spatially
	▼
Step 8	Interpret results
	▼
Step 9	Prioritize monitoring sites

Step 1 - Identify regional management objectives: Regional management objectives are identified within the context of existing plans, policy statements and environmental conditions. This is a key step in the setting priorities for water monitoring to address climate change. Typically, the setting of regional management objectives considers environmental, technical, management and socioeconomic concerns.

Step 2 - Review temperature and precipitation data: The review of available temperature and precipitation data is an essential step. Available data that could be used includes Canadian climate normals from 1971 to 2000 and monthly average temperature and precipitation values. This data is readily available from Environment Canada for 1480 meteorological stations across Canada (http://climate.weatheroffice.gc.ca/climate_normals/index_e.html). The temperature and precipitation data can be compiled as a database, in spreadsheets or within a GIS platform.

Step 3 - (If possible) Interpolate temperature and precipitation data: If the study area is large and includes several climate stations, spatial interpolation of temperature and precipitation data may be done in GIS. Interpolation requires that the stations be located across the study area and that the data from the stations are representative of the study area's temperature and precipitation normals.

Step 4 - (Optional) Obtain climate change projections: Where available, projections of future regional temperature and precipitation regimes will help identify the likely impacts of climate change.

Step 5 - Produce ombrothermic diagrams: Ombrothermic diagrams can be used to identify areas that may be vulnerable to climatic conditions. For comparison purposes, the scales should be kept constant between the different graphs. In cold and temperate cold climates, Bagnoulds and Gaussen (1957) suggest that the ombrothermic diagram can be adjusted to account for precipitation in the form of snow that accumulates on the ground during the cold season. In spring, the snowmelt results in an abundance of humidity which contributes to plant growth in a way that is similar to rain.

Step 6 - Calculate Ombrothermic Index: The ombrothermic index is computed within a database, spreadsheet or GIS environment. In regions where potential evapotranspiration is less than precipitation the index should be calculated on a monthly basis using Equation 2.2. Where potential evapotranspiration is greater than precipitation the index can be calculated on an annual basis using Equation 2.1.

Step 7 - Map Ombrothermic Index spatially: In this step, the ombrothermic index results are mapped spatially. The selected months or seasons to be mapped in a GIS environment should relate to the regional management objectives identified in step 1. Spatial interpolation of the ombrothermic index between stations can be done. Step 7 can be applied to both actual and future conditions. Separate mapping of temperature and precipitation averages may also contribute to setting priorities for water monitoring networks.

Step 8 - Interpret results: Results are interpreted in relation to the regional management objectives. Mapped ombrothermic indices will identify regions that are more vulnerable to climate change (i.e., areas that will experience excessive dryness or excessive rainfall conditions). In this step, the evolution of the ombrothermic values with time is based on projected future climate conditions.

Step 9 - Prioritize monitoring sites: The existing monitoring sites are overlaid on top of mapped ombrothermic indices to identify which regions are covered and uncovered for monitoring.

The Swiss Example

The mapping of ombrothermic$_i$ values (step 7) has been carried out in Switzerland to assess biophysical vulnerability to climate change for present and future conditions.[1] Priceputu and Greppin (2005) mapped monthly and seasonal ombrothermic index values for 2000. They also mapped predicted ombrothermic monthly values for 2100 using temperature/precipitation relationship evolution models in an attempt to predict the spatial impacts of climate change.

Figures A2.5 and A2.6 show computed ombrothermic indices in Switzerland for current May conditions (based on 1951-200 data) and projected conditions for May 2100. On the figures, the lower computed ombrothermic$_i$ values are < -300 (darker blue areas) and the higher computed ombrothermic$_i$ values are > 0 (red areas). The areas in the blue range represent regions that currently experience excessive rainfall conditions and the areas in the red range are regions that experience drought. The black line is the boundary of Switzerland. A comparison of Figures A2.5 and A2.6 reveals that the authors of the study expect significant changes in climatic conditions in the future.

The literature contains many examples of the use of the ombrothermic method for various climate studies. (See Appendix C: Information Sources – Methods for Setting Priorities: Ombrothermic Method.)

Figure A2.5: Ombrothermic$_i$ Indices for Current May Conditions in Switzerland [2]

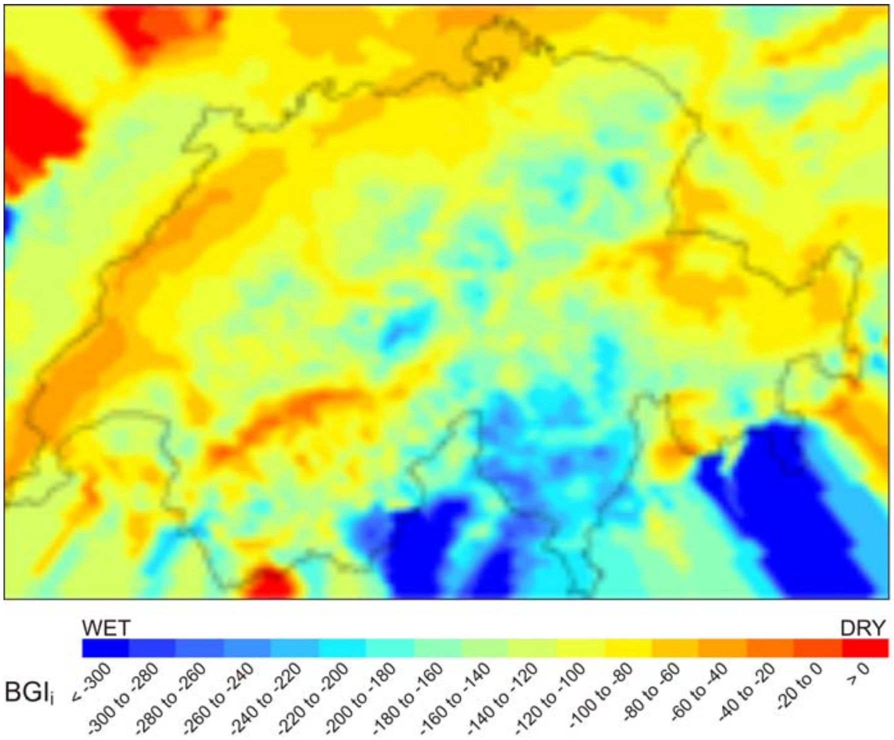
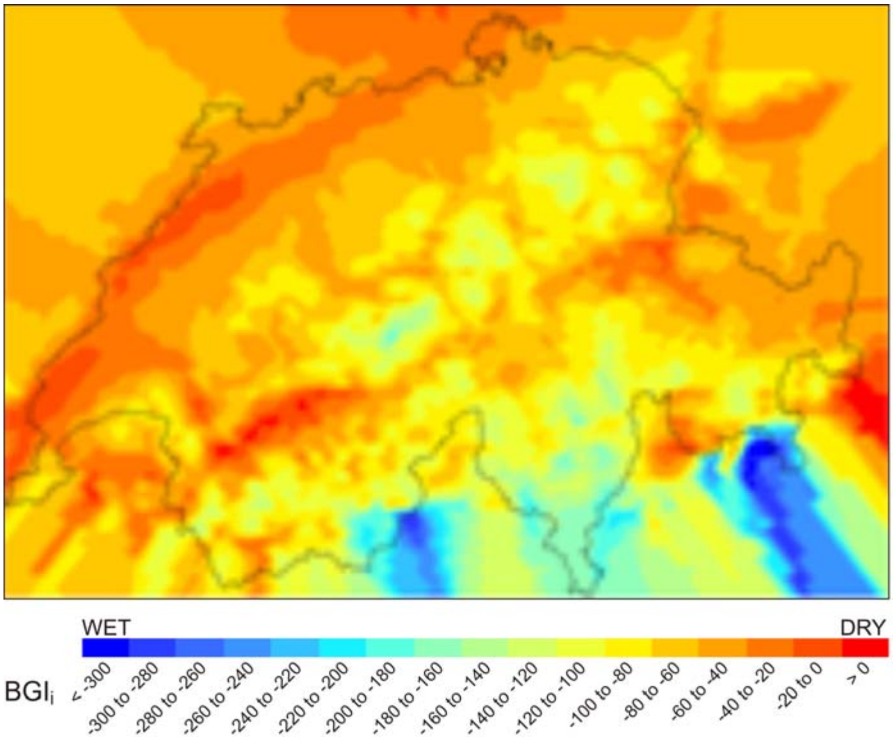


Figure A2.6: Projected Ombrothermic$_i$ Indices for May 2100 in Switzerland [3]



2.3 REQUIRED RESOURCES

To carry out ombrothermic analysis, the following resources are needed:

Data and software resources required:

- At least 30 years of historic climatological data on temperature and precipitation. This is the standard record length for determining climate normals and records of this length are generally readily available.[4]

- Statistical, spreadsheet, and graphing software to develop ombrothermic graphs.

- Interpolation of data from irregularly spaced climatological/meterological stations to a regular regional grid for spatial analysis.[5]

- (Optional) Climate change projections for future temperatures and precipitation in each region, either statistically downscaled from global model outputs, or derived from regional climate models if available. Priceputu and Greppin (2005) used outputs from two scenarios to bracket projected ranges of change.

- GIS software (e.g., ArcGIS) for mapping regions and ombrothermic humidity/aridity index results.

Level of effort and expertise required:

- For jurisdictions where there is spatially distributed temperature and precipitation data and regional climate change projections (optional), ombrothermic analysis will require a familiarity with precipitation and temperature data and competent analytical and GIS skills.

- If spatially distributed temperature and precipitation data must be derived, a person with modelling expertise will be required. The level of effort may be relatively high.

2.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

Ombrothermic analysis is a useful way to help define regional priorities for water monitoring networks for climate change adaptation in Canada for the following reasons:

- Temperature and precipitation are primary climate variables, and projections for future climate change are based on General Circulation Models (GCMs) and regional downscaled models. Temperature and precipitation are primary drivers of patterns and changes in stream hydrologic patterns, affecting runoff, seasonal and spatial patterns of discharge, and episodic events.

- The ombrothermic method presents a comparative analysis of average temporal and spatial patterns in temperature and precipitation that is considered reasonably predictive of conditions that represent water excess and water deficit. Therefore this method would be applicable for regions that may be sensitive to current and future perturbations in temperature and precipitation due to climate change.

- Ombrothermic mapping is spatially flexible, but may be best applied on regional or provincial/territorial scale. The scale limitations can be terrain dependent as greater differences in temperature and precipitation patterns may be more evident over short distances in areas of higher relief.

The original ombrothermic annual index was developed for dry Mediterranean climates, and has to be modified for the relatively water-rich situation in most locations in Canada, except for perhaps a few dry continental areas. Assuming that the locations that are most vulnerable to water-related climate change impacts are those that experience the most drought or excessive rain periods, minimum and maximum ombrothermic$_i$ values can be mapped and can serve as indicators for detecting climate change impacts. Ombrothermic$_i$ can be mapped by months or seasons depending on the objectives.

In the future, other temperature-precipitation or water balance indices might be developed to better represent the wide range of Canadian climates and associated vulnerabilities to climate change.

2.5 IN SUMMARY

Together, precipitation and evaporation are the primary components of an ecosystem's water balance. Water balance is one of the main environmental conditions that influence the vulnerability of a region to climate change. The ombrothermic method is a relatively simple method that uses generally readily available temperature and precipitation data to produce diagrams and a humidity/aridity index, which can be used to evaluate regional exposure and sensitivity to climate change as a function of precipitation and temperature – the driver of evaporation potential. The identified regional vulnerability to climate change can be useful in the setting priorities for water monitoring networks to address climate change adaptation.

Table A2.2 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements for ombrothermic analysis.

Table A2.2: Summary of the Ombrothermic Method Characteristics

FEATURES	REQUIREMENTS
Types of criteria / parameters	Ombrothermic diagram and index analysis, an integrated measure of temperature and precipitation over time, as an indicator of sensitivity to climate change.
Data needs	Historic climatological data on temperature and precipitation interpolated to a regular regional grid for spatial analysis; climate change projections for future temperatures and precipitation.
Software	GIS software for mapping regions, and ombrothermic humidity/aridity index results; data base management software for manipulation of temperature and precipitation data; statistical, spreadsheet, and/or graphing software to develop ombrothermic graphs.
Expertise	Competent analytical and GIS skills; if spatially distributed temperature and precipitation data must be derived, a person with modelling expertise would be required.
Scale considerations	Spatially flexible, however may be best applied on a large regional or province / territory scale depending on terrain conditions.

ENDNOTES

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[1] Priceputu, A. M. and H. Greppin. 2005. Modelling Climate Change Impacts and Vulnerability in Switzerland. Chapter 14 of Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment. Haurie A. and Viguier, L. pp 355-381.

[2] Image kindly provided by Professor H. Greppin, Department of Botany and Plant Biology, University of Geneva, Switzerland.

[3] Ibid.

[4] Canadian climate normals from 1971 to 2000 including monthly average temperature and precipitation values are readily available for 1480 meteorological stations across Canada from Environment Canada - http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html

[5] Gyalistras, D, 2003. Development and validation of a high-resulution monthly gridded temperature and precipitation data set for Switzerland (1951-2000). Clim. Res. 25:55-83. referenced in Priceputu and Greppin (2005) discusses the temperature and precipitation data preparation applied in Switzerland.
Other examples: Application of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) by the PRISM Climate Group, Oregon State University, http://www.prismclimate.org (documentation: http://prism.oregonstate.edu/docs/index.phtml) for development of regular spatial temperature and precipitation, accounting for topography, interpolated from meteorological station data in the United States.

A.3. WATER RESOURCES VULNERABILITY INDICATORS ANALYSIS

This section provides detailed information on how to apply Water Resources Vulnerability Indicators Analysis (WRVIA) to set priorities for water monitoring networks for climate change adaptation. Regional WRVIA has been applied to the continental United States to evaluate the vulnerability to climate change of regional water resources and water dependent resources. The analysis uses indicators to assess key aspects of water supply and use (such as stream flow, evapotranspiration losses, water quality, water withdrawals and settlement in the floodplain) to identify watersheds where water resources are currently most vulnerable to increased stress and where current vulnerability could be exacerbated or relieved by changes in mean climate and extreme events. The premise of the WRVIA is that identifying watersheds that are potentially vulnerable to adverse effects is useful for anticipating where climate change impacts might be greatest.

In the WRVIA, vulnerability is expressed as a relative measure of the extent to which the water resources or systems in a watershed might be impacted by changes in hydrology. For example low vulnerability is assigned a score of 1 while high vulnerability is assigned a score of 3. This allows a relative ranking of the vulnerability of watersheds in a region. The case study used in this section is really a sensitivity analysis, as it looks only at the relative measure of the extent to which the water resources or systems in a watershed might be impacted by changes in hydrology and does not consider exposure or adaptive capacity, the other two constituents of vulnerability.

The relatively simple WRVIA method uses available water resources data to produce maps in a GIS environment. The maps of watershed vulnerabilities can help set priorities for water monitoring networks to address climate change adaptation.

3.1 BACKGROUND INFORMATION

WRVIA is based on the concept that water resources that are currently stressed are more likely to be vulnerable to future climate change than watersheds that are not currently stressed.[1] Water managers in the U.S. identified a series of water resources indicators to evaluate potential regional vulnerabilities of watersheds in the U.S. based on current climate conditions.[2] The following criteria were used to select the vulnerability indicators:

- appropriateness and relevance to the water resource issue(s) likely to be affected by the projected changes in climate
- transparency of the measure in terms of its data inputs, formulation and interpretation, and
- feasibility based on data availability and time frame.

The indicators used in the U.S. are summarized in Table A3.1. Indicators were categorized as to whether they related primarily to:

1. Water supply, distribution and consumptive use; or
2. Instream use, water quality and ecosystem support.

Three classes of vulnerability were assigned to each indicator (1 = low, 2 = medium and 3 = high). Numeric ranges were defined for each class based on expert opinion, scientific knowledge and suitability to the study area conditions. Some of the indicators that may be relevant for setting priorities for water monitoring networks for climate change adaptation in Canada include the following:

- ***Level of development in terms of water withdrawal compared to stream flow****:* off-stream and in-stream water uses may be more vulnerable to climate change and adaptability may be more challenging in highly developed watersheds as there is less water “to spare”.

- ***Natural variability of unregulated stream flows:*** streams with high flow variability may be more vulnerable to small hydrologic changes generated by climate change.

- ***Dryness ratio:*** areas that have low precipitation and high evapotranspiration potential are more vulnerable to climate change impacts relating to agricultural productivity, ecosystem development and human uses.

- ***Groundwater depletion:*** where existing withdrawal rates may exceed recharge, increasing groundwater use as an adaptive strategy may be limited.

- ***Institutional flexibility:*** the vulnerability to climate change, and the ability to adapt to it can be measured in terms of the ability to use strategies such as water transfers and the buying and selling of water rights. This indicator is not applicable to jurisdictions which do not use “water market systems” and “water rights”. (This is an adaptive capacity indicator.)

- ***Flood risk:*** climate change vulnerability (and adaptability) relates to the size of the population within the floodplains are more vulnerable to potential floods generated by climate change.

- ***Ecosystem thermal sensitivity:*** ecosystems have adapted to existing climatic conditions and may be affected by significant temperature changes relating to climate change. For example, the vulnerability of aquatic communities is greater in streams where water temperatures are close to tolerance thresholds for aquatic populations.” (This is an adaptive capacity indicator.)

- ***Dissolved oxygen:*** the vulnerability of aquatic communities is greater in streams where current levels of dissolved oxygen are low.

- ***Species at risk:*** the vulnerability of species at risk may be greater in watersheds that currently have the greatest number of threatened and endangered water-dependent species.

- ***Freeze/thaw dates:*** ecosystems may be more vulnerable to climate change in areas where the number of freeze/thaw days are the greatest.

- ***Probability of rain-on-snow events:*** ecosystems may be more vulnerable to climate change where there are higher probabilities of rain-on-snow events, and

- ***Probability of ground freezing events:*** ecosystems may be more vulnerable to climate change where there are higher probabilities of ground freezing events.

