Tools for climate change vulnerability assessment for watersheds

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TOOLS FOR CLIMATE CHANGE VULNERABILITY ASSESSMENTS FOR WATERSHEDS

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EXECUTIVE SUMMARY

It is expected that the impacts of climate change on Canada's water resources will be significant. Climate induced changes in precipitation and air temperature will lead to earlier timing of peak flows, greater frequency of flooding, and more extreme drought conditions. Changes in climate and the related impacts on terrestrial and freshwater environments will also affect nutrient cycling, stream temperatures, the distribution, concentration, and timing of contaminants, as well as the transport and concentrations of sediments in watercourses. Such changes are consequential to human communities and freshwater ecosystems and as a result social-ecological systems in Canada are "*vulnerable*" to the effects of climate change.

This compendium of tools was prepared for use by technical experts, adaptation planners and resource managers to develop climate change vulnerability assessments of water quantity and water quality at a watershed scale.

Drawing guidance from the Intergovernmental Panel on Climate Change (IPCC) this compendium defines vulnerability assessment as a process for assessing, measuring, and/or characterizing the exposure, sensitivity, and adaptive capacity of watersheds to climate change. The purpose of a vulnerability assessment is to generate knowledge that improves understanding of the implications of climate change. The knowledge generated by a vulnerability assessment can inform allocation of resources for climate change planning and adaptation.

The range of approaches available for assessing vulnerability include an "*impact assessment*" (focusing on exposure to future climate and sensitivity of the system to that change), a "*first order vulnerability assessment*" (focusing on exposure and sensitivity to both biophysical and socio-economic impacts), and a "*second order vulnerability assessment*" (a first order assessment that includes a consideration of adaptive capacity). These approaches represent "*top-down*" methods of assessing local impacts on human communities and ecosystems. "*Bottom-up*" or participatory approaches represent distinct though complementary approaches which draw upon the perspectives and knowledge of communities to understand current and future vulnerabilities. The selected approach will largely depend on the available knowledge, data, technical abilities, and capacity (people, time, and money).

To identify tools relevant to the Canadian context, Canadian and international case studies of watershed-scale vulnerability assessments were used. Tools were selected to be representative of a broad range of water resource issues, data needs, and technical capabilities.

The tools in this compendium are varied and diverse. They range from indicator-based approaches to sophisticated hydrological models that calculate exposure to flood events under future projections of climate change. They also range from qualitative to quantitative approaches that address a broad range of characteristics of social-ecological systems.

This compendium describes tools in a variety of ways. First, an "*at a glance*" overview summarizes the full suite of tools that are described in more detail. For each tool, a summary is provided describing the approach, inputs/outputs, user considerations, and citations where readers can go for more information. Next, a framework for classifying tools according to the dimensions, components, and elements of vulnerability is also provided. The purpose of this classification is to represent the full range of considerations and commonalities across all vulnerability assessments and related tools. Lastly, more tools were identified than are described here and as a result the reference list includes more citations than are referenced in the report so it can be used as a searchable resource.

RÉSUMÉ

On prévoit que les changements climatiques auront d'importants impacts sur les ressources en eau du Canada. Les changements provoqués par le climat dans les précipitations et la température de l'air se traduiront en effet par des débits de pointe plus précoces, une fréquence accrue d'inondations et des conditions de sécheresse plus extrêmes. Les changements climatiques et les impacts qui leur sont associés sur les milieux terrestres et d'eau douce influenceront également le cycle des éléments nutritifs; la température des cours d'eau; la distribution et la concentration des contaminants; les périodes de contamination; ainsi que le transport et la concentration des sédiments dans les cours d'eau. De tels changements sont lourds de conséquences pour les collectivités humaines et les écosystèmes d'eau douce, de sorte que les systèmes socioécologiques sont « *vulnérables* » aux effets des changements climatiques.

Le présent recueil d'outils a été préparé pour aider les experts techniques, les planificateurs de mesures d'adaptation et les gestionnaires de ressources à effectuer des évaluations de la vulnérabilité des ressources en eau (quantité et qualité) aux changements climatiques à l'échelle du bassin versant.

En s'appuyant sur les orientations du Groupe d'experts intergouvernemental sur l'évolution du climat (GEIEC), le présent recueil définit l'évaluation de la vulnérabilité comme un processus destiné à évaluer, à mesurer et/ou à caractériser l'<u>exposition</u>, la <u>sensibilité</u> et la <u>capacité d'adaptation</u> des bassins versants aux changements climatiques. L'objectif d'une évaluation de la vulnérabilité est de <u>générer des connaissances</u> qui permettront de mieux comprendre les conséquences des changements climatiques. Les connaissances générées par une évaluation de la vulnérabilité peuvent guider l'allocation des ressources aux fins de la planification et de l'adaptation relatives aux changements climatiques.

Parmi l'éventail des méthodes disponibles pour évaluer la vulnérabilité, mentionnons l'« *étude d'impact* » (axée sur l'exposition aux futurs changements climatiques et sur la sensibilité d'un système donné à ces changements); l'« *évaluation de la vulnérabilité de premier niveau* » (axée sur l'exposition et la sensibilité aux impacts aussi bien biophysiques que socioéconomiques); et l'« *évaluation de la vulnérabilité de second niveau* » (une évaluation de premier niveau qui comprend aussi une évaluation de la capacité d'adaptation). Ces méthodes, destinées à évaluer les impacts locaux sur les collectivités humaines et les écosystèmes, sont de type « *descendant* ». Les méthodes « *ascendantes* » ou participatives sont des approches distinctes mais complémentaires, qui se fondent sur les points de vue et les connaissances des collectivités pour comprendre les vulnérabilités présentes et futures. Le choix de l'approche dépendra en grande partie des connaissances, des données, des compétences techniques et des ressources (humaines et financières; temps) disponibles.

Pour identifier des outils adaptés au contexte canadien, nous avons utilisé des études de cas canadiennes et internationales portant sur des évaluations de la vulnérabilité à l'échelle du bassin versant. Par ailleurs, nous avons sélectionné les outils de manière à illustrer un large éventail d'enjeux, de besoins en données et de compétences techniques.

Les outils réunis dans le présent recueil sont diversifiés, allant de méthodes basées sur des indicateurs à des modèles hydrologiques sophistiqués, qui calculent le degré d'exposition aux inondations en fonction des projections futures de changements climatiques. Ils comptent également des méthodes qualitatives et quantitatives, qui ciblent un large éventail de caractéristiques propres aux systèmes socioécologiques.

Le présent recueil décrit les outils de différentes façons. D'abord, un survol rapide résume l'ensemble des outils, qui sont ensuite décrits plus en détail. Pour chaque outil est fourni un résumé, dans lequel sont présentés l'approche adoptée, les données d'entrée et de sortie, des conseils à l'utilisateur et de la documentation que peut consulter le lecteur pour obtenir plus d'information. Le recueil présente ensuite un cadre conçu pour classer les outils selon les dimensions, les composantes et les éléments utilisés pour caractériser la vulnérabilité. L'objectif de ce classement est de représenter l'éventail complet des caractéristiques et des points communs de toutes les évaluations de la vulnérabilité et des outils qui leur sont associés. Enfin, il est à noter que nous avons recensé un plus grand nombre d'outils que ceux décrits dans le présent recueil; par conséquent, la bibliographie contient plus de références que les références citées dans le rapport et peut donc servir d'outil de recherche.

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1. INTRODUCTION

Climate change impacts to Canada's water resources could be significant. Increases in the frequency of flooding and droughts and increased water consumption are expected, for instance. Human communities and freshwater ecosystems in Canada are "vulnerable" to the impacts of climate change on water resources.

This compendium of tools was prepared for use by technical experts, adaptation planners and resources managers to develop climate change vulnerability assessments of water quantity and water quality at a watershed scale. This compendium includes tools from case studies and examples of watershed-scale vulnerability assessments from Canada and other jurisdictions around the world.

To gather input for this compendium a survey was sent to experts in climate change vulnerability and adaptation across provincial, territorial, and federal jurisdictions in Canada (see Appendix A). This report integrates results from that survey and adds to it a relatively broad and thorough review of the literature on vulnerability assessment of watersheds. The suite of tools represents a subset of all available options and will not likely address all of the potential needs of end users across Canadian jurisdictions. The reference list includes additional citations as a searchable resource for more information.

1.1 What Is Vulnerability?

Drawing guidance from the Intergovernmental Panel on Climate Change (IPCC), this compendium defines vulnerability as:

"…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 is a function of the character, magnitude and rate of climate change and the variation to which a [social-ecological] *system is exposed, its sensitivity and its adaptive capacity."* (from Parry et al. 2007)

Vulnerability is driven by dimensions of exposure, sensitivity, and adaptive capacity which can either be quantitatively measured or qualitatively characterized. These dimensions or measures can be defined as follows[1]:

- Exposure is a measure of the magnitude and extent (i.e., spatial and temporal scales) of exposure to climate change impacts.
- Sensitivity is a measure how a system is likely to respond when exposed to a climate-induced stress.
- Adaptive capacity is a measure of the potential, ability, or opportunities available to decrease exposure or sensitivity of a system to a climate induced stress (i.e., adapt).

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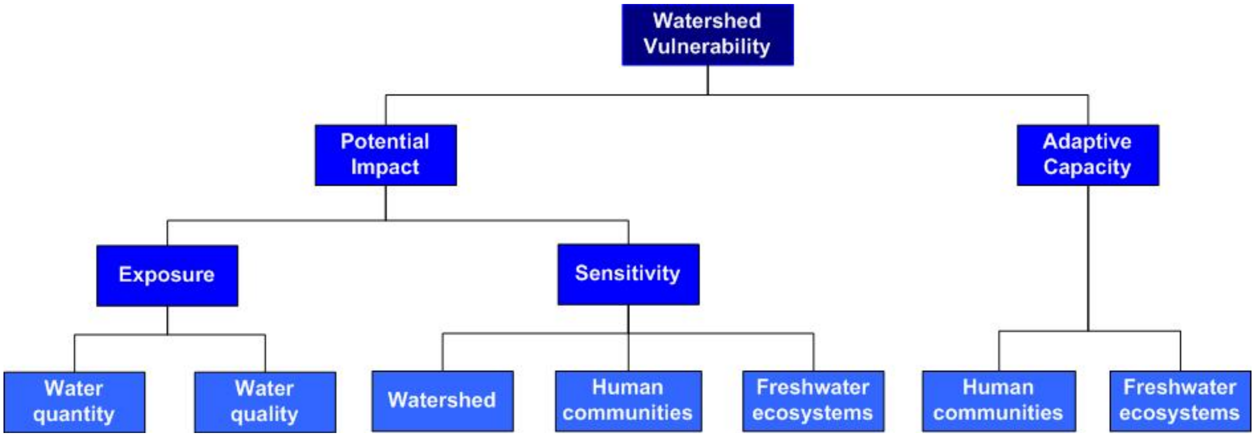
[1] These definitions are informed by those provided by Metzger (2005), Fussel and Klein (2006), and Glick et al. (2011).

These definitions are useful for defining watershed vulnerability for this compendium because they allow for a sorting of relevant tools into more detailed characterizations of vulnerability. Figure 1 outlines the core elements of a vulnerability assessment of watersheds, while Figure 2 summarizes the more detailed dimensions and measures for these elements.

Figure 1: Elements of watershed vulnerability assessment



1.2 What Is a Vulnerability Assessment?

Vulnerability assessment is a process for assessing, measuring, and/or characterizing the exposure, sensitivity, and adaptive capacity of a natural or human system to disturbance.

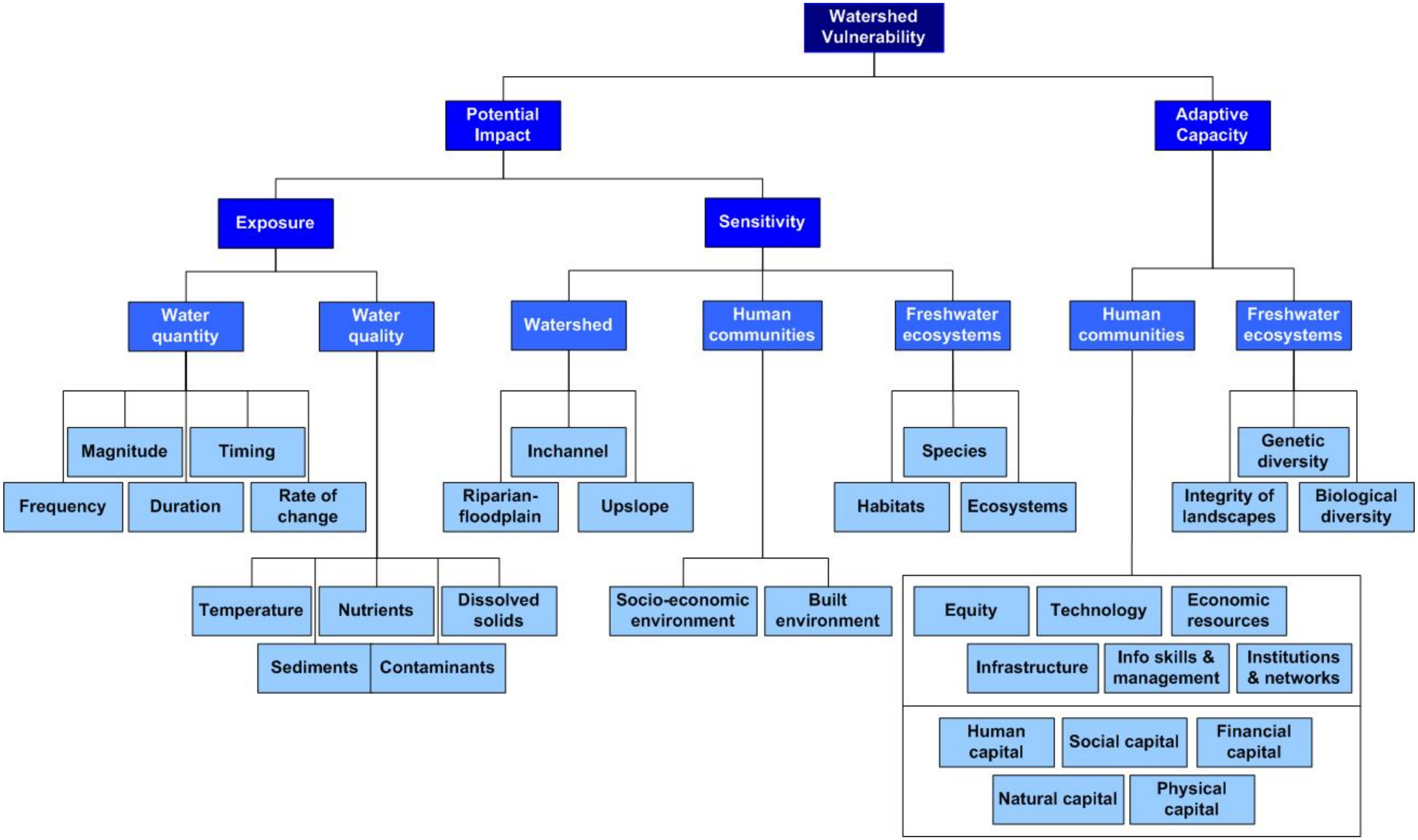
A range of approaches is available for assessing vulnerability (e.g., Fussel and Klein 2006). As illustrated in Figure 1, an "*impact assessment*" focuses on understanding biophysical changes in terms of the <u>exposure</u> to future change in climate and <u>sensitivity</u> of the environment to that change.