Table A3.1: Water Resources Indicators [3]

INDICATOR	DESCRIPTION	CRITERIA THRESHOLD* 1=Low Vulnerability; 2=Medium Vulnerability; 3=High Vulnerability
WATER SUPPLY, DISTRIBUTION, AND CONSUMPTIVE USE INDICATORS		
Level of Development Q_W/Q_S	Ratio of total annual surface and groundwater withdrawal in 1990 (Q_W) to unregulated mean annual stream flow (Q_S).	Vulnerability class: 1 (<0.2), 2 (0.2-0.85), 3 (>0.85). This ratio reflects the extent to which watershed's water resources are developed for consumptive uses.
Natural Variability $\sigma Q_S/Q_S$ = CV	Coefficient of variation (CV) of unregulated stream flow, computed as the ratio of the standard deviation of unregulated annual stream flow (σQ_S) to the unregulated mean annual stream flow (Q_s).	Vulnerability class: 1 (<33%), 2 (33-67%), 3 (>67%). Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes.
Dryness Ratio $(P-Q_S)/P$	Share of total average annual precipitation (P) that is lost through evapotranspiration (ET) where ET is defines as $P-Q_S$.	Vulnerability class: 1 (<63%), 2 (63-78%), 3 (>78%). Regions with the highest evapotranspiration losses are most vulnerable to relatively small changes in precipitation.
Groundwater Depletion Q_{GW}/Q_{Base}	Ratio of average groundwater withdrawals (Q_{GW}) in 1990 to annual average baseflow (Q_{Base}), reflecting the extent that groundwater use rates may be exceeding recharge.	Vulnerability class: 1 (<8%), 2 (8-25%), 3 (>25%). Regions with high depletion rates are vulnerable to long-run changes in hydrology.
Industrial Water Use Flexibility	Share of total annual average industrial water use that is consumed (i.e., not returned to the system).	Vulnerability class: 1 (<20%), 2 (20-40%), 3 (>40%). Greater rates of consumptive use by industry can indicate more intensive use of relatively expensive water-saving technologies and, therefore, less flexibility in achieving further water savings in periods of low supply.
Institutional Flexibility	An integer-based flexibility score ranging from zero to five assigned to each state based on the relative degree of barriers to water trading.	Vulnerability class: 1 (score 0 or 1), 2 (score 2 or 3), 3 (score 4 or 5). Flexible water trading/market systems are less vulnerable and better adapted to hydrologic changes.

INDICATOR	DESCRIPTION	CRITERIA THRESHOLD* 1=Low Vulnerability; 2=Medium Vulnerability; 3=High Vulnerability
INSTREAM USE, WATER QUALITY, AND ECOSYSTEM SUPPORT INDICATORS		
Flood Risk	Population within the 500-year flood plain.	Vulnerability class: 1 (<20,000), 2 (20,000-200,000), 3 (>200,000).
Navigation	Average annual expenditures on dredging activities in navigable waterways.	Vulnerability class: 1 (<$2 million), 2 ($2-$20 million), 3 (>$20 million). Higher expenditures indicate relative importance of waterway and magnitude of existing efforts to clear waterway. Higher stream flows could result in greater deposition of sediment, while lower stream flows could require additional dredging to maintain navigable waterways.
Ecosystem Thermal Sensitivity	Sensitivity to changes in extreme temperatures. Combines vulnerability of two subindicators: Heat – The average annual number of days with maximum temperatures exceeding 35ºC. Cold – The average annual number of days with average temperatures below 0ºC.	Vulnerability class: maximum of heat or cold subindicators classifications. Heat vulnerability class: 1 (<15 days), 2 (15-40 days), 3 (>40 days). Extreme heat is a significant source of stress on ecosystems. Even regions adapted to relatively high temperatures may not easily tolerate even small increases in maximum temperatures. Cold vulnerability class: 1 (<32 days), 2 (32-85 days), 3 (>85 days). Many ecosystems, particularly lakes and forests, have evolved with specific cold weather requirements.
Dissolved Oxygen	Percent of observations of ambient concentrations less than 5 mg/L.	Vulnerability class: 1 (<3%), 2 (3-15%), 3 (>15%). Dissolved oxygen levels in waterways decline with increasing temperatures, causing stress in aquatic wildlife.
Low Flow Sensitivity	Unregulated mean baseflow in L/km^2, the amount of stream flow originating from groundwater outflow.	Vulnerability class: 1 (>2.580 L/km^2), 2 (0.711-2.580 L/km^2), 3 (<0.711L/km^2). Baseflow is a measure of the capacity of a watershed to sustain instream flows during low-flow periods. Aquatic ecosystems within watersheds with relatively low baseflows are most vulnerable to periods of severe and sustained drought.
Species at Risk	Number of aquatic/wetland species known to be at risk, either threatened or endangered.	Vulnerability class: 1 (<7 species), 2 (7-13 species), 3 (>13 species).

*Vulnerability classifications were generally determined after examination of the data distributions

3.2 WATER RESOURCE VULNERABILITY INDICATORS METHOD IN DETAIL

The steps in the WRVIA are summarized in Figure A3.1 Additional steps may be necessary depending on the management objectives identified in step 1.

Figure A3.1: Procedure for the WRVIA

STEPS	
Step 1	Identify regional management objectives
	▼
Step 2	Review available water resources data
	▼
Step 3	Select appropriate water resource indicator
	▼
Step 4	Collect selected water resource data
	▼
Step 5	Set vulnerability classes
	▼
Step 6	Calculate indicator values
	▼
Step 7	Assign vulnerability class to indicator values
	▼
Step 8	(Optional) Combine indicator classes to form component index
	▼
Step 9	Map vulnerability spatially
	▼
Step 10	Interpret results
	▼

STEPS	
Step 11	Prioritize monitoring sites

Step 1 - Identify regional management objectives: Regional management objectives are identified within the context of existing plans, policy statements and environmental conditions. This is a key step in the setting priorities for water monitoring to address climate change. Existing and potential climate change impacts on water resources to consider could include greater frequency of flood and drought, less groundwater recharge, lower groundwater levels, less stream baseflow, deterioration of water quality, greater water use during summer but less water availability, etc. Typically, the setting of regional management objectives considers environmental, technical, management and socioeconomic concerns.

Step 2 - Review available water resources data: This review is carried out to determine what data sets are available, the length of record, and the spatial coverage of key water resource data.

Step 3 - Select appropriate water resource indicator: The suite of water resource vulnerability indicators is selected based on their relevance to the identified regional management objectives (step 1) and the results of the available water resources data review (step 2).

Climate change impacts on water resources should also be considered. Potential impacts include greater frequency of flood and drought, less groundwater recharge (which leads to lower groundwater levels which leads to less stream discharge which leads to lower summer flows which leads to deterioration of habitat), deterioration of water quality, greater water use during summer but less water availability, etc.

Step 4 - Collect selected water resource data: The data required to analyse the selected indicators is compiled in a database, spreadsheet, or within a GIS environment.

Step 5 - Set vulnerability classes: In this step, vulnerability classes are set for each water resource vulnerability indicator to correspond to low, moderate and high vulnerability. The U.S. study authors set their vulnerability class ranges using expert opinion.[4] The ranges defined by them and shown in Table A3.1 may be used as a starting point.

Step 6 - Calculate indicator values: Values for the indicator(s) are measured or computed within a database or spreadsheet environment. The U.S. study authors suggest that indicators that relate to a particular component of interest (e.g., water supply, distribution and consumptive use) can be grouped to form an index if desired.[5]

Step 7 - Assign vulnerability class to indicator values: The measured or computed indicator values are assigned to a vulnerability class within the database or spreadsheet environment.

Step 8 (optional) - Combine indicator classes to form component index: If desired, indicators relating to a particular component of interest (e.g., water supply, distribution and consumptive use) can be grouped to form an index.[6]

Step 9 - Map vulnerability spatially: Vulnerability classes are mapped spatially in a GIS environment for each selected water resource component (indicator or index) to illustrate regional patterns of relative vulnerability or sensitivity to climate change for the water resource functions of interest. The indicators and/or indices may also be mapped in GIS.
Step 10 - Interpret results: Results are interpreted in relation to the regional management objectives.

Step 11 - Prioritize monitoring sites: The locations of existing monitoring sites are overlaid on top of the mapped vulnerability to identify covered and uncovered regions.

The Southern Ontario Example

In 2010, the Ontario Ministry of the Environment carried out a WRVIA to assess the sensitivity of certain southern Ontario watersheds to climate change. The five indicators used were scored from 1 (low sensitivity) to 3 (high sensitivity). These indicators were selected based on their relevance to two monitoring networks, potential climate change impacts, and the data available at a southern Ontario scale.[7]

The water resource sensitivity indicators selected were:

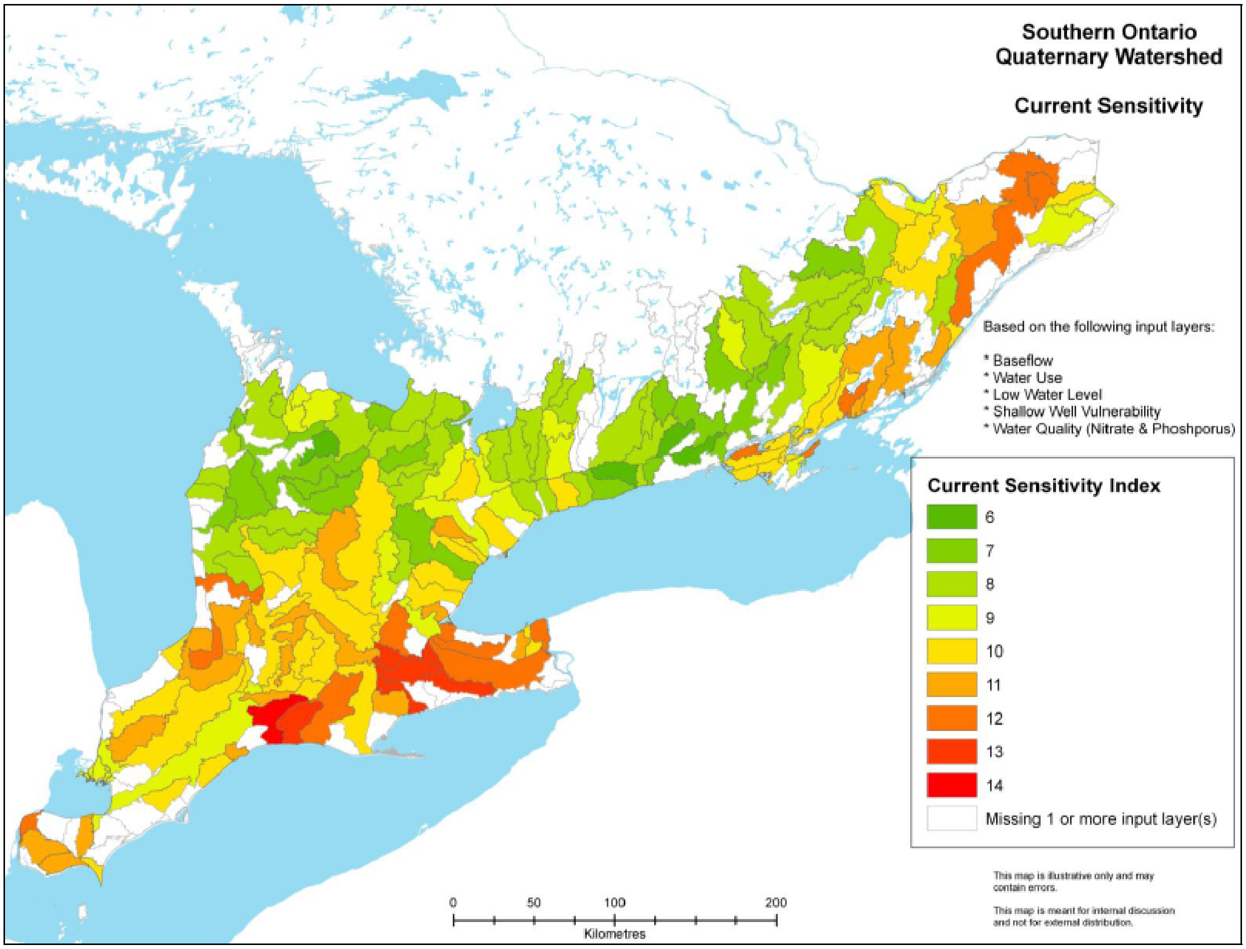
- Low water level/drought
- Shallow water well vulnerability
- Water use/demand
- Baseflow contribution
- Stream water quality.

Indicator scores were determined for each sub-watershed in southern Ontario for which the data was available. The final score for each sub-watershed – the sub-watershed's sensitivity index – is the sum of the scores of the individual indicators. Figure A3.2 shows the mapped results of the computed sensitivity index. The sub-watersheds with the lowest computed sensitivity received a score of 6 and those with the highest sensitivity received a score of 14. The total scores were used to identify watersheds that were highly sensitive to climate change impacts related to the indicators chosen. The results are being used to help set the priorities for two water monitoring networks – one for groundwater monitoring and the other for surface water quality monitoring – for use in climate change detection and adaptation within the Great Lakes Basin.

The Ministry will evaluate existing monitoring networks and make recommendations for enhancements based on:

- Local sensitivity assessment
- Potential climate change impacts
- Watershed characteristics from source protection studies and local knowledge.

Figure A3.2: Sensitivity Index for setting priorities for water monitoring networks to address climate change adaptation in a Southern Ontario Quaternary Watershed.[8]



3.3 REQUIRED RESOURCES

The WRVIA requires the following resources:

Data and software resources required:

- The data required in a WRVIA will depend on the selected indicators, which are relevant to the conditions in specific jurisdictions and the regional management objectives. Several data sets are needed to implement this kind of assessment of vulnerability. A review of the availability and quality of water resource data is necessary and good spatial coverage of the data is essential.

- The method requires basic supporting software for data set management and for calculation of the indicators and indices (database software and/or spreadsheet software capability). GIS software capability is also required, along with technical expertise in the use of the required software.

Level of effort and expertise required:

- Depending on the selected regional management objectives, a WRVIA may require ecological, hydrological, hydrogeological and hydraulic expertise to develop and assess indicators and set vulnerability classes.

3.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

This approach is well suited for assessing the regional sensitivity and vulnerability of watersheds and for identifying priorities for water monitoring networks for climate change adaptation. WRVIA approach was originally developed at a watershed scale. The method has been applied at a national scale in the U.S.[9], but could also be applied on a smaller regional scale as illustrated by the Southern Ontario Quaternary Watershed analysis.[10]

The following limitations to the WRVIA have been noted:

- indicators are selected by expert judgement, and alternatives are possible
- definition of vulnerability classes is also judgement-based
- aggregated indices are simple averages of the component indicators, with no weighting.[11]

3.5 IN SUMMARY

A Water Resource Vulnerability Indicator Analysis is a relatively simple method of evaluating the regional vulnerabilities of watersheds to climate change impacts. It uses vulnerability indicators based on commonly available water resources data, such as stream flow, flood plain mapping, water withdrawals, precipitation and evapotranspiration data. The selected indicators will depend on regional management objectives and the availability of appropriate data sets. Vulnerability is assessed through measuring or computing indicator values, assigning them to a vulnerability scale, and then mapping the results. The method requires basic database software and/or spreadsheet software capability along with competent analytical and GIS skills. The concept may be applied to national or to smaller regional scales.

Depending on the selected regional management objectives, the method may require ecological, hydrological, hydrogeological and hydraulic expertise to develop and assess indicators.

Table A3.2 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements for the WRVIA.

Table A3.2: Summary of the Water Resources Vulnerability Indicators Analysis Characteristics

FEATURES	REQUIREMENTS
Types of criteria/ parameters	Vulnerability or sensitivity indicators to assess regional vulnerabilities of watersheds to climate change.
Data needs	Data needs are driven by the vulnerability indicators selected; potentially many data sets needed with good spatial coverage (e.g., discharge/stream flow, population density, flood plain designations, annual surface and ground water withdrawals, precipitation and evapotranspiration, etc.).
Software	Basic supporting software for data set management, and for calculation of indicators and indices; GIS software.
Expertise	Expertise in GIS, data management and statistical analyses; need ecological/hydrogeological expertise to develop and assess indicators.
Scale considerations	Can be applied at the watershed, regional or national scale.

ENDNOTES

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[1] Hurd, B., N. Leary, R. Jones, and J. Smith, 1999. Relative regional vulnerability of water resources to climate change. Journal of the American Water Resources Association 35(6):1399-1409.

[2] Ibid.

[3] Adapted from Hurd, B., N. Leary, R. Jones, and J. Smith. 1999. Relative regional vulnerability of water resources to climate change, 1999. Journal of the American Water Resources Association 35(6):1399-1409.

[4] Hurd, B., N. Leary, R. Jones, and J. Smith, 1999. Relative regional vulnerability of water resources to climate change. 1999. Journal of the American Water Resources Association 35(6):1399-1409.

[5] Ibid.

[6] Ibid.

[7] MacRitchie, S.M., P.K. Goel, G. Kaltenecker, F. Fleischer, A. Jamieson, M. Millar, L. Ramanathan, C. Worte, D. Grgic, K. Zaletnik Hering, 2010. An approach for evaluating two monitoring networks for climate change detection and adaptation in Great Lakes watersheds in Ontario. Poster, IAGLR May 2010.

[8] Ibid.

[9] Hurd, B., N. Leary, R. Jones, and J. Smith. 1999. Relative regional vulnerability of water resources to climate change, 1999. Journal of the American Water Resources Association 35(6):1399-1409.

[10] MacRitchie, S.M., P.K. Goel, G. Kaltenecker, F. Fleischer, A. Jamieson, M. Millar, L. Ramanathan, C. Worte, D. Grgic, K. Zaletnik Hering, 2010. An approach for evaluating two monitoring networks for climate change detection and adaptation in Great Lakes watersheds in Ontario. Poster, IAGLR May 2010.

[11] Hurd, B., N. Leary, R. Jones, and J. Smith. 1999. Relative regional vulnerability of water resources to climate change, 1999. Journal of the American Water Resources Association 35(6):1399-1409.

APPENDIX B

Methods for Evaluating Water Monitoring Networks for Climate Change Adaptation

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APPENDIX B: METHODS FOR EVALUATING WATER MONITORING NETWORKS FOR CLIMATE CHANGE ADAPTATION

Three methods were identified based on the following attributes: applicability at different scales; relatively moderate expertise and data requirements; and ability to produce results that are commensurate with the monitoring objectives in terms of scope and level of detail. The three methods are:

1) Audit Approach
2) Monte Carlo Network Degradation Approach
3) Multivariate Methods

The relative simplicity of these methods, particularly the first two methods, was a key reason for their selection. References for and brief descriptions of other monitoring network evaluation methods are provided in Appendix C.

Selection of which of the statistical methods (Monte Carlo and there are two multivariate methods) to use could involve testing of each of the methods with the same set of data. The optimal method would produce results with the least amount of variance.

B.1. AUDIT APPROACH

The audit approach is a relatively simple way to evaluate water monitoring networks for climate change adaption purposes. It incorporates expert knowledge of existing networks in a methodical and detailed review of existing and proposed stations against pre-set criteria. A number of network scenarios are then evaluated against their ability to meet overall network objectives and cost.