A "*first order vulnerability assessment*" is an impact assessment with the addition of socio-economic considerations and non-climatic factors (i.e., all elements of exposure and sensitivity in Figure 2).

A "*second order vulnerability assessment*" includes the first order vulnerability assessment and adds an assessment of adaptive capacity (i.e., all elements of exposure, sensitivity, and adaptive capacity in Figure 2). This approach recognizes that human and ecological systems will have some capacity to respond to the effects of climate change which needs to be considered.

The tools provided can be used in any of the different approaches to vulnerability assessment. The selection of an approach will depend on the available knowledge and data, technical abilities, capacity (people, time, and money) and information needed by decision-makers in a particular situation.

Figure 2: A framework for classifying tools based on how they characterize vulnerability of watersheds. Tree is organized according to the dimensions, underlying components, and elements for characterizing vulnerability.



The range of approaches described herein represent "*top-down*" and technical ways of assessing vulnerability. In some situations, however, "*bottom-up*" or participatory approaches may be more appropriate ways of understanding current and future vulnerabilities of human communities and ecosystems (see Box 1).

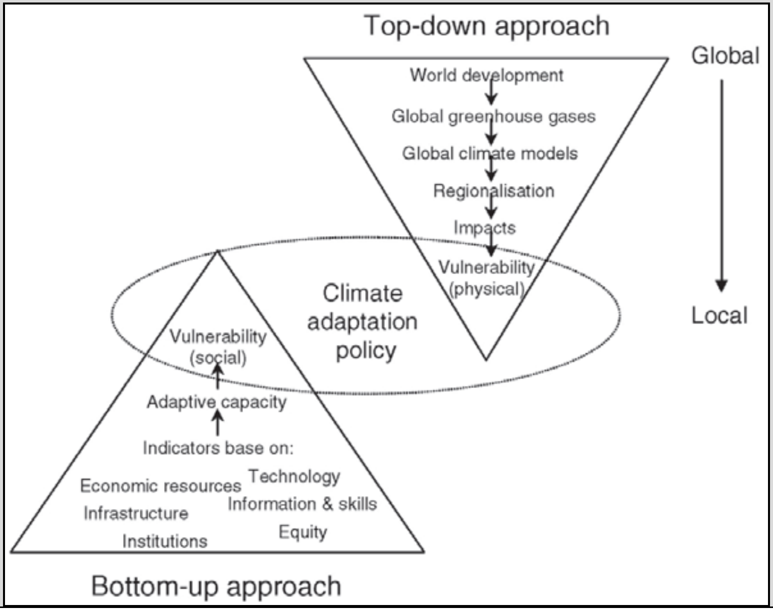
Box 1: "Top-down" versus "bottom-up" approaches for assessing vulnerability

Vulnerability assessment in this compendium is largely focused on approaches that use tools for the purpose of cause and effect prediction – i.e., global climate models and downscaling approaches as inputs into biophysical models to predict impacts and vulnerabilities so as to inform climate change adaptation (termed a "top-down" approach).

Another commonly used approach to vulnerability assessment has a very different emphasis. This approach emphasizes social and economic well-being by focusing on past and present conditions to develop an understanding of vulnerabilities and future adaptation (termed a "bottom-up" approach). In place of the predictive biophysical tools, this approach uses scenarios analysis or visioning processes with affected stakeholders and end users to understand social vulnerabilities which can then be used to identify the best opportunities for climate change adaptation (see Case Study 3.5; Black 2010a, 2010b; Nesbitt 2010; Rowan et al., 2011. For examples of stakeholder engagement see Agrawala 2011; Bardsley and Rogers 2010; Gardner et al. 2009).

Though addressing the problem of climate change vulnerability and adaptation from distinct perspectives and using different techniques, these two approaches are complementary (Dessai and Hulme 2004; Cohen 2011).

Figure 3: Top-down and bottom-up approaches to understanding vulnerability and its role in climate change vulnerability and adaptation (Dessai and Hulme 2004)



There are some common elements within the range of approaches to vulnerability assessment:

- identifying the conceptual framework for vulnerability assessment (which requires clarifying purpose, components of vulnerability, and assessment targets based on past, present, or future stakeholder interests)
- evaluating climate change impacts (using alternative climate scenarios)
- identifying measures or indicators to evaluate vulnerability and
- using the results for climate change planning and adaptation (beyond the scope of this compendium).

1.3 When Should a Vulnerability Assessment Be Used?

The purpose of a vulnerability assessment is to generate knowledge that improves understanding of the implications of climate change. The knowledge generated by a vulnerability assessment is used to inform allocation of resources for climate change planning and adaptation (e.g., Dessai and Hulme 2004). Some examples of when vulnerability assessments have been used include:

- providing insight into the actions needed to prevent loss of life, damages, or disasters (Cutter 1996)
- understanding vulnerability as a prerequisite for developing adaptation policies that promote equitable and sustainable development (Vogel and O'Brien 2004)
- anticipating where impacts may be greatest at a Canada-wide scale, setting priorities for regional assessment of climate change impacts and adaptation strategies, and monitoring climate change effects (Hurd et al. 1999)
- understanding the economic costs to communities and infrastructure due to extreme weather events (Lemmen et al. 2007; for example the costs from extreme weather events in Canada from 1996-2006 were greater than for all previous years on record combined)
- developing policies and adaptation plans for vulnerable areas, sectors, groups, etc. as well as reducing climate change risk (Mohan and Sinha 2010).

The location and timing of a vulnerability assessment will be affected by the availability of sufficient expertise, time, and financial resources.

1.4 Who Should Use This Compendium?

In general, the audience for this compendium includes specialists involved in assessing vulnerability to climate change (i.e., technical experts including natural and social scientists) and those involved in planning and implementing climate change adaptation in urban, rural, and remote watersheds across Canada (i.e., adaptation planners, decision makers, and resource managers).

In particular, the audience for this compendium includes:

Technical experts who assess the impact of climate change on water resources, human communities, and freshwater ecosystems. This audience could include engineers, biologists, and social scientists in academia, government, or private sectors. They would use the tools described in this compendium and provide results to the adaptation planners and decision makers.