The audit method described here was used in New Brunswick to evaluate and rank the stream flow gauging stations in the provincial hydrometric network in order to create a more cost-effective network.[1] The approach is easily transferable to evaluating water monitoring networks for climate change adaptation planning. Criteria are developed for the evaluation. The criteria would reflect factors that are relevant to regional climate change adaptation priorities. These might include the "suitability" of the station site, representation of the regional hydrology, usefulness for estimation purposes (e.g., for ungauged sites), and servicing of client needs for climate change adaptation actions and strategies. Each station is then audited in a roundtable session that involves the operators and managers responsible for the networks and climate change specialists involved in water monitoring. Existing and proposed stations are scored against the evaluation criteria and ranked using the sum of points accumulated for each priority consideration. The results of the evaluation and ranking of the stations are used to construct alternate network scenarios and sets of network objectives for use in making network design decisions. A cost benefit analysis can be conducted by comparing the benefits of each scenario (total station audit points) and increase or decrease in operating costs that would be incurred by the implementation of the scenario.

1.1 BACKGROUND INFORMATION

The evaluation of the New Brunswick water monitoring network began with certain analyses and assessments of the network. This included consideration of basic principles of hydrometric design and how well the existing network met those principles. The water resource specialists who carried out the evaluation in New Brunswick described the network design criteria they used.[2] A number of methodologies were investigated to establish network criteria for regional hydrology purposes. Ultimately, the researchers developed a hypothetical "minimum" coverage network based on physiographic-climatic zones as the representative hydrologic units, as well as a "target" or "optimal" network based on hydrologic regions for which relationships could be defined to allow for estimations of stream flow at ungauged sites.

Other references on hydrometric network design are noted in Appendix C: Information Sources – Information Sources – Water Monitoring Networks and Network Design.

1.2 AUDIT APPROACH IN DETAIL

The steps for an audit approach are summarized in Figure B1.1. The audit process described here uses a roundtable or workshop session to accomplish the assessment or “auditing” of the stations. Both existing and proposed stations are rated against the same factors. Proposed stations are those stations that may have been suggested by the pre-audit investigations or those stations necessary to address needs not currently served.

Figure B1.1: Procedure for the Audit Approach [3]

STEPS	
Step 1	Establish monitoring goals and network objectives
	▼
Step 2	(Optional) If the required information is not available, conduct assessments and investigations; those results are integrated by the audit
	▼
Step 3	Establish criteria for evaluation of each station in network
	▼
Step 4	Organise monitoring stations
	▼
Step 5	Convene roundtable session

STEPS	
	▼
Step 6	Assess individual stations
	▼
Step 7	Rate stations and assign audit points
	▼
Step 8	Identify “constraints of practicality”
	▼
Step 9	Construct alternate network scenarios
	▼
Step 10	Assess impacts and cost implications of network alternatives
	▼
Step 11	Formulate recommendations for monitoring networks for climate change adaptation

Step 1 - Establish monitoring goals and network objectives: The monitoring goals and network objectives are used in the evaluation. The monitoring goals typically include the need to detect trends and evaluate the effectiveness of adaptation management strategies. The monitoring goals also influence which evaluation criteria are used in the analysis.

Step 2 - (Optional) If the required information is not available, conduct assessments and investigations; those results are integrated by the audit: The types of assessments carried out will depend on the type of monitoring network(s) being evaluated, the state of knowledge of the existing network(s) and the monitoring goals and evaluation criteria.

Step 3 - Establish criteria for evaluation of each station in network: The criteria will depend on the monitoring goals and evaluation criteria and also on the nature and characteristics of the monitoring network. Criteria may include: site characteristics, usefulness of data for transfer to ungauged sites, identified client needs for climate change adaptation strategies, and the value and regional importance of the water resources and services.

Step 4 - Organise monitoring stations: “Organise” the monitoring stations so that they are grouped to facilitate the ranking deliberations. Stream flow gauging stations may be organised according to drainage basins. The stations being audited may include proposed as well as existing stations.

Step 5 - Convene roundtable session: Convene a roundtable session or workshop to carry out the audit. Participants include those with the required knowledge of the network(s) being audited and the expertise to evaluate stations against the criteria. These individuals may include the operators and managers responsible for the network(s) and climate change planners.

Step 6 - Assess individual stations: Assess (score) each station individually in terms of the extent to which the station meets the evaluation criteria. Assess both existing and proposed stations.

Step 7 - Rate stations and assign audit points: Base the ranking on the composite of points accumulated for all criteria. The higher the total station audit points accumulated by a particular station, the higher the relative value of benefits derived from the station. Rank the total set of existing and proposed stations in order of accumulated station audit points.

Step 8 - Identify "constraints of practicality": This step provides an opportunity to qualify the ranking in light of certain constraints. For example, network agencies may have formal and legal commitments that require them to maintain certain stations.

Step 9 - Construct alternate network scenarios: A simplistic gauging strategy based on the audit ranking might include as many stations as permitted by funding levels and operating budgets, in descending order of points achieved in the evaluation. However, incorporating the "constraints of practicality" may alter this type of scenario. The scenarios may ranged from a minimum monitoring for climate change adaptation including formal commitments to an all-inclusive option addressing all identified needs including an "optimal" adaptation network.

Step 10 - Assess impacts and cost implications of network alternatives: Assess the impacts of each network alternative as well as the cost implications of each alternative (i.e., resulting increase or decrease in operating cost) against the overall network objectives. A cost benefit analysis can be done by comparing the benefits of each scenario (total station audit points) and the increase or decrease in operating costs resulting from the implementation of the scenario (i.e., by adding new stations to address deficiencies or closing existing stations that became redundant for a particular scenario).

Step 11 - Formulate recommendations for monitoring networks for climate change adaptation: Using the audit results, and with reference to the monitoring goals and network objectives established in Step 1, formulate recommendations for monitoring networks requirements for climate change adaptation.

The New Brunswick Example [4]

The following example describes how the audit approach was used to evaluate New Brunswick's hydrometric network of stream flow gauges.

In this evaluation a number of network assessments were carried out prior to the audit so that the results of those assessments could be used in the audit process. This included:

- Criteria were developed for a minimum regional network and for a target regional network, and appropriate networks were identified that would satisfy those criteria. Those appropriate networks were compared to the existing network to identify deficient and/or redundant elements in the existing configuration.

- User surveys were done to determine if the existing network was meeting user needs.

The audit approach was then used to integrate the results of these assessment and other factors. A set of criteria ("priority considerations") was used to "audit" the network's individual stations. The criteria used are presented in Table B1.1.

Table B1.1: New Brunswick Network Evaluation Station Audit Criteria [5]

CRITERIA "PRIORITY CONSIDERATIONS"	RATIONALE
FOR SITE CHARACTERISTICS	
Mean annual flow less than 25 m^3/s; 25 to 125 m^3/s; greater than 125 m^3/s	Large drainages provide more representative sample for province as whole
Water level only	These stations provide less information than flow station
Quality of record	The better the quality of record the greater the information value
Period of record (years) 0 to 5 6 to 10 11 to 15 16 to 25 26 to 40 Greater than 40	Short records need to be extended to establish a record. Once record is established it is of decreasing value, with exception of very long records, which become valuable for index purposes
Proximity to climate station	Stations whose record may be readily related to comparative meteorological data have added information value
IDENTIFIED CLIENT NEEDS – REGIONAL HYDROLOGY	
Identified for minimum flow network	Only stations identified as essential for regional hydrology were assigned these points
Regional hydrology priority(importance for estimation)	Stations that would contribute to enhanced data transfer capabilities were scored here

CRITERIA “PRIORITY CONSIDERATIONS”	RATIONALE
Importance for long term index monitoring/inventories	Primarily stations serving national index network, as well as some others of importance for transboundary areas
Importance for "special" regional needs (e.g., small basin data, technical pilot projects, etc.)	Also includes special studies and jurisdictional responsibilities
Client priority: Water supply "Other" infrastructure (transportation, sewerage, etc.) Flooding Environmental impacts Fisheries Energy Navigation and recreation	Based on user surveys and station audit; weightings were determined by consensus of team members
Also serves identified operational need	Extra points assigned for stations that served both regional and operational needs
IDENTIFIED CLIENT NEEDS - OPERATIONAL	
Importance for federal obligations/responsibilities (treaties, agreements, boards, etc.)	Only stations serving formal federal commitments included here
Importance for provincial responsibilities (agreements, boards, etc.)	Only stations serving formal provincial commitments included here
Client priority: Water supply "Other" infrastructure (transportation, sewerage, etc.) Flooding Environmental impacts Fisheries Energy Navigation and recreation	Based on user surveys and station audit; weightings were determined by consensus of team members
Also serves identified regional hydrology need	Extra points assigned for stations that served both regional and operational needs
REGIONAL IMPORTANCE OF WATER RESOURCES	
Population density	Pro-rated general indicator of intensity of water use

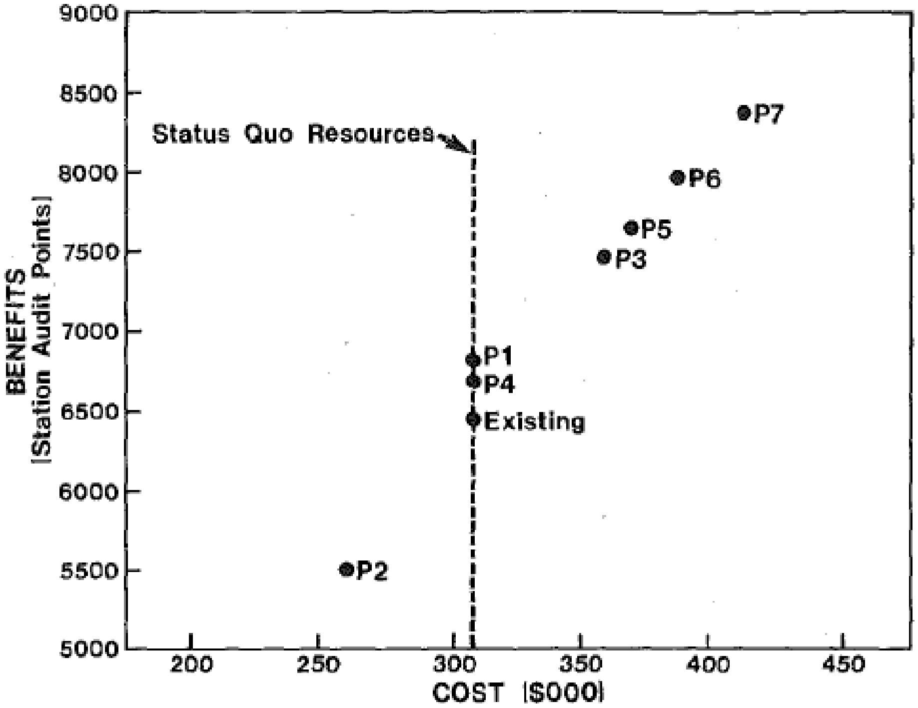
CRITERIA “PRIORITY CONSIDERATIONS”	RATIONALE
Municipal water use	Pro-rated from an inventory of surface supplies; adjusted for sources outside basin
Industrial water use	Pro-rated from industrial water user survey inventory of surface supplies
Fisheries priority	Generalized Canada Land Inventory sport fishing capability
Hydro potential Major Small scale None identified	Based on departmental inventory of major potential sites and an Acres Consulting study of potential small-scale sites
Economic pressure	Based on inventories of existing and proposed capital works
Flooding	Priority sites identified by federal and provincial departments
Water quality problems/issues	Based on ambient values and known point sources of pollutants
Water shortage potential	Water use analysis model using high-growth projections and hypothesized low flows

A roundtable session comprising all study team members and the operators and managers responsible for the network was convened to complete the audit exercise. The existing and proposed stations were organized by drainage basin and participants assessed the stations against the evaluation criteria and how well they met the network objectives. Decisions were reached by consensus. The consensus-building, the sharing of information, and the overall integrating nature of the exercise, was found to be one of the most valuable elements of the whole evaluation exercise.[6]

The stations were rated against the criteria and ranked on the basis of the composite of points accumulated. A number of alternate network scenarios were identified using the prioritized ordering of the stations. The alternate networks scenarios addressed different objectives, ranging from minimum delivery of a "public good" mandate to all inclusive delivery of identified needs, including an "optimal" regional stream flow network. The final results included the identification of specific network improvements designed to satisfy hydrometric needs. These improvements were presented in the form of a list of network adjustment scenarios that could be used as a management guide.

The audit process did not include any determination of a dollar value for benefits; only an ordering of relative worth. A cost benefit analysis was conducted in terms of the total station audit points (benefits) versus the increase or decrease in implementation costs that would be incurred by adding new stations or closing existing ones according to the alternate network scenario requirements. A graphical depiction of this analysis is shown in Figure B1.2.

Figure B1.2: Relative Benefits and Costs of Network Scenarios [7]



The water resource specialists who reported on the New Brunswick example found that the application of the audit process to the network evaluation provided the following key management tools:

- A rationale for reallocating existing resources from lower to higher priorities
- An ordering of priorities for allocation of additional resources
- An ordering of priorities for an imposed reduction of resources.

1.3 REQUIRED RESOURCES

The audit approach method requires the following resources:

Data and software resources required:

- The data required will depend on the evaluation framework and criteria used. At a minimum the audit will require hydrologic network information and questionnaire/survey inputs from experts/operators, agency scientists, and data users.

- Software to do basic tabulation is required; information management and GIS mapping software would be an asset.

Level of effort and expertise required:

- Expert knowledge of the network(s) being evaluated, such as knowledge about the suitability of the station sites, how representative the network data are of the regional hydrology, usefulness network data for estimation purposes and data transfer to ungauged areas, etc.

- Ability to organise and run a roundtable audit workshop

- Ability to use of software to tabulate results. Ability to use information management systems and GIS software capability an asset.

1.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

The audit approach methodology is flexible. The objectives can be customised to match management priorities, as can be the form of the results. The evaluation framework can be easily adapted and applied to most situations.[8]

Jurisdictions might consider applying the audit approach method as a first step in assessing the adequacy of a hydrometric and/or climatological monitoring network. An audit can identify over-sampled or under-sampled areas, and can highlight parts of the network that are considered by operators or users to provide data that is unrepresentative or inadequate. Rectification of inadequate sampling at one or more specific gauge locations could be rectified on the basis of the audit results.

1.5 IN SUMMARY

The audit approach is a relatively simple way to evaluate water monitoring networks for climate change adaption purposes. It incorporates expert knowledge of existing networks in a methodical and detailed review of existing and proposed stations against pre-set criteria. Monitoring goals and evaluation criteria are set. A roundtable workshop is convened with operators and managers responsible for the water monitoring network and climate change planners. Workshop participants assess each station, existing or proposed, in terms of the extent to which it meets the evaluation criteria and network goals. Network stations are then ranked according to the points obtained in the audit process. The results of the evaluation and ranking of the stations are used to construct alternate network scenarios. These are assessed against their ability to meet network objectives. A cost benefit analysis can be conducted by comparing the benefits and implementation costs of each scenario.

The audit method relies on expert knowledge of the network being evaluated and well articulated criteria. The ability to organise and run a roundtable audit workshop is also required. It requires basic software for the tabulation of the audit results. GIS mapping and information management software and capabilities would be an asset.

The audit approach may be applied to at a wide range of scales, from national to smaller regions.

Table B1.2 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements.

Table B1.2 Summary of the Audit Approach Characteristics

FEATURES	REQUIREMENTS
Data needs	Hydrologic network information; questionnaire/survey inputs from experts/operators, agency scientists, data users, climate change experts and planners
Software	Basic tabulation software, information management and GIS mapping software would be an asset
Expertise	Expert knowledge of the network(s) being evaluated, such as knowledge about the suitability of the station sites, how representative the network data are of the regional hydrology, usefulness network data for estimation purposes and data transfer to ungauged areas, etcetera; also the ability to organise and run a roundtable audit workshop.
Applicable scenario	Meteorological networks or hydrological networks

Scale considerations	Relatively scale independent; can be applied to scale required by jurisdiction whether it be at a national, regional, watershed or at a smaller scale

ENDNOTES

[1] Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

[2] Ibid.

[3] Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

[4] Ibid.

[5] After Table 2 *in* Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

[6] Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

[7] Figure 2 *in* Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

[8] Davar, Z.K. and W.A. Brimley. 1990. Hydrometric network evaluation: audit approach. Journal of Water Resources Planning and Management, 116 (1): 134-146.

B.2. NETWORK DEGRADATION ANALYSIS – MONTE CARLO

Network degradation analysis (NDA) is used to evaluate existing meteorological or hydrometric monitoring networks and to determine the network density required to meet a particular monitoring goal or goals. The NDA simulates a systematic decrease or “degradation” of a network’s sampling station density and determines how well each successive degraded network performs compared to the full network. Monte Carlo sampling, the random selection of stations from the entire network of existing stations, is used to create the simulated degraded networks. The degraded networks created are subsets of the full network, with less spatial and/or temporal data densities than the full network.

This NDA method has been used in numerous applications. For the U.S. Climate Reference Network (CRN), the National Oceanic and Atmospheric Administration (NOAA) has used it to determine the spatial density and total number of monitoring stations required to improve the capacity to observe climate change and temporal variability across the U.S. The goal of the CRN is “to provide homogeneous observations of temperature and precipitation from benchmark stations that can be coupled with historical observations for adequate detection and attribution of climate change”.[1] The analysis conducted for the CRN divided the 48 conterminous states into 115 grid cells and within each grid cell created hypothetical networks from representative subsamples of stations, selected by Monte Carlo sampling, from an existing higher-density baseline network. The adequate number of CRN stations was defined as the number of stations required to reproduce, within certain predetermined error limits, observed annual temperature and precipitation trends across the U.S. Although the study concentrated on a definition of climatic behaviour that emphasized trends, the researchers assert that their technique can be applied to other measures of climate behaviour.[2]

The NDA method is also used in cost-benefit analysis of monitoring networks and in the determination of the relationship between station density and network performance.

This evaluation method assumes that the existing full monitoring network, or other sampling data, generally provides reasonable representation of the true values of the parameters measured. Although NDA can be used to evaluate the adequacy of existing network density in areas that are generally well sampled, it does not give direct inputs on optimal locations for gauges to be removed or added.

2.1 BACKGROUND INFORMATION

Degraded Network Analysis using Monte Carlo Re-sampling Technique

The Monte Carlo sampling technique uses a computer program to randomly select stations from the full network to create new “degraded” networks which have less spatial and/or temporal density. The ability of the smaller network to detect changes in the parameter values over time is determined by looking at the difference between the full network prediction and the smaller network prediction. The difference is estimated from the results of repeated sampling of the same size randomly selected from the full network. For example, sampling can be repeated, say 100 times or more, for each lower spatial resolution network with a certain number of stations. Each sampling for a specific network size is called a "realization". The difference in results from the full network and each of the realizations of the smaller network is measured by a value called the mean absolute error (MAE), which measures how well the degraded network predicts the trends that were predicted from the data collected by the full network.