Adaptation planners who develop adaptation actions and policies that can be taken to avoid or mitigate potential impacts on the built environment and natural resources. They may be involved in prioritizing resources (time, people, money) for management strategies, infrastructure, and development activities.

Decision makers/resource managers who have statutory responsibilities for managing human and/or ecosystem needs for water. They may include stakeholders with responsibilities that include stewardship of water and its users (e.g., water purveyors, municipalities, drinking water experts, conservation organizations).

1.5 How Should This Compendium Be Used?

Readers undertaking a vulnerability assessment should first clearly express the purpose of the assessment and the framework for conducting the assessment. These considerations will depend on the local context and stakeholders involved in a vulnerability assessment and are not discussed in this document. To serve the intended purpose and the identified framework, an appropriate set of tools must also be used. This compendium assists in the selection of appropriate tools (i.e., models, approaches, and resources) for conducting a vulnerability assessment.

Section 2 provides a review of tools that are relevant to the Canadian context. This section is not intended to be read from beginning to end. Isolated sections can be reviewed based on a reader’s interest after scanning the range of options summarized in Section 1.6. Technical experts will be needed to evaluate a tool, understanding its relevance, and assessing its feasibility of application in a watershed of interest.

The suite of tools presented here were selected on the basis of developing a set that are representative of a broad range of water resource issues, data needs, and technical capabilities while still being relevant to the Canadian context. More tools were identified than are described here and as a result the reference list includes more citations than are referenced in the report so it can be used as a searchable resource.

Section 2 also provides a range of tools organized by dimensions of vulnerability (exposure, sensitivity, and adaptive capacity), as well as by important components of watershed characterization (freshwater ecosystems and human communities).

- Section 2.1 summarizes tools for selecting climate scenarios for a vulnerability assessment.
- Section 2.2 summarizes tools for assessing exposure of a watershed and its water resources (i.e., water quantity / quality) to the effects of climate change.
- Section 2.3 summarizes tools for assessing sensitivity of watersheds, human communities, and freshwater ecosystems.
- Section 2.4 summarizes tools for assessing adaptive capacity of human communities and freshwater ecosystems.
- Section 2.5 summarizes other tools for supporting vulnerability assessments of watersheds.

Section 3 presents five case studies of vulnerability assessments applied to coastal, interior, mountainous, and northern watersheds.

1.6 What Tools are Described in this Compendium?

The tools in this compendium are varied and diverse – ranging from indicator based approaches (see Box 2) to sophisticated hydrological models that calculate exposure to flood events under future projections of climate change. In some cases, these tools represent new applications of or adjustments to existing tools by making them “climate aware”. Tools include both qualitative and quantitative approaches that address a broad range of characteristics of social-ecological systems. They were included in this compendium for their particular relevance to the Canadian landscape, which includes being relevant across a range of physiographic settings (see Canada’s ecozones in Figure 4) and being relevant to the climate stressors of likely interest to human communities and ecosystems across Canadian jurisdictions (Lemmen et al. 2008).

Figure 4: Ecozones of Canada (Federal, Provincial and Territorial Governments of Canada 2010)

Box 2: Use of indicators to estimate vulnerability

Indicators are used in some form in most vulnerability assessments. Throughout the literature, indices and indicators are often synonymously called themes, components, or sub-indices (index) and proxies (indicators). For clarity in this compendium, an indicator is defined as single measure of a characteristic (e.g., water temperature), the units of which can be described by a particular metric (e.g., annual maximum temperature). An index is defined as a composite, or aggregate, measure of several indicators or indices. These terms are used even though they may not be consistent with the language of the original studies.

Discussions about the types of indicators used to assess different dimensions of vulnerability (exposure, sensitivity, and adaptive capacity) are provided in subsequent sections (and in Case Studies 3.1 and 3.2 (social vulnerability indicators) and in 3.4 (physical and social indicators). Indicators relevant to these dimensions are often selected based on the literature, the nature of the hazard, the conceptual framework of a vulnerability assessment, as well as data availability. Key considerations when identifying and selecting indicators include:

(1) appropriateness and relevance to dimension of interest;
(2) transparency (not too complicated, should be repeatable);
(3) feasibility (considering cost of data collection and time availability); and
(4) size and composition of each indicator (absolute vs. relative values, areal measure, etc.).

A set of relevant indicators can be developed through statistical approaches (e.g., factor analysis, Principal Component Analysis, and Monte Carlo analysis) or participatory methods (e.g., household surveys, semi-structured interviews, discourse analysis, cognitive mapping, and thought experiments). Sources of data will vary widely and may include census data, local reports, peer reviewed articles, and observations from meteorological / hydrological stations.

Once the indicators and their respective data sources have been identified and validated, indicators can be calculated and aggregated. Methods of aggregation for vulnerability assessment, and their respective strengths and weaknesses, are discussed in greater detail in Section 2.5.1.

Figure 2 provides a framework for classifying tools according to the dimensions, components, and elements of vulnerability. Distinctions among the elements are delineated by soft boundaries because some tools can be classified in multiple branches of the tree. A smaller version of the framework is used as a key throughout Section 2 to highlight the relevance of a section to the framework.

The purpose of this framework is to organize and better understand the range of available tools. This framework represents the full range of considerations and commonalities across all vulnerability assessments and related tools. It does not represent all of the things that should be considered in an individual vulnerability assessment. Detailed considerations will be driven by the specific needs of end users and decisions that will be affected by the results from a vulnerability assessment.

Table 1 and Table 2 provide an "*at a glance*" overview of the full suite of tools summarized in Section 2 which relates to the classification presented in Figure 2.

Table 1: Overview of tools for assessing vulnerability of watersheds

Dimensions	Components	Tool groupings	Tool sub-groupings / examples
Exposure (Section 2.2)	Water Quantity / Water Quality	Lumped models (Section 2.2.1)	• Canadian Water Evaluation Tool • ForHyM & ForWaDy • Hydrologic Evaluation of Landfill Performance • Thornthwaite Monthly Water Balance Model • Water Resources Evaluation of Non-Point Silvicultural Sources (WinWrnsHyd & ECA-Alberta)
		Semi-distributed models (Section 2.2.2)	• Hydrological Simulation Program-FORTRAN Model • Water Evaluation and Planning System
		Fully-distributed models (Section 2.2.3)	• MIKE SHE • Variable Infiltration Capacity Model
		Indicators, indices, and statistical models (Section 2.2.4)	• Precipitation minus potential evapotranspiration (P-PET) • Isaak et al. 2010 • Swansburg et al. 2004
Sensitivity (Section 2.3)	Watersheds (Section 2.3.1)	Indicators of watershed condition or function	• Upslope • Riparian-floodplain • Inchannel
		Biological indicators	• Macroinvertebrates • Fish
		Coupled or integrated watershed models	• Many possible examples
	Human Communities (Section 2.3.2)	Social vulnerability analysis	• Many possible examples
		Engineering vulnerability assessment	• Public Infrastructure Engineering Vulnerability Committee
		Risk assessment	• Many possible examples
	Freshwater Ecosystems (Section 2.3.3)	Bioclimate envelope models	• Many possible examples
		Species or life history susceptibility	• NatureServe Climate Change Vulnerability Index • System for Assessing Vulnerability of Species
		Habitat or species models	• Conceptual models • Indicator-threshold approaches – Water temperature guidelines – Flow standards • Dynamic systems models
Adaptive Capacity (Section 2.4)	Human Communities (Section 2.4.1)	Determinants of adaptive capacity	• Economic resources • Technology • Information, skills, and management • Infrastructure • Equity • Institutions and networks
		Assets of adaptive capacity	• Human • Social • Natural • Physical • Financial
	Freshwater Ecosystems (Section 2.4.2)	Indicators of ecosystem resilience	• Genetic diversity • Integrity of landscape mosaics • Biological diversity

Table 2: Overview of tools to support vulnerability assessments of watersheds

Analytical tasks	**Tools**
Selecting future climate scenarios (Section 2.1)	Synthetic approach
	Analogue approach
	Scatter plot method
	Percentile rank method
Aggregating dimensions of vulnerability (Section 2.5.1)	Simple averaging technique
	Weighted averaging technique
	Pareto ranking
	Data Envelopment Analysis (DEA)
	Vulnerability maps
	Vulnerability profile
Understanding the effect of uncertainties (Section 2.5.2)	Sensitivity analysis
	Scenario analysis
Communicating uncertainty (Section 2.5.3)	Likelihood of occurrence
	Confidence in statements

2. TOOLS FOR VULNERABILITY ASSESSMENT OF WATERSHEDS

2.1 Tools for Selecting Future Climate Scenarios

Four general approaches are available for developing a range of climate scenarios to use in a vulnerability assessment of watersheds (described in more detail in EBNFLO Environmental and AquaResource Inc. 2010):

(i) Synthetic approach
(ii) Analogue approach
(iii) Scatter plot method
(iv) Percentile rank method

One of the simplest approaches is a synthetic approach which requires using current climate information and selecting an arbitrary range and magnitude of change in relevant climate variables as inputs into a modelling or assessment approach (e.g., increasing annual average air temperatures by 1˚, 2˚, and 4˚C, and varying annual precipitation by ±10% and ±20%). Concerns, however, are that such arbitrary adjustments may not be physically realistic, would not be comparable to other studies. Given its simplicity it is not recommended for use in some jurisdictions (e.g., EBNFLO Environmental and AquaResource Inc. 2010), yet has been applied by others (e.g., Johnson and Weaver 2009; Tarekegn and Tadege no date).

An analogue approach is relatively simple, though somewhat more defensible in that it requires applying realistic climate conditions from a different watershed or from a different time series at a location of interest for a vulnerability assessment. A different time series could reflect a recent or paleologic time period of extreme climate conditions or conditions associated with a distinct climate event or regime at the location of interest. Alternatively, climate conditions from a watershed with warmer/drier conditions at a southern latitude could be used to infer the vulnerability of a watershed in a more northern location.

However, climate conditions from a watershed with warmer or drier conditions at a southern latitude should be used with caution to infer the vulnerability of a watershed in a more northern location affected by cold region conditions such as permafrost, prolonged snow cover and cold soils.

Another limitation with this approach is that climate conditions will not necessarily be consistent with the conditions projected under the standardized IPCC emissions scenarios and thus would not be comparable to many other studies. Despite the improvements over a synthetic approach, there are still limitations and reservations about its use in part due to the inability of the past to appropriately represent the future (e.g., Dessai and Hulme 2004; EBNFLO Environmental and AquaResource Inc. 2010).

Global and regional climate model data are fundamental drivers of exposure and the other tools described in this compendium. Given the importance of climate data, Table 3 provides a summary of data sources for global and regional climate model results. These information sources cover a breadth of organizations, regions, and spatial scales for which climate data are available for Canada (regional, Canada-wide, continental, or international sources). These data also vary according to their spatial resolution, and there is some overlap in GCM models and emissions scenarios represented by these sources. A review of climate downscaling tools/techniques was beyond the scope of this compendium though other resources are available to provide this information (e.g., UNFCCC 2008 as well as some of the web sites in Table 3).

Table 3: Tools and sources of climate data (air temperature (AT) and precipitation (P)) for Canadian jurisdictions (websites last accessed December 19, 2011).

Organization	Geographic extent	Data, models, and emissions scenarios	Web link
Canadian Climate Change Scenarios Network (CCSN)	Canada	Raw historic and future AT & P data from multiple global climate models and Canadian Regional Climate model forced with multiple GCM-emissions scenarios.	http://cccsn.ca/?page=download-intro
Canadian Centre for Climate Modelling and Analysis (CCMA)	Canada	Raw or pre-defined historic and future AT & P data from Canadian global climate and regional climate models for multiple emission scenarios.	http://www.cccma.ec.gc.ca/data/data.shtml
Ouranos Consortium	Canada	Pre-defined historic and future AT & P variables from 4 global models, 2 regional models, and multiple SRES emissions scenarios	http://loki.qc.ec.gc.ca/DAI/DAI-e.html
PCIC Regional Analysis Tool	Pacific and Yukon Regions	Pre-defined AT & P variables from 7 global models and multiple emissions scenarios.	http://pacificclimate.org/tools-and-data/regional-analysis-tool
PCIC Climate Western North America	western North America	Pre-defined historic and future AT & P data from 3 global-emissions scenarios.	http://pacificclimate.org/tools-and-data/climatewna
North American Regional Climate Change Assessment Program (NARCCAP)	North America	Raw AT & P data from multiple regional climate models and 5 global models forced with A2 SRES emissions scenario.	http://www.narccap.ucar.edu
The Nature Conservancy	Global	Pre-defined AT & P variables from 16 global models forced with A2, A1B, and B1 emissions scenarios.	http://www.climatewizard.org
Intergovernmental Panel on Climate Change (IPCC)	Global	Raw AT & P data for all global models and SRES emissions scenarios.	http://www.ipcc-data.org/

A large ensemble of Global Circulation Models (GCMs), regional climate models, and downscaling approaches are available to estimate future climate conditions in a vulnerability assessment. Likewise multiple emission scenarios can be used as climate forcings in these models[2]. Each model

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[2] The most recent standardized scenarios used as climate forcings in Global Circulation Models are represented by the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). These scenarios were used in the 2007 IPCC Fourth Assessment Report (AR4). New climate forcing scenarios are being developed for the upcoming IPCC Fifth Assessment Report (AR5) which are termed Representative Concentration Pathways (RCPs) (Moss et al. 2008). These new scenarios are expressed in terms of carbon dioxide equivalents rather than direct emissions as previously done in SRES.