The MAE is calculated by the following equation:

Equation B2.1: Mean Absolute Error

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y - f_i\right|$$

Where

MAE is the mean absolute error in trends of a parameter
f_i is the predicted value of the trend of a parameter for a specific realization of a degraded network
y is the expected value of the trend of a parameter (using the full network)
i is the realization (1, 2,… *n*)
n is the number of realizations (100 times in the U.S. example)

The acceptable degraded network size is determined based on an allowable mean absolute error.

As noted above, the Monte Carlo sampling technique was used in a NDA to estimate station density for the U.S. CRN. It was used to evaluate the performance of a degraded network (a network composed of a smaller number of stations) compared with a full network (a network composed of all the stations that are available in a region).[3] Because it uses less data, the smaller network is expected to less accurately predict the annual temperature and precipitation trends in the U.S., than the full network. The authors of the U.S. study noted the following advantages of Monte Carlo sampling:

- the effect of multiple network configurations and poorly distributed lower spatial distribution networks are averaged out, and

- the influence of undetected inhomogeneous station records is reduced.[4]

2.2 NETWORK DEGRADATION ANALYSIS IN DETAIL

The steps for an NDA-Monte Carlo analysis are summarized in Figure B2.1. The analysis described here uses observed annual temperature and precipitation trends as the measure by which the degraded networks to the full-density network are compared. Other measures of climate behaviour could be used.[5]

Figure B2.1: Procedure for the NDA – Monte Carlo

STEPS		
Step 1	Establish monitoring goals and evaluation criteria	
	▼	
Step 2	Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. temperature, precipitation or flow)	
	▼	
Step 3	Review and compile historic monitoring data for selected parameters	
	▼	
Step 4	Perform Monte Carlo sampling and analysis as follows:	
	▼	
	Step 4a	Randomly sample from the full network of stations to select the desired number of stations for the smaller network; this step is done for each network size scenario
		▼
	Step 4b	Compute the average of the parameter value for each year of data to generate an “ensemble time series” of the spatially averaged parameter
		▼
	Step 4c	Compute the trends for each ensemble time series of the degraded network scenario
		▼
	Step 4d	Repeat steps 4a to 4c to create multiple realizations for the degraded network scenario and calculate mean absolute error (*MAE*) for the trends
		▼
	Step 4e	Repeat steps 4a to 4d for all possible degraded network size scenarios
		▼
	Step 4f	Determine the relationship between mean absolute error and degraded network size by doing a regression analysis

STEPS		
		▼
	Step 4g	From the relationship of step 4f, obtain the required number of stations for selected *MAE* values for the parameter
	▼	
Step 5	Formulate recommendations on monitoring networks requirements for climate change adaptation.	

Step 1 - Establish monitoring goals and evaluation criteria: The monitoring goals typically include the need to detect trends and evaluate the effectiveness of adaptation management strategies. The monitoring goals also influence which evaluation criteria are used in the analysis. For the method described here, the evaluation criteria could be the differences between the annual temperature and precipitation trends computed from the degraded network and that obtained from the full network.

Step 2 - Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. temperature, precipitation or flow): Identify the monitoring network(s) to be evaluated based on the monitoring goals defined in Step 1. Select the parameter(s) to be used in analysis (e.g. temperature, precipitation or flow). The parameters selected will depend on both the monitoring goals and evaluation criteria established in Step 1.

Step 3 - Review and compile historic monitoring data for selected parameters: Provide information on the data sets that are available, the length of record, and the spatial coverage of the selected parameter(s). (Note: Some of this information may have been retrieved in order to establish the evaluation criteria of Step 1.) A mapping of the location of the available stations would be useful at this stage. The data required to analyse the selected parameter(s) can be compiled in the form of a database or spreadsheet(s).

Step 4 - Perform Monte Carlo sampling and analysis as follows:

Step 4a - Randomly sample from the full network of stations to select the desired number of stations for the smaller network; this step is done for each network size scenario: A subset of a certain number (N_s) of stations is randomly selected from the full network of stations to create a degraded network size scenario. This step is done with sophisticated software that has Monte Carlo sampling and statistical capability. The sampling is done without replacement, so a station can only be included once in the same sample.

Step 4b - Compute the average of the parameter value for each year of data to generate an "ensemble time series" of the spatially averaged parameter: The ensemble time series of the spatially averaged parameter for the scenario are compiled. The ensemble time series of a sample of a specific degraded network size are composed of the series of years and the average value of the parameter calculated from the parameter's values collected over that time period.

Step 4c - Compute the trends for each ensemble time series of the degraded network scenario: The trends (e.g., the change of the average temperature over time) are computed for each ensemble time series of the same degraded network scenario.

Step 4d - Repeat steps 4a to 4c to create multiple realizations for the degraded network scenario and calculate mean absolute error (MAE) for the trends: Steps 4a to 4c are repeated 100 times to generate multiple realizations for the degraded network scenario and the MAE is computed for the 100 trends associated with degraded network scenario of N_s stations.

Step 4e - Repeat steps 4a to 4d for all possible degraded network size scenarios: Steps 4a to 4d are repeated for all possible degraded network size of N_s stations ($N_s = 1, 2, 3,... N\text{-}1$).

Step 4f - Determine the relationship between mean absolute error and degraded network size by doing a regression analysis: In this step, a regression between mean absolute error and degraded network size is obtained using each of the 100 realizations for each degraded network size. Regression analysis is a mathematical technique used to find the relationship between a dependent variable and an independent variable. For the regression analysis a graph is produced by plotting the MAE values against the number of stations. The graph shows how the number of stations needed varies with a range of predetermined levels of error (MAE).

Step 4g - From the relationship of step 4f, obtain the required number of stations for selected MAE values for the parameter: Using the regression obtained in step 4f or a graphical representation of that regression determine the required number of stations for selected MAE values for the parameter.

Step 5 - Formulate recommendations on monitoring networks requirements for climate change adaptation: Summarize recommendations on potential degraded network sizes based on the monitoring goals and evaluation criteria established in Step 1.

The North-Central New-Mexico, U.S. Example

The following example describes how the NDA-Monte Carlo procedure was applied to monitoring network stations in a part of north-central New Mexico. The area was one of the 115 grid cells in the U.S. Climate Reference Network study referred to above. Each grid cell in that study extended over 2.5° latitude and 3.5° longitude. [6]

For the overall study, and to examine how the rate of representativeness of the data deteriorates with decreased monitoring density, the researchers used the NDA-Monte Carlo method to systematically decrease the network resolution by selectively removing stations from the initial full-density network. They established that the ideal density for the climate monitoring network would be the density of stations for which the data when analysed reproduced the observed trends identified by the data from the full-density network to within a certain range of error.

The full network of north-central New Mexico was composed of 38 stations which had been measuring temperature (and precipitation) for the last 30 years. A simple regression analysis of that station data showed that the mean annual temperatures had increased over that record period. The Monte Carlo re-sampling technique was used to evaluate how degraded networks would perform in the following manner:[7]

1) The full network of 38 stations ($N = 38$) was randomly re-sampled, without replacement (without using the same station more than once in a sample). The size of the subset included N_s stations, where N_s is greater than or equal to 1, and N_s is less than N. For this example, we can assume that the first sample size was composed of 3 randomly selected stations ($N_s = 3$) having a mean annual temperature time series from 1971 to 2000.

For example the time series of the 3 randomly selected stations could appear as follows[8]:

T_1 = {(1971, 11.21°C); (1972, 11.26°C); (1973, 11.35°C)… (2000, 11.50 °C)}
T_2 = {(1971, 10.91°C); (1972, 11.30°C); (1973, 11.41°C);… (2000, 11.53 °C)}
T_3 = {(1971, 11.84°C); (1972, 11.43°C); (1973, 11.29°C);… (2000, 11.47 °C)}

Time series are (year, average temperature calculated from the year's monitoring data from that station); (year, average temperature...); etc.

2) The ensemble time series of spatially averaged temperature were compiled from the data of the 3-station network. For example an ensemble time series from the first realization of the randomly drawn 3-station network is computed as follows:

Equation B2.2: Ensemble Time Series

$$\hat{T}_1 = \frac{1}{3}\sum_{j=1}^{3} T_j$$

Where

$\hat{T}_1$ is an ensemble time series derived from the first realization of 3 randomly selected stations
T_j is a time series from the *j* th station
j is the station (1, 2, 3 in this case)

To illustrate this step, using the above T1, T2, T3 time series, the ensemble time series for the first realization is:

$\hat{T}_1$ = {(1971, 11.32°C); (1972, 11.33°C); (1973, 11.35°C); … (2000, 11.50°C)}[9]

3) The trends for each realization of an N_s-station ensemble time series were then computed. The trend is essentially the slope of the relationship of predicted temperature and time expressed in years. For example, the trend in the first ensemble time series could be an increase in temperature of about 0.01°C per year (or 0.1°C per decade).

4) Steps 1 to 3 were repeated 100 times to generate multiple realizations for a N_s-station degraded network (in this case $N_s = 3$).

5) For each N_s -station degraded network, the mean absolute error for trends was computed as follows:

Equation B2.3: Mean absolute error for the trends

$$MAE_s = \frac{1}{100}\sum_{k=1}^{100}\left|\frac{\Delta\overline{T}}{\Delta t} - \frac{\Delta\hat{T}_k}{\Delta t}\right|$$

Where

MAE_s is the mean absolute error for trends for the N_s -station network

$\Delta\overline{T}/\Delta t$ is the temperature trend for the full network time series

$\Delta\hat{T}_k/\Delta t$ is the temperature trend for the k^{th} realization of a N_s -station network

j is the realization (1, 2,… 100)

For $N_s = 3$, the computed MAE_s was about 0.079°C per decade (as read from Figure B2.2.

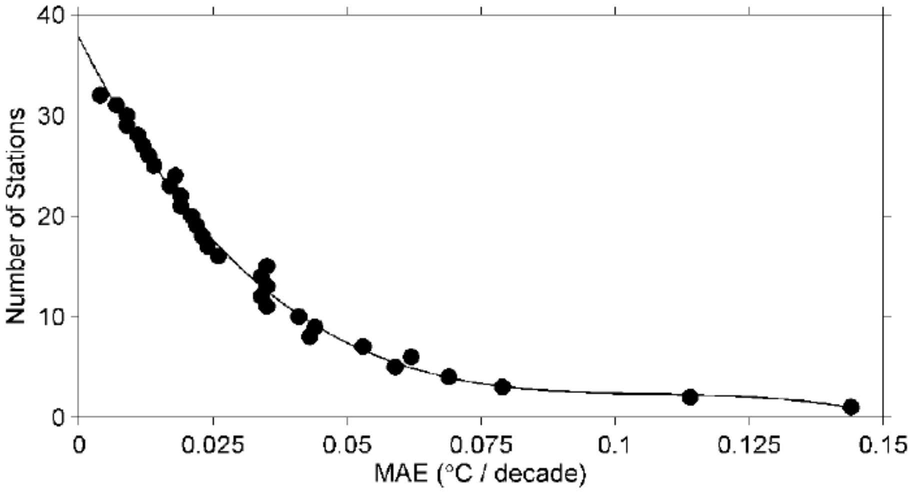
6) Steps 1-4 were repeated for all possible degraded network size ($N_s = 1, 2, \ldots 37$).

7) Then a regression was performed between the MEA_s values and N_s. using a fourth-order polynomial to provide a better fit than lower order polynomials. A fourth order polynomial may be expressed as follows:

$$N_s = a_0 + a_1 MAE_s^1 + \ldots + a_4 MAE_s^4$$

Figure B2.2 shows the relationship for north-central New Mexico.

Figure B2.2: Relationship between MAE and N_s in a degraded network [10]



8) Using a graph such as Figure B2.2 or using the regression polynomial, with a set goal in MAE, one can determine the appropriate number of stations to achieve that goal. For example, 3 stations are expected to predict temperature trends between 1971 and 2000 in central-north New-Mexico with a MAE_s of 0.080°C. If the goal is to obtain a MAE_s of less than 0.025°C, then at least 15 stations are required in the degraded network.

U.S.- wide result

In the overall study, using the NDA-Monte Carlo analysis of temperature and precipitation trends in the U.S., it was found that a network of 327 stations for the contiguous U.S. was able to detect temperature and precipitation trends within the acceptable error limits of 0.10°C per decade for temperature and 2.0% of mean annual precipitation per decade for precipitation.

Other Studies

Network Degradation Analyses have been used in similar applications. For example, and also at the national scale in the U.S., this approach has been used to determine the network density which would be able to reproduce interannual variability in temperature and precipitation data.[11]

A Monte Carlo analysis was also performed in the U.S. to assess the effects of limited station density on the uncertainties in the temporal variations of heavy precipitation event frequencies observed between 1895 and 2004.[12]

2.3 REQUIRED RESOURCES

The NDA-Monte Carlo method requires the following resources:

Data and software resources required:

- The data required in a NDA will depend on the monitoring goals and the selected parameter(s), such as temperature, precipitation and stream flow.
- The method requires basic data management, database software and/or spreadsheet software as well as sophisticated supporting software for the calculations. The statistical software must have Monte Carlo sampling capabilities and statistical analysis capabilities. GIS software capability could be used for mapped presentation of the networks – existing and proposed.

Level of effort and expertise required:

- Technical expertise in the use of the required statistical software and for the determination of mean absolute error is required.

Note: Depending on the selected management objectives and evaluation criteria, an NDA-Monte Carlo study could require advanced hydrological modelling expertise if distributed hydrological watershed models are used to evaluate trends in climate change.[13]

2.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

This approach is well suited where there is a desire to reduce the number of stations in a network composed of a large number of stations. The method can evaluate the performance of degraded networks and ensure that they can still meet the regional management objectives for climate change adaptation.

An NDA may be applied to a national scale or smaller regions where there are several stations. In the U.S. example the method has been applied to 2.5° latitude by 3.5° longitude grid scale, but the results were compiled at a national scale.

As noted in the introduction to this section 2, an NDA does not give direct inputs on optimal locations for gauges to be removed or added. If analytic support is needed for such decisions, it is recommended that reduction/error minimization or modelling methods be considered.

2.5 IN SUMMARY

A Network Degradation Analysis is a relatively widely used method that can be employed when reducing the number of stations in a network is considered. The degradation of network density process can be used determine the relationship between station density and network performance in a cost-benefit analysis. The method can evaluate the performance of degraded networks and ensure that they can still meet the monitoring required for the climate change adaptation strategies.

The NDA method requires historic monitoring network data (e.g., for precipitation, temperature, and stream flow) from the full network, or some other representative sampling, so that statistical differences can be calculated between the historic data and data from the subsets. Results are presented in the form of tables and graphs of estimates and mean absolute error estimations for the different degraded network scenarios. The method requires basic database software and/or spreadsheet software capability along with sophisticated statistical software. Competent statistical skills are required to perform the analysis. The concept may be applied to national or to smaller regional scales.

Table B2.1 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements.

Table B2.1 Summary of the Network Degradation Analysis – Monte Carlo Characteristics

FEATURES	REQUIREMENTS
Data needs	Meteorological data (e.g. temperature, precipitation) or hydrometric data (e.g. stream flow)
Software	Basic supporting software for data management and sophisticated statistical software; GIS would be an asset
Expertise	Understanding of Monte Carlo sampling technique; statistical knowledge to perform mean absolute error calculations; competence in use of required software
Applicable scenario	Meteorological networks or hydrological networks
Scale considerations	Nationally or smaller scale

ENDNOTES

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[1] Janis, M.J., K.G. Hubbard, and K.T. Redmond. 2004. Station density strategy for monitoring long-term climatic change in the contiguous United States. Journal of Climate 17:151-162.

[2] Ibid.

[3] Ibid.

[4] This is explained in Janis, M.J., K.G. Hubbard, and K.T. Redmond. 2004. Station density strategy for monitoring long-term climatic change in the contiguous United States. Journal of Climate 17:151-162.
The technique assumes that stations are homogeneous within a defined network. However, if stations are not homogeneous within the region, the method attenuates the effects a station might have on the rest of the network.

[5] Ibid.

[6] Janis, M.J., K.G. Hubbard, and K.T. Redmond. 2004. Station density strategy for monitoring long-term climatic change in the contiguous United States. Journal of Climate 17:151-162.

[7] Adapted from Janis, M.J., K.G. Hubbard, and K.T. Redmond. 2004. Station density strategy for monitoring long-term climatic change in the contiguous United States. Journal of Climate 17:151-162.

[8] This time series was developed by JFSA using a fabricated data set to illustrate what a time series looks like.

[9] Ibid.

[10] Janis, M.J., K.G. Hubbard, and K.T. Redmond. 2004. Station density strategy for monitoring long-term climatic change in the contiguous United States. Journal of Climate 17:151-162.

[11] Vose, R.S., and M.J. Menne, 2004. A method to determine station density requirements for climate observing networks. Journal of Climate 17:2961-2971.

[12] Kunkel, K.E., T.R. Karl and D.R. Easterling, 2007. A Monte Carlo assessment of uncertainties in heavy precipitation frequency variations. Journal of Hydrometeorology 8:1152-1160.

[13] An example of a “Monte Carlo study” of physically based distributed parameter hydrologic model simulating overland and stream flow is described in: Krajewski, W. F., V. Lakshmi, K. P. Georgakakos, and S. C. Jain. 1991. A Monte Carlo study of rainfall sampling effect on a distributed catchment model, Water Resour. Res., 27(1), 119-128. The evaluation of the adequacy of the lesser data density was based on the evaluation of hydrologic characteristics, including peak flow, time to peak, and total runoff volumes.

B.3. MULTIVARIATE METHODS

Multivariate analysis methods are statistical techniques that are used to assess the statistical relationship between variables. The two methods described here, the Principal Component Analysis and the Clustering-based Analysis, can be used to identify groups of stations with similar behaviour (i.e., stations that record similar data over time). The similarity of stations is referred to as the "homogeneity" of stations and is of interest in network rationalization as interpolation of data between stations is best done between homogenous stations.

Multivariate analysis methods can also identify regions of low representation (fewer stations compared to temporal and spatial variations in data set) and regions with high representation and potentially redundant stations. This is useful for monitoring network evaluation and optimization for climate change adaptation.

It should be recognized however that these methods assume stationarity of time series which is no longer valid under a changing climate.