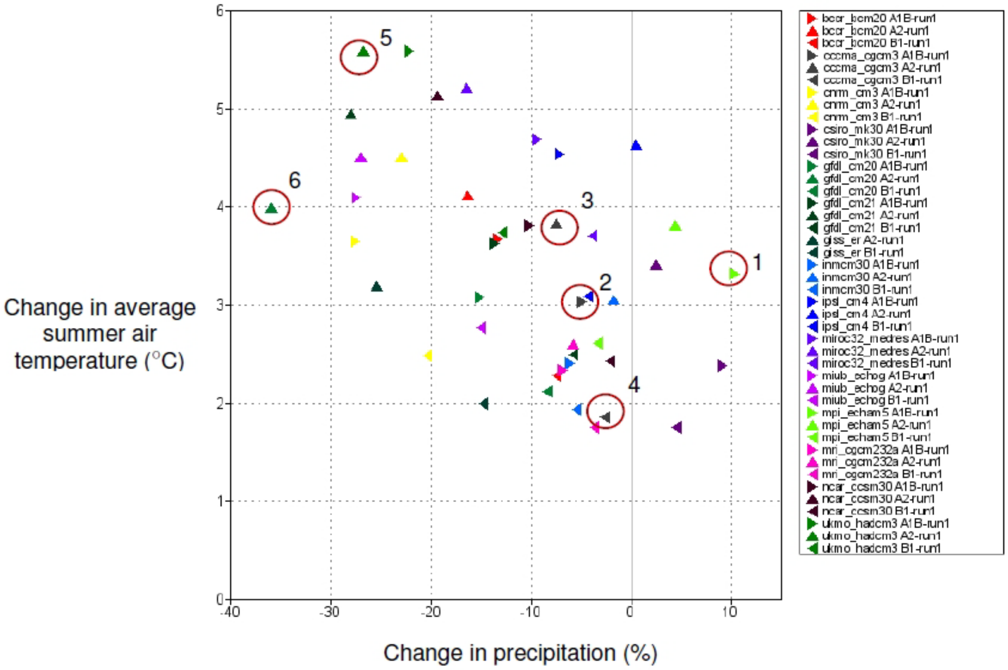
and emission scenario combination (i.e., climate scenario) represents an alternative and plausible reality about how future development and climate might unfold.

A challenge when conducting a vulnerability assessment is deciding on the most appropriate climate scenario to use given the wide range of climate scenarios. The emerging view is to use a range of climate scenarios because a range of climate scenarios provides a better understanding of possible future conditions than a single model and scenario (e.g., Tarekegn and Tadege no date; Lopez et al. 2009; Glick et al. 2010; EBNFLO Environmental and AquaResource Inc. 2010; Nelitz et al. 2010; Zhang et al. 2011).

The user of climate model data should be aware that the model results could be biased in some way. Reviews of how these models simulate the current climate have found that precipitation and temperature can be over predicted in some areas and under predicted in others. This bias can be corrected using various methods and it is recommended that the user should confirm if a bias correction has been applied to the climate projections.

A rigorous, realistic, and standardized approach would be to use a scatterplot method to examine the range of future climate scenarios. This approach requires plotting the results of projected changes in air temperature against precipitation from each climate scenario (e.g., Figure 5). The scatterplot can then be used to select climate scenarios that span the range of high and low changes in air temperature and precipitation. Ideally, as many climate scenarios as possible should be selected, with a minimum of four to represent high and low changes across both axes. A major constraint with this approach is that it is more analytically intensive than the above methods.

Figure 5: Illustration of the range of predictions in air temperature and precipitation across climate scenarios. Circles and numbers represent scenarios used in a vulnerability assessment in British Columbia (Nelitz et al. 2010)



A last consideration is to use a percentile rank method (illustrated in more detail in EBNFLO Environmental and AquaResource Inc. 2010). Building on the scatterplot method, the projected changes in air temperature from all climate scenarios are ranked according to their percentile. The same percentile ranking is applied to the projected precipitation projections (e.g., selecting climate scenarios providing the 95th, 75th, 25th, and 5th percentile ranks of change in air temperature and precipitation). These percentiles are then used as the basis for selecting climate scenarios. Again, this approach is more analytically intensive than some other methods and requires managing extensive quantities of data from many climate scenarios.

2.2 Tools for Assessing Exposure

The vulnerability of a watershed will be driven in large part by its exposure to climate change. For the purposes of this compendium, **exposure** is defined as *the magnitude, spatial extent, and rate of change in water resources (quality and/or quantity) due to climate change*.

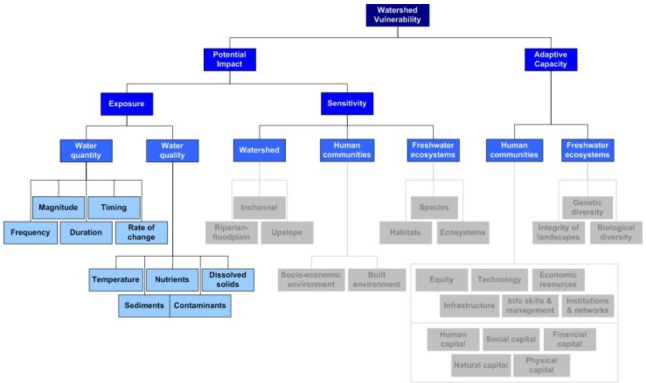
Many changes to water quantity are expected. Surface runoff is strongly influenced by changes to precipitation and air temperature and by changes to the amount of snow in winter.. Where winter air temperatures are continuously below zero, the amount of snow may increase with increasing precipitation. In locations where winter air temperature typically varies around freezing, the form of precipitation (snow vs. rain) may change due to temperature increases. Warmer air temperatures can also delay the accumulation of snowpack in the fall and advance the timing of snowmelt in the spring. For glacier influenced watersheds in northern and western Canada, rising summer air temperature increases annual ablation and glacial retreat, thus, altering summer streamflow. Decreasing summer and fall precipitation can exacerbate summer low flows, particularly for rainfall-dominated watersheds.

In watersheds heavily influenced by groundwater, rates of surface water and groundwater exchange can also change along a river reach. For forested watersheds, changes to precipitation and air temperature can influence evapotranspiration rates, which affect the soil water balance and, thus, soil wetness and runoff responsiveness. All of these changes to runoff can influence the quantity, timing, duration, and frequency of streamflows .

Most water quality changes observed so far are most likely due to causes other than climate change (CCSP 2008b). Despite the huge influence of human activities, water quality is sensitive to changing climate conditions. Changes in precipitation and air temperature can alter the composition, structure, and dynamics of terrestrial ecosystems and associated forest disturbance regimes (e.g., fire and disease).

These changes can influence biophysical processes in terrestrial and freshwater environments (e.g., US EPA 2008; CCSP 2008a) which in turn can affect nutrient concentrations in watercourses. Changes to runoff conditions, streamside vegetation, and air temperatures can impact stream temperatures, while changes to high and low flows can influence stream channel morphology, sediment transport, and concentrations of suspended sediments. Changes to the timing and intensity of runoff can also impact the distribution, concentration, and timing of contaminant loading.

The discussion below provides an overview of the tools that can be used to assess the exposure of a watershed to climate change. Knowing the basic structure or approach of a tool provides understanding of its complexity and the amount of data required for application. Tools below are grouped according to their basic structure or approach:



- <u>Lumped models</u> tend to have minimal data requirements, are fast to setup and calibrate, and are simple to apply, yet provide less information compared to more complex models.
- <u>Semi-distributed models</u> tend to be more physically based than lumped models, but less data intensive than fully-distributed models.
- <u>Fully-distributed models</u> tend to provide the highest accuracy and/or the most spatially intensive information, but require considerable data and expertise.
- <u>Indicators, indices, and statistical models</u> vary widely in their structure, information needs, and output.

These tools address a range of water quantity and quality processes from simple to complex. Selection of the appropriate tool requires consideration of information/data input needs, experience/skills required, intended application, output parameters, and the spatial/temporal scales of data. Contained within this range of tools are models that experts across Canada will generally be familiar and/or are considered particularly useful. Appendices B and C provide the full list of water quantity and water quality tools identified during this review. The information captured in these appendices includes a tool's name, parameters of relevance, example regions of application, and citations. While knowing where a tool has been applied provides some indication regarding the transferability of the tool, the list of example regions is neither sufficiently specific nor exhaustive to guarantee transferability to a specific watershed in Canada.

Given the dynamic nature of climate change impacts it is important that tools for assessing exposure be able to predict changes in climate and water resources over both space and time, though there are several challenges in doing so.

A first challenge is selecting the appropriate GCM models and emissions scenarios to provide inputs of air temperatures and/or precipitation. Section 2.1 summarizes sources for climate data in Canada and discusses alternative approaches for selecting or using multiple GCM/emission scenarios.

A second challenge is that most tools operate at temporal and spatial scales much smaller than GCMs. One option for addressing this discrepancy is to downscale climate data to finer spatial and temporal resolutions. Another option is to use output from multiple climate models or model runs to evaluate the effect of uncertainties (e.g., Prudhomme and Davies 2009a; 2009b).

A third challenge is that the effect of hydrological model selection on future predictions of hydrological response is poorly understood. For instance, some studies show that hydrological model complexity can have a major impact on climate change evaluations (e.g., Ludwig et al. 2009), while others show that hydrologic model selection can have a significant though smaller effect than alternative GCM models or downscaling approaches (e.g., Prudhomme and Davies 2009a; 2009b).

Finally, the ability of a hydrological model (driven by climate simulations) to reproduce reference hydrology may be low. Thus, model calibration will be an important part of an evaluation, and in some cases it may be most appropriate to base future predictions on relative changes in streamflow rather than absolute values. These challenges highlight that professional judgment is critical when selecting and using tools for climate change vulnerability assessments of watersheds to ensure the tools suit the study questions.

2.2.1 Lumped Models

CANWET (Canadian Water Evaluation Tool)

The Canadian Water Evaluation Tool (CANWET) is a continuous, combined distributed/lumped, GIS-based model designed to inform decision making around watershed management, water supply and wastewater treatment infrastructure, food security, and climate change adaptation.

The latest release is VB.Net database-driven and web-aware, and features an integrated open source GIS environment. It allows the user to generate input data for single or multiple basin analyses through GIS clipping routines. The model contains algorithms to correct for nutrient and sediment loss/retention/addition from reservoirs and wetlands, to estimate load contribution from point source discharge including septic system and livestock contributions, and to assess pollution mitigation techniques. Soil loss calculations consider variation in soil type and topography.

The model also provides for charting and mapping of simulated output, hydraulic routing of in-stream water quality concentrations and flows, climate change scenario analysis, web-based retrieval of input datasets, routing of point source discharges, and transformation of GIS layers into Google Earth overlays. It can link simulated output back to GIS for generating maps. Catchment output can be filtered by date, climate scenario, or theme (e.g. hydrology, nutrient load contributors, sediment, land use).

Inputs / outputs

The model requires three input files addressing meteorology, transport, and nutrients. It uses mean daily values for precipitation and temperature from the nearest two weather stations. Output contains daily and monthly water budget data, streamflow and bank erosion data, pollutant and nutrient loading, and inputs for a lake model.

User considerations

The user can utilize commonly available spatial data without requiring other software. Apparently, the model is considered easy to use relative to other more complex models with greater input requirements. The model was developed for use in Ontario and has been continuously upgraded for Canadian conditions. It operates on a subscription-based licensing system available for purchase from Greenland Technologies Group Ltd.

Documentation and support

A detailed user guide and technical manual are available. Training sessions are provided by Greenland International Consulting Ltd. On-site customized training and support are also available including software customization for special applications and consulting services for data development and model application. The model can be found at: www.grnland.com

ForHyM & ForWaDy

The Forest Hydrology Model (ForHyM) was designed to predict water fluxes within forests. The model was modified at the University of British Columbia to create the Forest Water Dynamics (ForWaDy) model. ForHyM is a lumped watershed model that runs at a monthly time-step (the latest version can run at a daily time-step). It simulates soil evaporation and plant evapotranspiration using empirical potential evapotranspiration algorithms based on a single vegetation layer and two soil layers. Snowmelt is modelled using a temperature-index (i.e. degree-day) approach. Unsaturated vertical soil water flux is proportionally related to the excess soil water content above field capacity. Streamflow is the sum of the percolation loss from the deepest soil layer. The model does not explicitly model channel routing.

The primary advancements incorporated in ForWaDy compared to ForHyM are that potential evapotranspiration is calculated using an energy balance approach and snowpack dynamics are simulated using the RHESSys Snow Model, which incorporates a generalized energy balance approach accounting for radiation, sensible and latent heat fluxes, and rainfall generated heat advection.

Inputs / outputs

ForHyM uses mean monthly precipitation and temperature as meteorological inputs, whereas ForWaDy uses daily values of precipitation, minimum and maximum air temperature, and solar radiation. Other inputs include latitude, altitude, slope gradient, slope aspect, and forest and soil characteristics. Fifteen parameters are used to calibrate the model to canopy and soil water fluxes, and to snowmelt. Outputs from ForHyM include vertical water flux through the forest canopy along with soil infiltration and percolation, snowpack water equivalent, snowmelt, and streamflow.

User considerations

Neither model simulates channel routing, which limits application of the models to water balance analysis for forest stands or small watersheds. The models also do not account for percolation losses to groundwater or topographic effects on hydrology, which makes the models most applicable to gently sloping areas with well-defined impermeable sub-soils (e.g. shallow bedrock). ForHyM can be applied to rainfall-dominated or snowmelt-dominated regimes, but cannot handle rain-on-snow events. The modified snow algorithms in ForWaDy can be applied to mixed regimes.

Based on the types and quantity of data inputs and calibration parameters, both models appear relatively simple to apply. ForHyM is formulated in STELLA, a computer modelling software, and receives inputs from Microsoft Excel. Excel uses Macros to convert the inputs into STELLA-ready format and to determine net radiation based on latitude, altitude, slope gradient, and slope aspect. Both models should be transferable to any location satisfying the limitations stated in the above section (i.e. impermeable sub-soil and gentle topography). ForHyM will be available for online public use in the near future. Currently, a blank Excel interface is available to organize data inputs for future use with the online tool.

Documentation and support

While detailed model descriptions were found online, no information was found regarding user documentation and support. The models can be found at:
http://watershed.for.unb.ca/research/forhym/
http://web.forestry.ubc.ca/ecomodels/moddev/forwady/forwady.htm

HELP (Hydrologic Evaluation of Landfill Performance)

The Hydrologic Evaluation of Landfill Performance (HELP) model is a lumped parameter, quasi 2-dimensional water balance model originally developed by the US EPA. The model was originally developed to estimate the water balance for municipal landfills, but has since been updated to apply to a variety of other settings including modelling groundwater recharge in southern BC. It operates at a daily time-step and incorporates multiple soil layers and a single vegetation layer. It simulates rainfall interception and evaporation using a range of algorithm complexities, and can account for seasonal variation in leaf area index. Snow accumulation and melt are modelled using a temperature-index (i.e. degree-day) approach with corrections for rain-on-snow conditions. Infiltration is calculated as the sum of rainfall and snowmelt minus interception, evaporation, and direct runoff. Unsaturated vertical drainage is calculated as a function of soil moisture storage and is assumed to occur by gravity drainage whenever the soil moisture is greater than the field capacity. Runoff is modelled using the US Department of Agriculture Soil Conservation Service curve number method. The model includes an empirical method for routing subsurface flow. A frozen soil component has been added to improve infiltration and runoff predictions in cold regions.