The inputs for these methods are meteorological and/or hydrometric data:

1) **Principal Component Analysis (PCA):** This method identifies groups of stations that have similar spatial and temporal properties. For example, Principal Component Analysis would be able to identify homogeneous stations, such as two stations located within 1 km from each other on a flat terrain that measure similar mean annual precipitation over time. The results of the analysis are expressed as correlation coefficients between the stations and principal components (a concept that is explained in section 3.1). The coefficients are presented in tables and graphs for ease of comparison. The PCA can also be used to identify relatively homogeneous and redundant stations. This method has been applied to precipitation data in the Appalachian Region of Québec, in order to identify homogeneous stations, and therefore redundant stations that could be closed.[1]

2) **Clustering-based Analysis (CBA):** This method identifies groups of stations that have similar spatial and temporal properties using cluster tree diagrams (or dendrograms). For example, the CBA method would be able to identify two homogeneous hydrometric stations located 5 km from each other on a river segment without incoming tributaries, which measure similar annual peak flow over time. CBA has been used to rationalize a stream flow monitoring network in and near the Pembina River basin in southern Manitoba. Although this method can be used to identify redundant stations, it does not differentiate between them. Accordingly, external criteria are required to select the most representative station(s)). However, the CBA could be used in combination with other statistical methods, such as the variance reduction or error minimization methods, to identify the station(s) that provide the most information. The CBA method has been applied to stream flow data from the Pembina River watershed in the Manitoba, Canada – North Dakota, U.S., in a rationalization process to reduce the number of hydrometric stations.[2]

These two multivariate methods are applicable at multiple scales. Both approaches require sophisticated statistical software, GIS software and data base/data management software. The methods require expertise in the use of the statistical and data management software. GIS skills are required for the presentation of results and higher level statistical and analytical skills are required for the implementation of both evaluation methods. The final selection of the stations is up to the judgement of the user.

3.1 BACKGROUND INFORMATION

Principal Component Analysis

PCA is a way of analysing large sets of empirical data to identify patterns in the data. It also provides a means of representing the data in a way that highlights similarities and differences within the data. These types of patterns can be hard to discern in large multi-dimensional data sets. An advantage of PCA is that once the patterns have been identified in the data, the method compresses the data by reducing the number of dimensions, without much loss of information.[3]

The mathematical procedures in the PCA involve several sets of statistical analysis. A number of possibly correlated variables, such as precipitation data recorded at different stations, are transformed into a smaller number of uncorrelated variables called principal components (or axes). The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. The variability is quantified using statistical measures called the sum of squares and correlation coefficients (these concepts are explained below). The first principal component is defined as the axis for which the sum of squares of the projections of the points on that axis is maximized.

The transformation from the larger number of variables to a smaller number of variables is done by a process called “orthogonal linear transformation”. The orthogonal linear transformations project the data to a new plane that is characterized by the greatest variance for each principal component. Note: “orthogonal” is to be perpendicular and a “plane” is an abstract surface such as those used in geometry.

As such, the first principal component (principal component of level or order $k = 1$) is chosen to explain, as much as possible, the variability in the data from the different stations. Each succeeding principal component (principal component of order $k = 2, 3, \ldots$) is chosen to explain, as much as possible, the remaining variability. The method uses computer programs to identify the principal components and to compute the correlation statistics. The first principal component will be the axis for which the sum of squares of the projections of the points on that axis is maximized. The sums of squares (SS) are defined as follows:

Equation B3.1: Sum of squares

$$SS = \sum_{i=1}^{n} \left(X_i - \overline{X} \right)^2$$

Where

SS is the sum of squares
X_i is i^{th} data point
$\overline{X}$ is the mean of the data
i is the data point
n is the number of data points

To define the second principal component or axis (of order k=2), the points are projected again and this time on a plane that is orthogonal to the first axis. The second axis is also defined so that the sum of squares of the projections of the points on that axis is maximized. The next axes are defined the same way as the second axis. Each successive principal component explains less and less of the variability (or total variance) in the data.

Once the principal components are obtained, a correlation coefficient between the variable (e.g., precipitation) and the principal component of order k is computed. The correlation coefficient is expressed as follows:

Equation B3.2: Correlation coefficient [4]

$$r_{jk} = C_{jk} \lambda_k^{1/2}$$

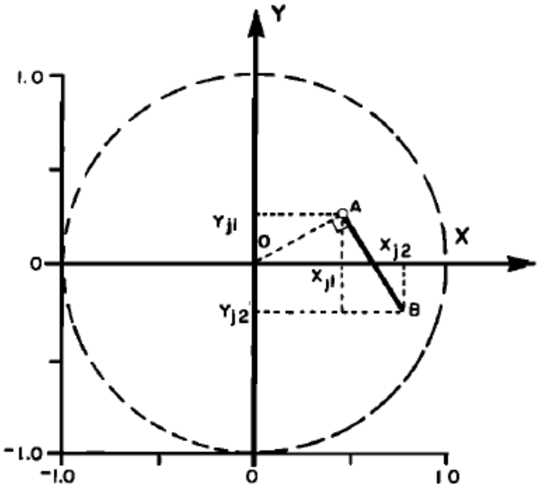
Where

r_{jk} is the correlation coefficient between the variable and the principal component of order k
C_{jk} is the eigenvector between station j and the principal component
λ_k is the eigenvalue of principal component k

Eigenvectors and eigenvalues are mathematical terms. “Eigen” means characteristic or innate. The eigenvectors with the largest eigenvalues correspond to the dimensions that have the strongest correlation in the data set. The results of a PCA are correlation coefficients between stations and principal components. The PCA multivariate method assumes that stations having similar correlation coefficients of the first principal components can be grouped together as they have a certain degree of statistical homogeneity. The number of principal components to consider will generally depend on the desired explained total variance.

In PCA analysis, graphical representations are used as it is difficult to identify homogeneous stations just by looking at tables. The results are usually presented in the three-dimensional graph in which each axis is a principal component. Figure B3.1 illustrates another, perhaps more meaningful, method that can be used to graphically represent the results of a PCA. On the figure a station *j* is represented by vector *AB* in the plane of principal components 2 and 3.

Figure B3.1: Graphical representation of the correlation coefficient of the first principal component in the plane of principal component 2 (x axis) and 3 (y axis) [5]



The coordinates of points A and B are as follows:

Equations B3.3 and B3.4: Points for vector AB [6]

Equation B3.3:

Point A = $(X_{j1},Y_{j1}) = (C_{j2}\lambda_2^{1/2}, C_{j3}\lambda_3^{1/2})$

Equation B3.4:

Point B = $(X_{j2},Y_{j2}) = \left(X_{j1} \pm \frac{C_{j1}\lambda_1^{1/2}}{\left[1+(X_{j1}/Y_{j1})^2\right]^{1/2}}, Y_{j1} - (X_{j1}/Y_{j1})(X_{j2} - X_{j1}) \right)$

It is noted that all variables have been defined previously.

The figure shows that, to respect the orthogonality of principle components, vector AB is drawn perpendicular to vector OA, which represents the multiple correlations between station *j* and the first principal component. All principal components can be represented this way. On this figure the circle centred on the origin represents multiple correlation coefficients equal to 1. When all vectors representing each station of a network are graphed, the stations that lie close to each other in the graph can be identified as homogeneous stations.

The authors of the Eaton River study, which is described below in section 2.2, took an additional step in the PCA, called the varimax method, which further defines the grouping of the stations. With the varimax method, the total explained variance is redistributed by rotating the principal axes.[7] The PCA method described here does not include the varimax however its application is described in Morin et al (1979). (See Appendix C: Information Sources - Evaluation Methods: Multivariate Methods).

Clustering-Based Analysis

A Clustering-Based Analysis (CBA) is a technique used to group similar stations (for example clusters of stations that fall within various hydrological or meteorological categories). CBA can be used to ensure that all geographical regions are represented in the network[8]. Several clustering methods can be found in the literature. The hierarchical clustering approach presented here is referred to as the average-linkage clustering method. Its procedure (or algorithm) can be summarized as follows:[9]

1) Define the similarity measure between all pairs of groups of stations where a single station is just a special case of a group. The similarity measures are represented by a lower diagonal matrix of similarity measure values between all possible pairs of stations. The similarity measure is defined as follows:

2) Identify the two groups, *A* and *B*, where the r_{XY} is a maximum and replace *A* and *B* with a new group *C* composed of the stations either in group A or group B or in both group A and B (group *C* is the union of groups *A* and *B*, or mathematically: $C = A \cup B$).

3) For each group not involved in the amalgamation in step 2, calculate the new values of r_{XC} as follows:

4) Using the updated group similarity values, repeat steps 2 and 3 until one group remains.

Equation B3.5: Similarity measure r_{XY}

$$r_{XY} = \frac{\sum_{i=1}^{n_x} \sum_{j=1}^{n_Y} r_{ij}}{n_X n_Y}$$

Where

r_{XY} is the similarity measure between all pairs of groups where a single station is just a special case of a group
r_{ij} is the correlation coefficient between stations *i* and *j*
X is a group of stations
Y is another group of stations
i is station in the group of stations *X*
j is a station in the group of stations *Y*
n_X is the number of stations in the group of stations *X*
n_Y is the number of stations in the group of stations *Y*

Equation B3.6: Similarity measure r_{XC}

$$r_{XC} = \frac{\sum_{i=1}^{n_x} \sum_{j=1}^{n_C} r_{ij}}{n_X n_C}$$

Where

r_{XC} is the amalgamated similarity measure between group *X* not involved in step 2 and new group *C*
r_{ij} is the similarity measure between stations *i* and *j*
X is a group of stations not involved in step 2
C is the new group of stations = $A \cup B$
i is station in the group of stations *X*
j is a station in the group of stations *C*
n_X is the number of stations in the group of stations *X*
n_C is the number of stations in the group of stations *C*

The above procedure is included in existing statistical software packages.

At each stage of the clustering process, a station is retained from each group of stations. This station is identified in a second phase that is not included in the hierarchical clustering algorithm. The selection of one particular station from a group of similar stations could involve considerations of many factors such as the length of data record at a station, the quality of the data, economic constraints, the users and uses of the data and a measure of overall similarity of the station with the other stations in the group. Other considerations are discussed by the authors of the hydrometric network evaluation.[10]

A matrix of similarities can be used in order to consider the multipurpose nature of stream flow data. The similarity matrix has been designed to consider different flow measurements components such as low flow data (e.g., annual low flows), average flow data (e.g. mean annual flows) and high flow data (e.g., maximum mean daily flows). The similarity matrix is defined as follows:

Equation B3.7: Similarity matrix

$$r_{ij} = \frac{1}{K}\sum_{k=1}^{K} w^k r_{ij}^k$$

Where

r_{ij} is the similarity matrix measure between stations *i* and *j*

r_{ij}^k is the correlation between stations *i* and *j* for similarity component *k*

w^k is a weight applied to component *k* which reflects the relative importance of the component

K is the number of components included in the composite station pair similarity

i and *j* are the stations being analysed for similarities

3.2 MULTIVARIATE METHODS IN DETAIL

Principal Component Analysis

The steps in the PCA are summarized in Figure B3.2.

Figure B3.2: Procedure for the PCA

STEPS		
Step 1	Establish monitoring goals and evaluation criteria.	
	▼	
Step 2	Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. precipitation)	
	▼	
Step 3	Review and compile historic monitoring data for selected parameters	
	▼	
Step 4	Perform principal component analysis as follows:	
	▼	
	Step 4a	Determine the principal component, the axis for which the sum of squares of the projections of the points on that axis is maximized
		▼
	Step 4b	Compute the correlation coefficients between the stations and the principal component
		▼
	Step 4c	Compute the explained variance for the principal component
		▼
	Step 4d	To determine the next axis, project the points on a plane that is orthogonal to the current principal component (or axis)
		▼
	Step 4e	Repeat steps 4a to 4d for the next principal component (of order 2, 3, etc.) until the total explained variance reaches an acceptable level
		▼

STEPS		
	Step 4f	Produce graphical representation of the results.
		▼
	Step 4g	(Optional) Plot confidence limits on the graph
		▼
	Step 4h	(Optional) Rotate axis to redistribute the total explained variance
		▼
	Step 4i	Identify homogeneous stations
		▼
Step 5	Select representative stations	
	▼	
Step 6	Formulate recommendations on monitoring networks requirements for climate change adaptation	

Step 1 - Establish monitoring goals and evaluation criteria: The monitoring goals typically include the need to detect trends and evaluate the effectiveness of adaptation management strategies. The monitoring goals also influence which evaluation criteria are used in the analysis. The PCA method described here can identify groups of stations whose data have similar behaviour and potentially redundant stations in an existing monitoring network.

Step 2 - Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. precipitation): Identify the monitoring network(s) to be evaluated based on the monitoring goals defined in Step 1. Select the parameter(s) to be used in analysis (e.g. precipitation). The parameters selected will depend on both the monitoring goals and evaluation criteria established in Step 1.

Step 3 - Review and compile historic monitoring data for selected parameters: The review and compilation of available parameter data will provide information on the data sets that are available, the length of record, and the spatial coverage of the selected parameter(s). (Note: Some of this information may have been retrieved in order to establish the evaluation criteria of Step 1.) A mapping of the location of the available stations would be useful at this stage. The data required to analyse the selected parameter(s) can be compiled in the form of a database or spreadsheet(s).

Step 4 - Perform the principal component analysis as follows:

Step 4a - Determine the principal component, the axis for which the sum of squares of the projections of the points on that axis is maximized: Determine the principal component, using equation B3.1. This step is done with sophisticated software that has PCA statistical capability.

Step 4b - Compute the correlation coefficients between the stations and the principal component: Correlation coefficients between the stations and the principal component are computed using the PCA software (equation B3.2).

Step 4c - Compute the explained variance for the principal component: The explained variance for the principal component is computed using the PCA software.

Step 4d - To determine the next axis, project the points on a plane that is orthogonal to the current axis: The points are projected on a plane that is orthogonal to the current axis for determination of the next principal component.

Step 4e - Repeat steps 4a to 4d for the next principal component (of order 2, 3, etc.) until the total explained variance reaches an acceptable level: The acceptable level would need to be defined.

Step 4f - Produce graphical representation of the results: The results are usually presented in the three-dimensional graph in which each axis is a principal component. The other method that can be used to visually illustrate the results of a PCA is presented in section 3.1. More information is provided by researchers who have used PCA in the study of precipitation station networks.[11]

Step 4g - (Optional) Plot confidence limits on the graph: Plot 80% (or another) confidence limit on the graph. More information is provided by researchers who have used PCA in the study of precipitation station networks. [12]

Step 4h - (Optional) Rotate axis to redistribute the total explained variance: The axis of the principal components can be rotated to redistribute the total variance between the principal axes. This step may provide more objectivity in the grouping process. The varimax method can be used to perform this rotation.

Step 4i - Identify homogeneous stations: Groups of similar (homogeneous) stations are identified using tabulated correlation coefficients and graphical representations.

Step 5 - Select representative stations: Identify representative stations if it is necessary to reduce the number of stations of a network. This step can consider geographical location and local conditions.

Step 6 - Formulate recommendations on monitoring networks requirements for climate change adaptation: Recommendations are summarized on potential groups of homogeneous stations based on the monitoring goals and evaluation criteria established in Step 1. The PCA can be used in combination with other evaluation methods of monitoring networks.

The Eaton River Precipitation Network PCA Example

The PCA procedure was applied to the Eaton River precipitation network located in the Appalachian region in Québec, Canada. In their publication, Morin et al. (1979) present an example in which eighty (80) 10-day cumulative precipitation amounts from 1966 to 1975 (eight 10-day cumulative amounts per year from the 75th day of each year to the 154th day of the year, for 10 years), from 14 stations were analysed, for the spring (and summer) season. This example was created by those authors for illustration purposes. Table B3.1 presents the correlation coefficients results for the spring scenario.

Table B3.1: Correlation coefficients between principal components and stations computed from eighty 10-day cumulative precipitation amounts in spring – No rotation of axis [13]

STATION NUMBER	PRINCIPAL COMPONENTS			MULTIPLE CORRELATION COEFFICIENT
	1	2	3	
1	0.887	0.304	0.260	0.974
2	0.945	-0.116	0.184	0.970
3	0.937	0.000	-0.186	0.956
4	0.907	-0.327	-0.022	0.965
5	0.948	0.146	-0.028	0.960
6	0.940	-0.162	0.177	0.971
7	0.945	0.072	0.039	0.949
8	0.945	-0.008	-0.121	0.953
9	0.950	0.043	-0.068	0.954
10	0.968	0.063	-0.015	0.971
11	0.952	-0.170	0.111	0.973
12	0.928	0.037	-0.209	0.952
13	0.971	0.051	-0.123	0.980
14	0.968	0.069	0.017	0.971
Eigenvalue	12.244	0.310	0.262	
Explained variance (%)	88.9	2.2	1.9	
Total explained variance (%)	88.9	91.1	93.0	

In the above example only three components were necessary to account for 93% of the total variance. Figure B3.3 is a graphical representation of the results. This figure was created since stations having similar behaviour could not be easily identified just by looking at the results presented in Table B3.1.

In this figure, the outer extremities of the vectors representing the multiple correlation coefficients are relatively close to the perfect multiple correlation circle. This indicates that three components are quite sufficient to explain the variability at the station sites.

The authors identified four groups of similar stations by comparing the relative positions of the vectors representing the stations: group 1 (station 1); group 2 (stations 5, 7, 10 and 14); group 3 (stations 3, 8, 9, 12 and 13); and group 4 (stations 2, 4, 6 and 11). It is noted that this grouping is somewhat arbitrary as the network could have been divided into smaller groups. The grouping is based on professional judgement and should be done in relation to identified regional monitoring goals.

The researchers of the Eaton River study used the varimax method (referred to at the end of Section 3.1) to further explain their groupings. In the varimax method the principal axes are rotated. Table B3.2 presents the correlation coefficients between the new principal axes and the stations. In the table, the highest correlation coefficient between each of the stations has been identified with the symbol *. When these highest correlation coefficients are used, three groups can be identified: group A (station 1); group B (stations 3, 5, 7, 8, 9, 10, 12, 13 and 14); and group C (stations 2, 4, 6 and 11). Group B is in fact a combination of the previously identified groups 2 and 3, and could as well be divided into two sub-groups. These three groups can also be seen on Figure B3.3.

Figure B3.3: Graphical representation of the PCA example [14]

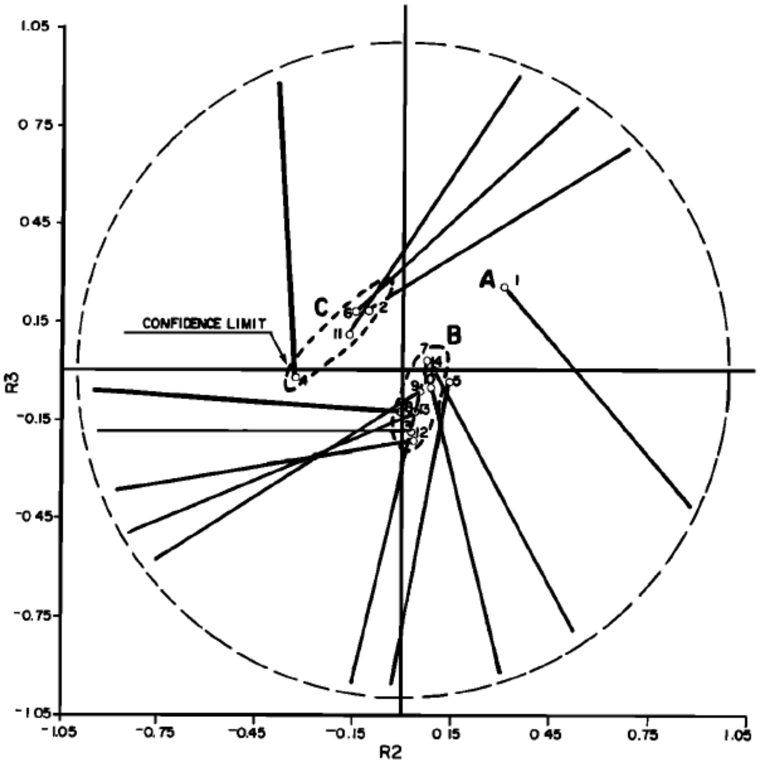


Table B3.2: Correlation coefficients between principal components and stations computed from eighty 10-day cumulative precipitation amounts in spring – after varimax rotation of axes with Kaiser normalization [15]

STATION NUMBER	PRINCIPAL COMPONENTS		
	1	2	3
1	0.408	0.359	**0.808***
2	0.430	**0.689***	0.531
3	**0.727***	0.485	0.387
4	0.527	**0.766***	0.260
5	**0.639***	0.427	0.575
6	0.423	**0.719***	0.496
7	**0.573***	0.502	0.567
8	**0.681***	0.515	0.423
9	**0.653***	0.494	0.489
10	**0.628***	0.506	0.542
11	0.480	**0.712***	0.458
12	**0.745***	0.444	0.393
13	**0.709***	0.485	0.473
14	**0.603***	0.511	0.564

Note: The highest correlation coefficient between each of the stations has been identified with the symbol *

The authors of the Eaton River precipitation network study determined confidence limits, represented by ellipses on Figure B3.3. As such, the 80% confidence limits were drawn for groups B and C. From those, it was observed that station 5 cannot be considered a member of group B. Another observation is that the ellipses have an elongated shape. When this happens, it is preferable to maintain more than one station to represent the group. The authors of the study suggest that looking at geographical location can help in the final grouping of stations. The study showed which stations were redundant and could be closed, if necessary.

Clustering-Based Analysis

The steps in the CBA are summarized in Figure B3.4.

Figure B3.4: Procedure for the CBA

STEPS	
Step 1	Establish monitoring goals and evaluation criteria

STEPS		
	▼	
Step 2	Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. flow)	
	▼	
Step 3	Review and compile historic monitoring data for selected parameters	
	▼	
Step 4	Perform clustering-based analysis:	
	▼	
	Step 4a	Calculate the similarity measure between all pairs of groups of stations
		▼
	Step 4b	(Optional) If more than one flow characteristic is being considered, compute the similarity matrix for multiple components (or flow characteristic)
		▼
	Step 4c	Identify two groups having the highest similarity measure and combine them into one group
		▼
	Step 4d	Compute the amalgamated similarity measure between all groups that were not combined in step 4c and the new group formed in step 4c
		▼
	Step 4e	Repeat steps 4c an 4d until one group remains
		▼
	Step 4f	Build the cluster three diagram based on the grouping of stations obtained in steps 4a to 4e
		▼
	Step 4g	Identify break points on the cluster tree diagram
		▼
	Step 4h	Determine the number of stations to be retained in the rationalized network
		▼

STEPS	
Step 5	Identify possible stations to be retained in monitoring network
	▼
Step 6	Formulate recommendations on the stations to be retained in monitoring network for climate change adaptation

Step 1 - Establish monitoring goals and evaluation criteria: The monitoring goals typically include the need to detect trends and evaluate the effectiveness of adaptation management strategies. The monitoring goals also influence which evaluation criteria are used in the analysis.

Step 2 - Select monitoring network(s) to be evaluated and the parameter(s) to be used in analysis (e.g. flow): Identify the monitoring network(s) to be evaluated based on the monitoring goals defined in Step 1. Select the flow characteristics for which similarities will be defined (e.g. mean annual flows, annual low flows, etc.). Annual extremes and average flow conditions are the most commonly used characteristics. For example, if water supply is an issue for climate change adaptation, then average annual flow could be of interest. If flood forecasting is an issue for climate change adaptation, then annual peak flow could be of interest. The parameters selected will depend on both the monitoring goals and evaluation criteria established in Step 1.

Step 3 - Review and compile historic monitoring data for selected parameters: The review and compilation of available parameter data will provide information on the data sets that are available, the length of record, and the spatial coverage of the selected parameter(s). (Note: Some of this information may have been retrieved in order to establish the evaluation criteria of Step 1.) A mapping of the location of the available stations would be useful at this stage. The data required to analyze the selected parameter(s) can be compiled in the form of a database or spreadsheet(s).

Step 4 - Perform clustering-based analysis: Perform the clustering-based analysis using statistical software as follows:

Step 4a - Calculate the similarity measure between all pairs of groups of stations: The similarity measure between all pairs of groups of stations is calculated using Equation B3.5.

Step 4b - (Optional) If more than one flow characteristic is being considered, compute the similarity matrix for multiple components (or flow characteristic): If more than one flow characteristic is being considered, compute the similarity matrix for multiple components (or flow characteristic) using Equation B3.7.

Step 4c - Identify two groups having the highest similarity measure and combine them into one group.

Step 4d - Compute the amalgamated similarity measure between all groups that were not combined in step 4c and the new group formed in step 4c: Compute the amalgamated similarity measure between all groups not involved in step 4c and the new group formed in step 4a or 4b (depending on the scenario).

Step 4e - Repeat steps 4c and 4d until one group remains.

Step 4f - Build the cluster tree diagram based on the grouping of stations obtained in steps 4a to 4e.: Build the cluster tree diagram (also called dendrogram) based on the grouping of stations obtained in steps 4a to 4e.

Step 4g - Identify break points on the cluster three diagrams: Identify break points on the cluster tree diagram. Break points can be obtained each time stations are grouped to form clusters in the cluster tree diagram.

Step 4h - Determine the number of stations to be retained in the rationalized network: Determine the number of stations to be retained in the rationalized network based on the break points and monitoring goals identified in Step 1.

Step 5 - Identify possible stations to be retained in monitoring network: Although this method can be used to identify redundant stations, it does not differentiate between them. Therefore, in a rationalization approach, stations to be retained must be selected using external criteria. This step can consider the criteria listed in step 1.

Step 6 - Formulate recommendations on the stations to be retained in monitoring network for climate change adaptation: Recommendations are summarized on stations to be retained in a monitoring network based on monitoring goals and evaluation criteria established in Step 1. The CBA can be used in combination with other evaluation methods of monitoring networks. The method could also be used in combination with other statistical methods, such as the variance reduction or error minimization methods, to identify the station(s) that provide the most information.

The Pembina River Stream Flow CBA Example

This method has been applied to stream flow data from the Pembina River watershed, which extends across both sides of the Manitoba, Canada – North Dakota, U.S. border.[16]

A total of 22 stream flow stations were analysed in order to identify clusters of stations that fall within various hydrometric data categories. The following three scenarios were considered:

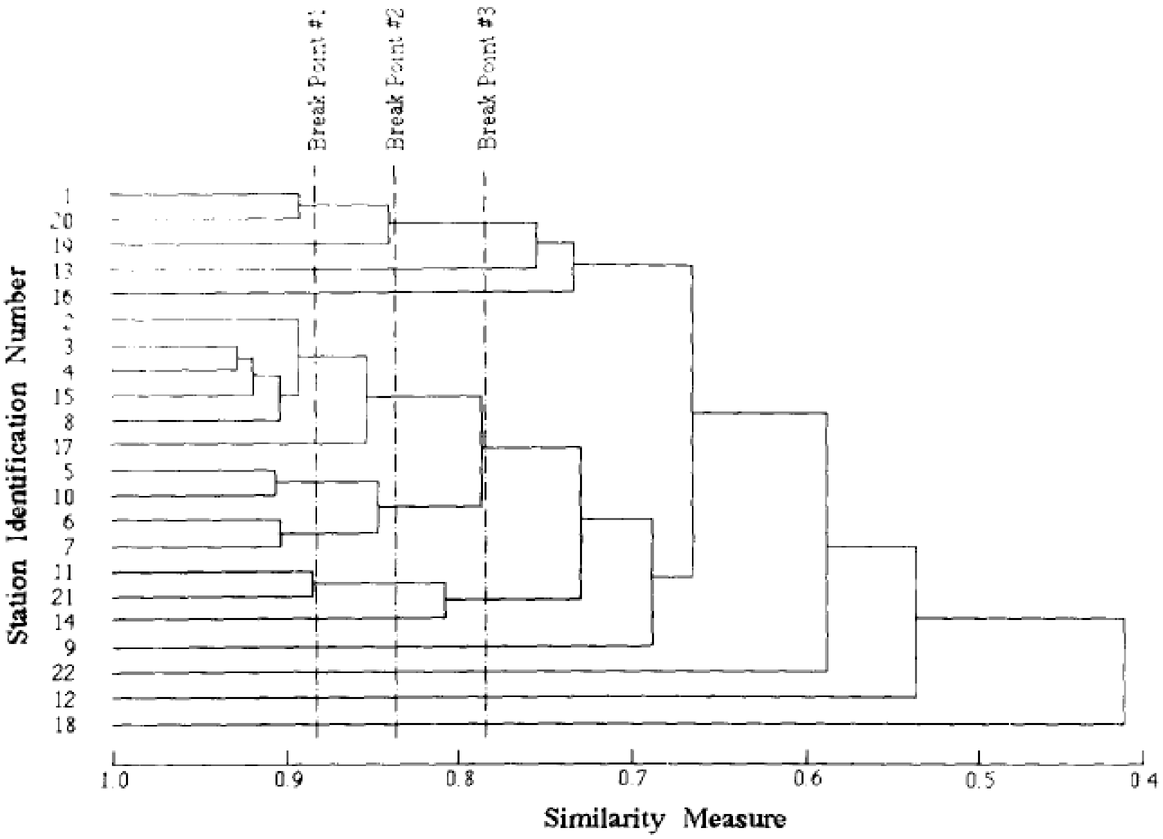
> **Scenario A:** Similarity of extremes (peak flow) only. This scenario could be applied to monitoring networks designed to enhance flood forecasting and analysis for climate change adaptation.

Scenario B: Similarity in seasonal values (annual flows) only. This scenario could be applied to monitoring networks designed to address problems of water supply for climate change adaptation.

Scenario C: Similarity in extremes and seasonal values weighted equally. This scenario could be applied to monitoring networks designed to be operated for a mix of requirements for climate change adaptation.

Figure B3.5 is a cluster tree obtained for similarity in annual peak flows (Scenario A). The figure shows the order at which the stations were successively amalgamated into groups (or clusters) at various values of the similarity measure. Each horizontal line in the diagram represents a group of one or more stations can be found at any value of the similarity measure axis. It is from these groups that representative stations can be selected. Three break points are identified on Figure B3.5. These break points can be used to determine the number of stations and the station membership for any group by following the tree to the extreme left, where the station numbers are identified. For example, by following the first horizontal line from the top that intersects the vertical line labelled break point #2, a cluster of three stations can be identified (stations 1, 20 and 19). Going from left to right, the diagram shows how smaller clusters become incorporated into larger clusters of stations. For example, at break point #3, the cluster of stations 5, 10, 6 and 7 is combined with the cluster of stations 3, 4, 15, 8, 2 and 17.

Figure B3.5: Example of cluster tree for annual peak flows [17]



In the above example (Figure B3.5), break point #3 could be used if 9 of the 22 stations were to be retained since there are 9 horizontal lines (or clusters) that intersect with the vertical line labelled break point #3. Several of these clusters are composed of 1 station (stations 13, 16, 9, 22, 12, 18), 2 are composed of 3 stations (stations 1, 20 and 19; and stations 11, 21 and 14) and the largest cluster is composed of 10 stations (2, 3, 4, 15, 8, 17, 5, 10, 6 and 7).

In the same example, if 9 the desired number of stations to be retained is 9 (break point #3), then only one of the stations should be selected in each of the clusters that are composed of more than one station. The authors of the study used a rationalization approach which takes into account external considerations for the selection of representative stations. The criteria used included the following:[18]

1) Overall similarity with the other stations in the cluster. The overall similarity can be given by the correlation of each station with the first principal component of the similarity matrix for the stations in the cluster.
2) Number and type of uses of the data at the station.
3) Unique users of the data.
4) Length of record.
5) Quality of data at a station.
6) Drainage area associated with the station and its location in the watershed relative to other stations already chosen from other clusters.
7) Temporal characteristic of the station (e.g. seasonal or annual station).
8) Controlled flow considerations (regulated or unregulated station).
9) Spatial coverage of sites.

Table B3.3 summarizes their findings for Scenario A.

Table B3.3: Summary of station selection for Scenario A [19]

Break point no.	Similarity measure	Cluster no.	Stations in cluster	Selected station	Reasons	No. of stations remaining
1	0.884	1	1, 20	1	1 has longest record and is most downstream	14
		2	11, 21	21	21 is active	
		3	6, 7	7	7 is active and has longer record	
		4	3, 4, 15, 8, 2	4	4 is better predictor of other stations; user B is unique; station location	

Break point no.	Similarity measure	Cluster no.	Stations in cluster	Selected station	Reasons	No. of stations remaining
		5	5, 10	10	10 is a tributary station; main stem is covered by other stations	
2	0.840	1	1, 20, 19	1	1 has longest record; is most downstream	11
		2	11, 21	21	21 is active	
		3	3, 4, 15, 8, 2, 17	4	4 is better predictor of other stations; user B is unique; station location	
		4	5, 10, 6, 7	7	7 has an unique use; larger number of users; second best predictor	
3	0.787	1	1, 20, 19	1	1 has longest record and is most downstream	9
		2	11, 21, 14	14	14 is within the watershed	
		3	3, 4, 15, 8, 2, 17, 5, 10, 6, 7	4	4 is on the main stem and is located in an ungauged section of the river; user B is unique; best predictor	

3.3 REQUIRED RESOURCES

The multivariate methods require the following resources:

Data and software resources required:

- Various data can be used in the multivariate methods, however this is usually meteorological data (precipitation) in the case of the PCA and hydrometric data (stream flow) in the case of the CBA. The data requirements will depend on the identified monitoring goals.

- The method requires basic database software and/or spreadsheet software capability for data management and relatively sophisticated supporting software for the PCA and clustering calculations. If a statistical software package is used it must have PCA or CBA capabilities. GIS software capability could be used for presentation of results.

Level of effort and expertise required:

- Multiple analytical and statistical expertise and skills are required as are the technical expertise and skills to use the required statistical software. Professional judgement and knowledge of the network(s) is also required for making the final selection of stations. GIS skills for presentation of results may be required.

3.4 APPLICABILITY, LIMITATIONS AND SOLUTIONS

This approach is well suited where there is a desire to identify homogeneous stations in a network composed of a large number of stations. PCA has been applied to precipitation stations over a fixed time increment in order to define groups of stations with similar meteorology. PCA can also be used to identify redundant stations. CBA has been applied to stream flow data in order to identify homogeneous stations in a rationalization process to reduce the number of hydrometric stations. It can be used to identify regions that are not well represented, as well as regions with redundant stations. The CBA will not explicitly identify the optimal number of stations to retain in a network. Also, CBA does not provide the information required for selecting redundant stations in a region and would need to be combined with variance reduction or error minimization methods (i.e., Variance Reduction / Information Gain Approaches, Geostatistical Methods and Minimization of Error see Appendix C: Information Sources – Evaluation Methods) to identify which stations provide the most information and which could be eliminated.[20]

The multivariate methods of analysis may be applied at multiple scales – national, regional or local – where enough stations are available. Homogeneous gauging networks will be characterized by high correlation coefficients in the case of the PCA and high similarity measures in the case of the CBA.

3.5 IN SUMMARY

The multivariate analysis methods are relatively widely used statistical techniques that can be employed where there is a need to identify homogeneous stations (stations that have recorded similar data over time) within a network or where reducing or increasing the number of stations in a network may need to be considered. The methods are used to evaluate existing networks to ensure that they can meet the monitoring required for the climate change adaptation strategies.

The methods can be applied using commonly available data and large data sets, such as precipitation and stream flow records. The method requires basic database software and/or spreadsheet software capability along with sophisticated statistical software. Commensurate analytical and statistical skills are required to perform the analysis. The concepts may be applied to multiple scales depending on the number of available stations.

Table B3.4 summarizes data requirements (type amount, complexity), level of expertise and initiation effort required and software requirements.

Table B3.4: Summary of the multivariate methods characteristics

FEATURES	REQUIREMENTS
Data needs	Various data; generally used with meteorological data (e.g. precipitation) or hydrometric data (e.g. stream flow)
Software	Basic supporting software for data management and sophisticated statistical software with PCA and CBA capabilities; GIS software for presentation of results an asset
Expertise	Multiple statistical and analytical skills; professional judgement and knowledge of the network(s) is also required for making the final selection of stations; GIS skills for presentation of results
Applicable scenario	Climatological networks or hydrological networks and other networks
Scale considerations	Multiple scales

ENDNOTE

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[12] Ibid.

[13] Ibid.

[14] Ibid.

[15] Ibid.

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[16] Ibid.

[17] Ibid.

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[19] Ibid

[20] Ibid.

APPENDIX C

Supporting Materials

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Appendix C: Supporting Materials

List of Tables

C.1. GLOSSARY OF BASIC CONCEPTS AND DEFINITIONS

The following terms are defined for the purposes of this document:

Adaptation: Adjustment in natural or human systems in response to actual or expected climate stimuli and their effects, which moderates harm or exploits beneficial opportunities. There are various types of adaptation, including anticipatory, autonomous and planned adaptation.[1]

Adaptive capacity: The whole of capabilities, resources and institutions of a country, region, community or group to implement effective adaptation measures.[1]

Algorithm: A process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer.[2]

Annual Bagnouls-Gaussen humidity/aridity index (BGI) (or annual ombrothermic index): This index is the summation, for the twelve months of the year, of the difference between mean monthly air temperature (in °C) multiplied by 2 and the average total monthly precipitation (in mm) all of which is multiplied by the proportion of months in a year where the double of the temperature value (in °C) is greater than the precipitation value (in mm).[3]

Anticipatory adaptation: Adaptation activities that are conducted before the climate change impacts are observed.[1]

Aquifer: A water-bearing strata of rock or sediment capable of yielding supplies of water; typically is unconsolidated deposits or sandstone, limestone or granite; and can be classified as confined or unconfined. An unconfined aquifer is recharged directly by local rainfall, rivers and lakes, and the rate of recharge will be influenced by the permeability of the overlying rocks and soils.[4, 5]

Aridity (of land or a climate): Having little or no rain; too dry or barren to support vegetation.[2]

Audit approach: A method to evaluate water monitoring networks which incorporates expert knowledge of existing networks in a methodical and detailed review of existing and proposed stations against pre-set criteria. See Appendix B.1: Audit Approach.

Autonomous (or spontaneous) adaptation: To respond after the fact to climate change; for example, vegetation undergoes spontaneous adaptation. It is natural for a given ecosystem to be "behind" environmental conditions to some degree.[1]

Average-linkage clustering method: A hierarchical clustering method.[6]

Base flow (or baseflow): That part of stream discharge that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge to the surface water course.[7]

Base line (or baseline): The state against which change is measured. 'Current baseline' represents observable, present-day conditions. A 'future baseline' is a projected future set of conditions that excludes the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.[1]

Basic Valuation Method (BVM): An analytic approach used to differentiate areas, such as large or multiple watersheds or ecoregions, based on relative differences in the ecosystem services provided. It is one of the methods used for setting priorities for water monitoring networks. See Appendix A.1: Basic Valuation Method for Ecosystem Services.

Benefit transfer: An application of monetary values from one particular analysis to another policy-decision setting, often in a geographic area other than the one in which the original study was performed.[8]

Biophysical vulnerability: See *Vulnerability.*

Climate: Climate in a narrow sense is usually defined as the average weather or, more rigorously, as the statistical description in terms of the mean and variability of relevant variables over a period of time ranging from months to thousands or millions of years. Variables taken into account most often include surface temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.[1]

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing factors, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.[1]

Climate change adaptation: See *Climate change* and *Adaptation.*

Climate change impacts: Adverse and beneficial effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts.[1]

Climate model: A numerical representation of the climate system based on the physical, chemical and biological properties of its components; their interactions and feedback processes; and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity. Coupled Atmosphere- Ocean General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system. More complex models include active chemistry and biology.[1]

Climate normal: Arithmetic calculations based on observed climate values for a given location over a specified time period and used to describe the climatic characteristics of that location. The World Meteorological Organization (WMO) considers 30 years long enough to eliminate year-to-year variations. Thus, the WMO climatological standard period for normals calculations is defined as consecutive periods of 30 years (e.g., January 1, 1901 to December 31, 1930) and should be updated every decade.[1]

Climate projection: The calculated response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based on simulations by climate models. Since climate projections are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized, they are subject to substantial uncertainty.[1]

Climate scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships and assumptions of radiative forcing, typically constructed for explicit use as input to climate change impact models. A 'climate change scenario' is the difference between a climate scenario and the current climate.[1]

Climate variability: See *Natural climate variability*

Cluster: A natural subgroup of a population, used for statistical sampling or analysis.[2]

Clustering-based Analysis (CBA): This method identifies groups of stations that have similar spatial and temporal properties using cluster tree diagrams (or dendrograms). It is one of the multivariate methods used for evaluating water monitoring networks for climate change adaptation. See Appendix B.3: Multivariate Methods.

Cluster tree diagram (or dendrogram): A diagram with a structure of branching connecting lines, showing how the stations are successively amalgamated into groups, or clusters, at various values of the similarity measure.

Confidence limits (in statistics): A statistical term for a pair of numbers that predict the range of values within which a particular parameter lies for a given level of confidence (probability).

Consumptive use of water: Refers to the portion of water withdrawn from a source such as a lake, river or aquifer and assumed to be lost or otherwise not returned to the source as the extracted water is incorporated into processes and/or products. Some definitions include losses due to evaporation as a consumptive use of water.[5]

Correlated variables (in statistics): Variables that have a mutual relationship or connection.

Correlation coefficient (in statistics): A number between +1 and −1 calculated so as to represent the linear interdependence of two variables or sets of data.[2]

Cost-benefit: Relating to or denoting a process that assesses the relation between the cost of an undertaking and the value of the resulting benefits.[2]

Critical infrastructure: Physical and information-technology facilities, networks, services and assets that, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of a population or the effective functioning of governments.[1]

Cryosphere: The term which describes the portions of the earth's surface where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (which includes permafrost).

Degraded network: Lower-density network.[11]

Desertification: Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. The United Nations Convention to Combat Desertification defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.[10]

Diagonal matrix (in mathematics): A matrix having non-zero elements only in the diagonal running from the upper left to the lower right.[2]

Downscaling: A method that derives local- to regional-scale (10-100 kilometres) information from larger-scale models or data analyses.[1]

Drought: The phenomenon that exists when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that often adversely affect land resources and production systems. Drought has been defined in a number of ways (e.g., agricultural drought, meteorological drought and hydrological drought). A mega-drought is a long, drawn-out and pervasive drought, lasting much longer than normal, usually a decade or more.[1]

Dryness ratio: Share of total average annual precipitation that is lost through evapotranspiration, where evapotranspiration is defined as the precipitation minus the unregulated mean annual stream flow.[9]

Ecosystem services: Ecological processes or functions having monetary or non-monetary value to individuals or society at large. There are: 1) supporting services, such as productivity or biodiversity maintenance; 2) provisioning services, such as food, fibre or fish; 3) regulating services, such as climate regulation or carbon sequestration; and 4) cultural services, such as tourism or spiritual and aesthetic appreciation.[1]

Eigenvector (in mathematics and physics): A vector which when operated on by a given operator gives a scalar multiple of itself.[2]

Eigenvalue (in mathematics and physics): Each of a set of values of a parameter for which a differential equation has a non-zero solution (an eigenfunction) under given conditions or any number such that a given matrix minus that number times the identity matrix has zero determinant.[2]

Empirical data: Data based on, concerned with, or verifiable by observation or experience rather than theory or pure logic.[2]

Ensemble time series: A collection of multiple series of values of a quantity obtained at successive times, often with equal intervals between them.[11]

Error minimization method: Statistical method/technique used for evaluating monitoring networks. See Appendix C: Information Sources – Evaluation Methods: Geostatistical Methods and Minimization of Error Evaluation Methods.

Evapotranspiration: The combined process of water evaporation from the earth's surface and transpiration from vegetation.[1]

Exposure: The nature and degree to which a system is exposed to significant climatic variations.[1]

Extreme weather event: An event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th or 90th percentile. By definition, the characteristics of what is called “extreme weather'” may vary from place to place.[1]

Feedback: An interaction mechanism between processes in a system, which results when an initial process triggers changes in a second process and that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it. [1]

Floodplain: An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.[2]

Freeze-up and break-up periods: Time of year when ice forms (freeze-up) on surface water systems, lakes, rivers and sea, and the time of year when ice retreats from same (break-up).[1]

General Circulation Models (GCMs and AOGCMs): See *Climate model*.

Geographic Information System (GIS): A system for storing and manipulating geographical information on computer.[2]

Greenhouse gas (GHG): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, by the atmosphere itself and by clouds. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O),methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere. In addition, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances.[1]

Grid cells: A unit that represents a single position on an array of equally sized (square) cells arranged in rows and columns. Each grid cell is referenced by its geographical x,y location. Also known as pixel in raster GIS.

Groundwater depletion: Ratio of average groundwater withdrawals to annual average baseflow reflecting the extent that groundwater use rates may be exceeding recharge.[12]

Hedonic pricing: Pricing of a marketed good is related to its characteristics, or the services it provides. For example, the price of a car reflects the characteristics of that car—transportation, comfort, style, luxury, fuel economy, etc**.** The hedonic pricing method is used to estimate economic values for ecosystem or environmental services that directly affect market prices. It is most commonly applied to variations in housing prices that reflect the value of local environmental attributes.[13]

Hierarchical clustering algorithm: A technique used to group similar gauging stations.[14]

High-flotation tires: A tire with low pressure and with a very large contact area with the ground. Such tires may not necessarily be used for high-flotation gear. [15]

Homogeneous: In statistics, homogeneity arises in describing the properties of a dataset, or several datasets, and relates to the validity of the assumption that the statistical properties of any one part of an overall dataset are the same as any other part. In meta-analysis, which combines the data from several studies, homogeneity measures the differences or similarities between the several studies.

Hydrologic services: Wide range of services from the supply of water for household use to the mitigation of flood damages. As it is a diverse group, hydrologic services can be organized into five broad categories: improvement of extractive water supply, improvement of in-stream water supply, water damage mitigation, and provision of water related cultural services, and water-associated supporting services.[17]

Hydrologic systems: Cycle in which water evaporates from the oceans and the land surface, is carried over the earth in atmospheric circulation as water vapour, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.[18]

Hydrometric: Pertaining to the measurement of different components of the hydrologic cycle. The term "hydrometric data" is used to refer to stream flow and water levels data (e.g., http://www.wateroffice.ec.gc.ca/index_e.html)

Hydrometric network: A group of data collection activities for different components of the hydrological cycle that are designed and operated to address a single objective or a set of compatible objectives.[19]

Information gain approaches: Statistical methods used for evaluating monitoring networks. See Appendix C: Information Sources – Evaluation Methods: Variance Reduction/Information Gain Approaches.

Inhomogeneous: Not uniform in character or content; diverse.[2]

Intensity-duration-frequency (IDF) curve: Graphed curves constructed by plotting rainfall intensities of various durations. Statistical analysis, such as annual maxima series (AMS) or partial duration series (POT), is done on the precipitation data and the results are graphed by plotting probability distributions for several pre-selected rainfall durations. Information from the relationship between intensity-duration frequency (IDF) of extreme rainfall of various durations is needed in the hydraulic design of structures that control storm runoff, such as flood detention reservoirs, sewer systems etc.[21]

Intergovernmental Panel on Climate Change (IPCC): A panel established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to assess scientific, technical and socioeconomic information relevant for the understanding of climate change, its potential impacts, and options for adaptation and mitigation.[1]

Isostatic rebound (post glaciation): The rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period, through a process known as isostasy.

Mainstreaming: In the context of adaptation, mainstreaming refers to the integration of adaptation considerations (or climate risks) such that they become part of policies, programs and operations at all levels of decision-making. The goal is to make the adaptation process a component of existing decision-making and planning frameworks.[1]

Mean absolute error (MAE): A statistic used in Network Degradation Analysis. See Appendix B.2: Network Degradation Analysis – Monte Carlo.

Mitigation: Is any action taken to permanently eliminate or reduce the long-term risk and hazards of climate change to human life, property.

Monte Carlo sampling (in statistics): A technique which obtains a probabilistic approximation to the solution of a problem by using statistical sampling techniques.

Monthly Bagnouls-Gaussen humidity/aridity index (or monthly ombrothermic index): A value that is the difference between mean monthly air temperatures (in ^{o}C) multiplied by 2 and the average total monthly precipitation (in mm).[3] See Appendix A.2: Ombrothermic Analysis.

Multidimensional data: Data of several dimensions.

Multivariate methods: Multivariate methods are statistical techniques that involve the analysis of more than one statistical variable at a time. These methods can be used for evaluating water monitoring networks for climate change adaptation. See Appendix B.3: Multivariate Methods.

Natural capital: Natural capital refers to the earth's natural ecosystems as stocks or assets that provide resources and a flow of services.[9]

Natural climate variability: Natural climate variability refers to natural changes in climate that fall within the normal range of extremes for a particular region.

Net factor income: A non-market ecosystem valuation technique. [9] See Appendix A.1 Basic Valuation Method for Ecosystem Services – The Southern Ontario Greenbelt Example.

Network degradation analysis (NDA): NDA simulates a systematic decrease or "degradation" of a monitoring network's sampling station density and determines how well each successive degraded network performs compared to the full network. It is one of the methods used for evaluating water monitoring networks for climate change adaptation. See Appendix B.2: Network Degradation Analysis – Monte Carlo.

Non-market values: The monetary value of environmental goods and services, such as clean air and water, and healthy fish and wildlife populations, which are not traded in markets. Assigning monetary values to these goods and services relies on non-market valuation methods. [23]

No regret measure/policy: A measure or policy that would generate net social and/or economic benefits irrespective of whether or not climate change occurs.[1]

Ombrothermic analysis: An analytic approach that uses two parameters – precipitation and temperature – to assess the sensitivity of a region to climate change. It is one of the methods used for setting priorities for water monitoring networks. See Appendix A.2: Ombrothermic Analysis.

Ombrothermic diagram: Graph which shows the monthly variation of average temperature and precipitation over a year.

Ombrothermic index: See *Annual Bagnouls-Gaussen humidity/aridity index* and *Monthly Bagnouls-Gaussen humidity/aridity index.*

Orthogonal linear transformation (in mathematics): An orthogonal transformation is a linear transformation which preserves a symmetric inner product. In particular, an orthogonal transformation (technically, an orthonormal transformation) preserves lengths of vectors and angles between vectors. See Appendix B.3: Multivariate Methods.

Perfect multiple correlation circle (in a Principal Component Analysis): A circle that represents the perfect correlation between two variables. See Appendix B.3: Multivariate Methods.

Permafrost: Ground, which may consist of soil and/or rock, ice and organic material, which remains at or below 0°C for at least two consecutive years; also known as perennially frozen ground.[1]

Physiographic: Relating to physical geography, or the classification of landforms according to their geological structures and histories.

Polynomial (in mathematics): An expression of more than two algebraic terms, especially the sum of several terms that contain different powers of the same variable(s).[2]

Principal component (or principal axis): A principal component corresponds to a line that passes through the multidimensional mean and minimizes the sum of squares of the distances of the points from the line. See Appendix B.3: Multivariate Methods.

Principal Component Analysis (PCA): A way of identifying patterns in data, and expressing the data in such a way as to highlight their similarities and differences.[24] It is one of the Multivariate Methods used for evaluating water monitoring networks for climate change adaptation. See Appendix B.3: Multivariate Methods.

Rationalization: As in monitoring network rationalization, this is increasing the efficiency of the network and maximizing the information collected, and may involve decreasing the number of locations at which data are collected.

Realization (in statistics): A particular series which might be generated by a specified random process.[2]

Recurrence interval (return period): Average time until the next occurrence of a defined event. When the time to the next occurrence has a geometric distribution, the return period is equal to the inverse of probability of the event occurring in the next time period (i.e. $T = 1/P$, where T is the return period, in number of time intervals, and P is the probability of the next event's occurrence in a given time interval).[1]

Redundant stations: Water monitoring network stations that could be removed with little loss of information.[14]

Regression (in statistics): A measure of the relation between the mean value of one variable (e.g. output) and corresponding values of other variables (e.g., time and cost).[2]

Resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the same capacity for self-organization and the same capacity to adapt to stress and change.[1]

Risk (climate): A combination of the likelihood (probability of occurrence) and the consequences of an adverse event (e.g., climate-related hazard).[1]

Salt water intrusion: Displacement of freshwater or groundwater by the advance of salt water due to its greater density. This advancement usually occurs in coastal and estuarine areas and is due to reducing land-based influence (e.g., either from reduced run off and associated groundwater recharge or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative sea-level rise).[1]

Scenario: A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.[1]

Sea-level rise: An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean. Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift, relative sea-level can fall.[1]

Sensitivity: Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damage caused by an increase in the frequency of coastal flooding due to sea-level rise).[1]

Similarity matrix: A similarity matrix is a matrix of variables which express the similarity between two data points.

Similarity measure (in Clustering-based Analysis): A statistical measure of the correlation between all pairs of all possible groups of stations. See Appendix B.3: Multivariate Methods – Background Information.

Siltation: The deposition or accumulation of silt that is suspended throughout a body of standing water or in some considerable portion of it; especially the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir. The term often includes sedimentary particles ranging in size from colloidal clay to sand.[16]

Societal adaptive capacity: A society's adaptive capacity, which would depend on several factors including level of education, access to technology, effectiveness and strength of the society's institutions. See *Adaptive capacity*.[1]

Spatial coverage: An area on the surface of the earth or an altitude range covered by a data set.[25]

Spatial resolution: This term has various definitions which vary from one domain to another: In remote sensing, it is defined in terms of the diameter of the ground area that may be distinguished and is often comparable to the size of the earth's surface covered by a single pixel. In data collection, it can refer to the density of measurement network.

Storm surge: Generally used to refer to a temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place. Negative storm surges also occur and can present significant problems for navigation.[1]

Sum of squares: Represents the sum of squared differences between the mean of a dataset and the individual values of the dataset.

System: An entity consisting of diverse but interrelated components that function as a complex whole. Examples include the climate system, ecosystems and market economies.[1]

Thermosyphon: Refers to a method of passive heat exchange based on natural convection that circulates a liquid in a vertical closed-loop circuit without requiring a conventional pump.[26]

Time series (in statistics): A series of values of a quantity obtained at successive times, often with equal intervals between them.[2]

Trend (in statistics): The slope of linear regression from time.[27]

Tundra: As in Arctic tundra, is a treeless, level or gently undulating plain characteristic of arctic and subarctic regions. It supports a growth of mosses, lichens and numerous low shrubs and is underlain by permafrost.[16]

Uncertainty: An expression of the degree to which a value is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g. a range of values calculated by various models) or by qualitative statements (e.g. reflecting the judgment of a team of experts).[1]

Uncorrelated variables: Variables that do not have a mutual relationship or connection.

Ungauged site: A site at which data is not collected.

United Nations Framework Convention on Climate Change: The Convention was adopted on May 9, 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." It contains commitments for all parties. The Convention entered into force in March 1994. [1]

Variance (in statistics): A quantity equal to the square of the standard deviation.[2]

Variance reduction (in mathematics, more specifically in the theory of Monte Carlo methods): A procedure used to increase the precision of the estimates that can be obtained for a given number of iterations. Every output random variable from the simulation is associated with a variance which limits the precision of the simulation results. See Appendix B.2: Network Degradation Analysis – Monte Carlo

Varimax method (in a Principal Component Analysis): In this method the total explained variance is redistributed by rotating the principal axes. See Appendix B.3: Multivariate Methods.

Vector (mathematic): A quantity having direction as well as magnitude, especially as determining the position of one point in space relative to another.[2]

Vulnerability: Vulnerability is the susceptibility to be harmed. Vulnerability to climate change is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability to climate change is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity.[1]

Water balance: The accounting of water input and output and change in storage of the various components of the hydrologic cycle. [5]

Water budget: A summation of input, output, and net changes to a particular water resources system over a fixed period of time.[5]

Water right: (U.S. usage referred to in Appendix A.3: Water Resources Vulnerability Indicators Analysis) A right to use, in accordance with its priority, a certain amount of water; [28] or the right to use water diverted at a specific location on a water source, and putting it to recognized beneficial uses at set locations.[29]

(Canadian usage) The principles of the Common Law of Riparian Rights are the basis of the water-user permit systems in Ontario, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador. Under the common law, which was developed before water rights were legislated, individuals who own or occupy land beside lakes and rivers have the right to the natural flow of the water adjacent or through their property, unchanged in quantity or quality. The provinces have responsibility for administering water and supervising its allocation; their legislative jurisdiction over water is to be exercised in a manner equitable to all.

In Québec, water use permitting is based on Civil Law principles. Québec’s civil law states that water is not owned by anyone, but rather its use is common to all. The province therefore has a guardianship role to play to ensure the common good.

All provincial and territorial water allocation systems involve either a licensing or permitting system, for both surface and groundwater in all jurisdictions, except in British Columbia where there are no provisions for groundwater.

Water-use licence fees exist in all provinces and territories but they differ significantly. In most cases, these are one-time fees payable at the time of the application, supplemented with annual fees in certain situations. Some provinces have fixed prices while others have variable fees, depending on the volume of water used and type of use, such as: industrial, power generation, or agriculture. Generally speaking, fees are low, ranging from $20 to a few thousand dollars. In certain cases, such as in Ontario and Saskatchewan, some specific activities including agriculture are exempted from the fees. Revenues from water-use fees generally go into provincial general revenue funds. One notable exception is in Prince Edward Island, where the revenue from water withdrawal permits is used to offset the costs associated with the administration and implementation of the government's water-monitoring program.[30]

Watershed: The geographic area drained by a river.[2]

Water Resources Vulnerability Indicators Analysis (WRVIA): A methodology that uses indicators to assess key aspects of water supply and use (such as stream flow, evapotranspiration losses, water quality, water withdrawals and settlement in the floodplain) to identify watersheds where water resources are currently most vulnerable to increased stress and where current vulnerability could be exacerbated or relieved by changes in mean climate and extreme events. It is one of the methods used for setting priorities for water monitoring networks for climate change adaptation. See Appendix A.3: Water Resources Vulnerability Indicators Analysis.

Water stress: A condition in which the available freshwater supply relative to water withdrawals is an important constraint on development. Withdrawal exceeding 20% of renewable water supply has been used as an indicator of water stress. A crop is water stressed if soil-available water, and thus actual evapotranspiration, is less than potential evapotranspiration demands.[1]

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C.3. DESCRIPTIONS OF OTHER PRIORITIZATION METHODS

Table C1. Descriptions of Other Prioritization Methods

Method/ References	Types of Criteria/Parameters Employed	Data Needs	Software	Expertise	Scale Considerations
New Zealand biodiversity strategy (Leathwick and Julian 2009)	Representativeness based on river system type, extent of existing protection, added value (how much biodiversity protection would be gained)	Spatially relevant (GIS or other mapping) data to define regions (e.g., ecozones) and/or classes (types) of watersheds or rivers, e.g.,. data on elevation, gradient, flow velocity, major geological characteristic, watershed size, degree of groundwater influence, latitude, soil types, vegetation types, climatic zones, and land use type, or others.	River Environments Classification system (REC) or other data base support; selection software (purpose-developed in New Zealand, may be available) or other Decision Support Software (DSS) if desired - selection software can be substituted using GIS and a spreadsheet.	Data management, basic analysis, and GIS skills. Scientific familiarity with the region, and the processes of interest (e.g., climate change science, terrestrial-atmospheric interactions, plant biome processes, etc.). Familiarity with classification analyses, data base manipulation, and selection software or DSS (if desired for use); otherwise no specialized modeling expertise required.	The concept of representativeness is applicable to multiple scales (stream reach, watershed, ecoregion), and could be tailored to set priorities among areas within a province or territory, where areas could be defined according to the parameters used to define representativeness.
Germany – TERENO (Bogena et al. undated)	Representativeness based primarily on dominant biomes, dominant terrestrial processes and differing roles of ground water, surface water, soils and links to the atmosphere; regions already affected by environmental change, or likely to react sensitively in the future.	Maps or GIS-compatible data on some or all of the following (or other, depending on region): ecoregions (or biogeographic zones), elevation, vegetation biome distributions, soil types, groundwater contributions to hydrology, groundwater and surface water uses, land use types, data that characterize existing disturbances (e.g., industrial development, discharges, mining, forest harvesting), demographics and urbanization, distributions of existing study/monitoring areas, distributions of universities and related research institutions, distributions of climate variables or regions.	Data base and GIS software.	Data management, basic analysis, and GIS skills, scientific familiarity with the areas under consideration and the process of interest (e.g., climate change science, terrestrial-atmospheric interactions, plant biome processes, etc.); no specialized modeling or analytical skills.	Same as above

Method/ References	Types of Criteria/Parameters Employed	Data Needs	Software	Expertise	Scale Considerations
Natural Capital Project Modeling (Nelson et al. 2009).	Ecosystem service values with land use/land cover as its underlying basis, estimated using spatially explicit modeling that incorporates processes that drive production of the category of services of interest (e.g., water quantity and quality-related services).	A large variety of data needed, such as land use/land cover, soil types, elevation and surface aspect (or topology), vegetation cover, precipitation, flow, slope, possibly others depending on the parameters and services being estimated.	Integrated Valuation of Ecosystem Services and Tradeoffs (InVest), developed by the Natural Capital Project, Stanford University.	Assuming this modeling suite is available, the expertise to run the model would be needed; basic data management and analysis expertise. Data management and GIS skills and software would be needed.	The modeling approach to estimating ecosystems services offers greater spatial detail and accuracy due to incorporation of processes to estimate spatial variation of services produced, but by the same token, the greater detail is achieved through watershed-scale modeling. This scale is applicable to priority setting at the province/territory level, but would require multiple modeling applications, representing a substantial effort.
Advanced Terrestrial Ecosystem Analysis and Modeling team (ATEAM) (Schroter et al. 2005).	Ecosystem service values and future changes, based on land use change driven by projected climate change, integrated with projected future market changes and other socio-economic effects.	Extensive data inputs (see Table 5 in Schroter et al. 2005). Other data and expertise requirements would be similar to those for the Natural Capital modeling discussed above in Section 3.3.2.	ATEAM used a series of models, rigorously estimating each link in the chain, including a complex set of ecosystem models (e.g., water catchments, agricultural systems, forest systems, etc.) to estimate ecological impacts from future climate change from GCM projections. Outputs are used to estimate land use (and other) changes from which ecosystem service changes are estimated. Different models needed for each category of ecosystem service evaluated. The water system model used MacPDM (see Table 6 in Schroter et al. 2005), a hydrological model to simulate changes in	Extensive modeling expertise, including climate modeling, a wide variety of ecosystem modeling. Other expertise needed include data base manipulation and GIS.	ATEAM developed this approach at a continental (European) scale. The approach would be applicable at the province/territory scale, though it is a research level, complex and rigorous linked-modeling approach that is probably much more detailed than warranted for priority setting.

Method/ References	Types of Criteria/Parameters Employed	Data Needs	Software	Expertise	Scale Considerations
			streamflow and indicators of water resources based on the defined climate and land cover changes.		
Empirical Trends and Conceptual Models (U.S. EPA 2008, Ohlson et al. 2005, Johnson and Weaver 2009)	Vulnerability or sensitivity to climate change as parameters for setting priorities.	Data needs variable and depend on the systems being evaluated, but could include geology, topography, land use, population distributions, stream temperatures, slope, flows (e.g., average discharge, baseflow), nutrient concentrations, or many others. Analysis of empirical trends would need long-term data sets.	GIS may be valuable though not essential; also need data management and analysis software.	Expert knowledge of the system being evaluated, usually including expertise in multiple fields, also need data management and analysis expertise.	Conceptual modeling is flexible, but in this context would be best applied at the watershed scale.
Bayesian Networks, Neural Networks, and Fuzzy Set Methods	Vulnerability or sensitivity to climate change as parameters for setting priorities.	The types of useful data to support Bayesian model development, would depend on the systems being evaluated, but could include geology, topography, land use, population distributions, stream temperatures, slope, flows (e.g., average discharge, baseflow), nutrient concentrations, or many others.	Numerous software packages available to aid in development and display of Bayesian models (see http://www.csse.monash.edu.au/bai/ or http://people.cs.ubc.ca/~murphyk/Bayes/bnsoft.html, for reviews, and http://directory.google.com/Top/Computers/Artificial_Intelligence/Belief_Networks/Software/ for a listing and links to available software). Dedicated software is not requisite, but would be helpful. GIS may be valuable though not essential; also need data management and analysis software.	Development of Bayesian models or neural networks would require detailed knowledge of the system being evaluated, most likely covering multiple fields, and therefore multiple local/regional experts. It also requires knowledge of Bayes Theorem and Bayesian logic to structure the model.	Bayesian modeling and neural network development is flexible, but in this context would be best applied at the watershed scale.

Method/ References	Types of Criteria/Parameters Employed	Data Needs	Software	Expertise	Scale Considerations
Integrated Systems Modeling to Assess Climate Vulnerability – Brazilian Example (Krol et al. 2006)	vulnerability of water systems to climate change	Very data intensive due to complex and linked models. Data for model inputs including historical (or reconstructed) daily time series of temperature, precipitation, air humidity and wind speed data; future climatic conditions from a statistical scenario (or other) technique using long-term daily observations in combination with climate trends from Global Circulation Models; data on soil profiles, topography (terrain), vegetation cover, water flows, water use, lateral connectivity, and reservoir characteristics; demographic data, water withdrawals, irrigation data, crop yields, and several other data source; future projections of population growth and distribution.	Semi-arid Integrated Model – SIM used in this Brazilian example; or a similar array of linked models would have to be adapted and/or developed.	Extensive modeling expertise in several disciplines (hydrology, agriculture, socio-economics) needed;	Applicable on a regional, province/territory, or watershed scale.
Vulnerability of Water Resource Systems to Climate Change – the Yorkshire Drought Example (Fowler et al. 2003)	Vulnerability, reliability, and resilience (using applicable indices developed from model outputs) of a water supply system to climate change or current climate stresses.	A substantial diversity and quantity of data, including regionalized climate change projections; historic climate time series data; data to support calibration of a hydrologic model to the watershed or larger system of interest; and data on the water supply system characteristics (e.g., including reservoir capacities, operations conditions, etc.)	Several models needed, must be tailored to each application, including a rainfall model, evapotranspiration model, a watershed hydrologic model, and a water supply system model.	A substantial diversity of modeling expertise, as well as data management, analysis, and GIS skills.	The modeling approach applied on a regional basis, encompassing more than one river system. It is thus applicable on a provincial scale, but could as well be applied on a watershed scale.
Sensitivity of a Major River Basin to Climate	Vulnerability/sensitivity to climate change and reliability of the water	Gaged flow data and a naturalized flow data set from those records; reliable data on	ColSim reservoir operations and hydrologic model (or other regionally applicable reservoir	Expertise to estimate naturalized flows from gaged flows;	Large-scale regional (multi-state/river basin).

Method/ References	Types of Criteria/Parameters Employed	Data Needs	Software	Expertise	Scale Considerations
Change – Columbia River Example (Miles et al. 2000)	supply system.	water uses, magnitudes of evapotranspiration from reservoirs at different flows and temperatures (to support estimation of naturalized flows); long term data on these climate indices (e.g., ENSO, PDO).	operations/hhydrologic model);		
Method for Evaluating Climate Change Effects on a Hydropower Water System – Peribonka River, Quebec, Canada (Minville et al. 2009)	Responses of various aspects of hydropower production to changes in hydrologic regime with respect to climate change.	A current (historic) climate variable data set; data for model development or calibration (e.g., stream network information, channel cross-section, flow records, etc); information on reservoir operational rules	The Canadian regional climate model to project temperature and precipitation time series of data at a finer grid scale; a hydrologic model calibrated to the watershed or river basin of interest, possibly including reservoir or other water system operational characteristics (this example used the distributed hydrological model Hydrotel); an optimization model to project operation rule adaptations relative to future hydrologic regime changes; data management and statistical analytical software.	Good data management and statistical analytical skills; expertise to manipulate input data, run the hydrologic model, analyze and interpret model outputs, and possibly to calibrate or even develop said model; expertise to run an optimization model.	Mainly focused on a river basin/watershed scale.

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C.4. DESCRIPTIONS OF OTHER NETWORK EVALUATION METHODS

Table C2. Descriptions of Other Network Evaluation Methods

Method	Examples/ References	Data Needs	Software	Expertise	Applicable Scenarios (e.g., gauge types)	Scale Considerations
Variance Reduction/ Information Gain Approaches	Fiering (1965), Matalas 1968), Rouhani (1985)	Time series of data from gauges, depending on parameters of interest (surface water flows, ground water (well) data, and/or precipitation/temperature data. Possibly data (e.g., GIS overlays) on watershed and/or other strata delineations	AKRIP (an acronym for a kriging program), and/or other statistical software; GIS software; data base/data management software.	Multiple statistical and analytical skills, including cross-correlation analysis, kriging, matrix algebra (variogram analyses), iterative algorithms to minimize kriging variances; statistical/regression modeling to simulate data (e.g., flows) in ungauged areas from gauged data	Examples include hydrologic and climatological gauging data	Most variance reduction approaches are sensitive to major changes in contributions to variance and covariance. Therefore, methods probably best applied within a watershed, or within areas otherwise stratified by physical characteristics that drive variation in hydrologic and climate
Geostatistical Methods and Minimization of Error	Bastin et al. (1984), Morrissey et al. (1995), Cheng et al. (2008), Nour et al. (2006)	Rain (or other) gauge data; data (e.g., GIS overlays) on watershed and/or other strata delineations	Sophisticated statistical software; GIS software; data base/data management software.	Multiple statistical and analytical skills, including kriging and associated variogram calculations; iterative sub-sampling of existing gauge data to synthesize data sets from subsetted networks; standard and partitioned error calculation; spatial interpolation of data values (statistical modeling); statistical simulation of time series data for subsetted data sets; trend analysis and associated error estimation; GIS for gridding/subsetting study areas; overlaying and comparing results. Running models to generate time series rainfall data (e.g. GATE (Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment model)	Rain gauge networks; probably applicable to other gauge data	Though focused more on error estimation, this method is still sensitive to large changes in sources of variation in station characteristics and associated gauge data variability. Therefore, applicable to watersheds or sub-regional basis, or on spatially stratified areas. That is, the method could apply over large jurisdictions if stratification (by several possible methods) is used

Method	Examples/ References	Data Needs	Software	Expertise	Applicable Scenarios (e.g., gauge types)	Scale Considerations
Interpolation and Minimization of Error	Milewska and Hogg (2001), Moss and Tasker (1991), Moss (1982), Tasker (1986), Vose and Menne (2004), Hutchinson, et al. (2009)	Climatological time series by station (temperature, precipitation); hydrologic time series data from gauges; GIS data of study areas for results presentation and spatial analysis	Sophisticated statistical software; ANUSPLN; GIS software; data base/data management software	Multiple statistical and analytical skills, including interpolation methods (e.g., Gandin's point-to-point, Kagan's point-to-area); regression modeling; regional regressions; interpolation error analysis; generalized-least-squares (GLS); regression modeling; error estimation and analysis; trivariate thin-plate smoothing splines (a generalization of multivariate linear regression). Spatial (GIS) analysis of areal distribution of results	Climatological networks, hydrological networks	Variable - can apply Milewska and Hogg (2001) method on large scale (nationally, i.e., developed approximation approaches to account for non-compliance with variation assumptions). Can apply Vose and Menne (2004) example nationally using stratification by regular gridding. NARI and NAUGLS are applicable on a regional or watershed scale
Climate Network Density as Input to Hydrologic Modeling	St-Hilaire et al. (2003), Dong et al. (2005), Anctil et al. (2006)	Climatological data; hydrological data; watershed characteristics data for model calibration	HSAMI hydrological model; neural network rainfall-runoff model to forecast streamflow; or other hydrologic model. Sophisticated statistical software; data base/data management software	Modeling and model assessment skills. Multiple statistical and analytical skills, including kriging and associated variogram calculations; statistical data set subsampling techniques; optimization algorithms	Climatological networks, hydrological networks	Watershed scale

Method	Examples/ References	Data Needs	Software	Expertise	Applicable Scenarios (e.g., gauge types)	Scale Considerations
Modeling Methods	Strobl et al. (2006)	Hydrologic data; extensive GIS-compatible data on watershed characteristics (soil types, topography/elevation, land use, population, discharge permits, etc.)	Critical Sampling Points (CSP) method using Water Quality Monitoring Station Analysis (WQMSA) model	GIS-, fuzzy logic-, and simulation model-based modeling	Hydrologic networks	Watershed or subwatershed scale.
Entropy and Information Theory Methods	Markus et al (2003), Husain (1989), Caselton and Husain (1980), Husain (1987)	Hydrologic data	Sophisticated statistical and analytical software; computer program for GLS application (GLSNET); data base/data management software	Multiple statistical and analytical skills, knowledge of entropy equations and analyses; data interpolation, step-backwards techniques.	Hydrologic networks	Watershed scale
Optimization Methods	Mishra and Coulibaly (2009), and Langbein (1979), Mooley and Mohamed Ismail (1981)	Hydrologic data	Variable, can be quantitative or conceptual. Statistical, and data management and tabulation software	Statistical and analytical skills, especially optimization methods.	Hydrologic networks; climatologial networks	Multiple
BASINS/CAT	Imhoff et al. (2007)	Many of the types of data required as model inputs, including maps, temperature and precipitation by watershed area, are already incorporated and available within the system within the U.S. These would be needed if this modeling system were applied in	BASINS or other watershed hydrologic model, calibrated for each watershed to be assessed; CAT; data management and analysis software; GIS software.	Hydrologic modeling expertise, with ability to run CAT; data management and analysis e, and GIS skills.	Hydrologic networks	BASINS is a watershed model, but can be applied to sub-watersheds (e.g., drainages within a large watershed). It should be considered that for very large watersheds or river basins, gathering of data, model calibration and

Method	Examples/ References	Data Needs	Software	Expertise	Applicable Scenarios (e.g., gauge types)	Scale Considerations
		Canada. A source of spatially interpolated historic climate time series data is needed. Inputs needed to develop and calibrate the model to a watershed would include various physical measures in the watershed, including network linkages, channel profiles, flow data from various locations within the watershed for calibration, etc.				verification to historic flow data can be an extensive undertaking. While this would certainly generate valuable model results and informative sensitivity relationships, it would represent a time and cost-intensive effort as a basis for establishing regional priorities. To develop information on relative climate change sensitivities among all watersheds within a province or territory, modeling would have to be conducted on each watershed.

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