Inputs / outputs

Required model inputs are weather, soil, and design data, including evapotranspiration data and daily values of precipitation, temperature, and solar radiation. The model contains default evapotranspiration, precipitation, and soil databases for many US cities and material types, as well as a synthetic weather generator. Input and editing have been simplified with an interactive, full-screen, menu-driven interface.

User considerations

The model is considered easy to use and can be used for simulating stand-level processes in forests or small watersheds in rain, snow, and mixed regimes. Its application is limited in semi-arid environments and steep mountainous terrain. It does not explicitly consider lateral runoff and does not account for channel routing or road hydrology.

Documentation and support

The model is freely available for download along with a user guide and documentation, and a commercial version is also available. The model can be found at:
http://el.erdc.usace.army.mil/products.cfm?Topic=model&Type=landfill

Thornthwaite Monthly Water Balance Model

The Thornthwaite model is a monthly water balance model developed by the US Geological Survey that can be used to estimate water balance components for a specified location. It analyzes the allocation of water among various components of the hydrologic system using a monthly accounting procedure based on the methodology originally presented by Thornthwaite. The amount of monthly precipitation that is rain, snow, or mixed rain/snow are estimated based on temperature thresholds. Direct runoff from impervious surfaces is modelled as infiltration-excess overflow. Monthly snowmelt is calculated from the mean monthly temperature and a specified maximum melt rate. Actual evapotranspiration is derived from potential evapotranspiration, total liquid water input to the soil, soil moisture storage, and soil moisture loss. Monthly potential evapotranspiration is estimated from mean monthly temperature and is calculated as the climatic demand for water relative to the available energy. The amount of water that becomes runoff in a month is calculated based on a specified fraction of surplus water. The remaining surplus is carried over to the following month as storage. Total monthly runoff is calculated as direct runoff and runoff generated from surplus. The model can be used as a for research, teaching, or environmental assessments.

Inputs / outputs

The model requires an input data file containing mean monthly air temperature, monthly total precipitation, and seven input parameters (runoff factor, direct runoff factor, soil moisture storage capacity, latitude of the location, rain temperature threshold, snow temperature threshold, and maximum snowmelt rate). The range and default values for these parameters are set by the model. Output includes potential evapotranspiration, actual evapotranspiration, precipitation, precipitation minus evapotranspiration, soil moisture storage, soil moisture deficit, snow storage, water surplus, and total runoff.

User considerations

The model is considered easy to use, can run on any platform, and is driven by a graphical user interface in a window that behaves like any other window on the desktop. The user interface allows the water balance parameters to be easily modified. Tabular output is written to a popup window that can be saved. Specific variables can be selected for plotting in another popup window

Documentation and support

Software and documentation are freely available for download. The model can be found at:
http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/Thornthwaite.html

WRENSS (WinWrnsHyd & ECA-AB)

WinWrnsHyd and Equivalent Clearcut Area-Alberta (ECA-AB) are model implementations of the Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) handbook that was developed by the US EPA. The models have been used to estimate changes in average annual streamflows (yield) for evaluating the effects of existing and future forest management on water resources in southern BC and in Alberta.

WinWrnsHyd is a lumped parameter black-box hydrologic model with no explicit soil or vegetation representation. It models yield for different forest management regimes and accounts for forest regrowth using growth and yield curves. It does not account for runoff or channel routing. Differing initial regrowth conditions can be applied to analyze past, present, and future harvesting patterns. The effects of climatic and silvicultural variables on snow accumulation and evapotranspiration can be examined. It accounts for rain- and snow-dominated processes. Equations underlying the evapotranspiration calculations are analytical and account for leaf area index, whereas snowmelt calculations are empirical.

ECA-AB incorporates many components of the WinWrnsHyd model, but does not explicitly simulate evapotranspiration. It requires user-supplied information on long-term precipitation and streamflow to estimate changes in evapotranspiration and streamflow resulting from forest disturbance. Streamflow changes are based on the area harvested in a watershed, rate of forest regrowth, and water balance calculations of generated runoff (determined from long-term monthly precipitation and annual streamflows).

Inputs / outputs

Input parameters include clearcut size, basal area, and tree height regrowth equations for the relevant tree species. ECA-AB requires long-term monthly precipitation and annual streamflow data.

User considerations

The models are considered easy to use with modest input data requirements. The main limitation of the models is that their use does not extend beyond annual streamflow calculations. The accuracy of the model output depends on providing accurate information on the rates of hydrologic recovery following disturbance and on the availability of regional streamflow and precipitation data. Care should be taken when assessing absolute streamflows generated by the models.

Documentation and support

Model documentation for WinWrnsHyd can be found at:
http://www.westernsnowconference.org/sites/westernsnowconference.org/PDFs/2005Swanson.pdf

While detailed model descriptions for ECA-AB were found online, no information was found regarding user documentation and support. Information about ECA-AB can be obtained from Dr. Silins at the University of Alberta: http://rr.ualberta.ca/StaffProfiles/AcademicStaff/Silins.aspx

Other lumped models

- BROOK90
- CATCHMOD
- EPD-RIV1 (One Dimensional Riverine Hydrodynamic and Water Quality Model)
- FJQHW97
- HSAMI Hydrological Model
- IHACRES (Identification of Unit Hydrographs and Component Flows from Rainfalls, Evaporation and Streamflow Data Model)
- Intragravel Temperature Diffusion Model
- QUAL2K (River and Stream Water Quality Model)
- PDM (Probability Distributed Moisture Model)
- SAC-SMA (Sacramento Soil Moisture Accounting Model)
- SRM (Snowmelt-Runoff Model)
- WATBAL (Hydrological Water Balance Model)

2.2.2 Semi-distributed Models

HSPF (Hydrological Simulation Program-FORTRAN Model)

The Hydrologic Simulation Program Fortran Model (HSPF) developed by the US Environmental Protection Agency (EPA) simulates a broad range of surface and subsurface hydrologic and water quality processes in watersheds. It empirically simulates evapotranspiration from interception storage, upper and lower soil zone storages, active groundwater storage, and directly from baseflow. Explicit representation of vegetation in the model is limited. Infiltration, percolation, and runoff are simulated using empirical methods. Unsaturated zone storage is approximated using a single storage reservoir with inflow. Groundwater for each surface water basin is simulated as two storage reservoirs (active and deep). Snowmelt can be modelled using a temperature-index (i.e. degree-day) method or an energy balance method. Kinematic wave approximation is used to route flow to and within stream reaches. Lakes and water control structures are represented. HSPF has been used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, and flow diversions.

Inputs/outputs

The model runs at a daily or sub-daily time step for any period from a few minutes to hundreds of years. As a minimum, air temperature, precipitation, estimates of PET, land surface characteristics, and land management practices are required for watershed simulation. Additional inputs are required for the energy balance snowmelt module including solar radiation, dew point temperature, and wind. Wind, solar radiation, humidity, cloud cover, tillage practices, point sources, and/or pesticide applications may be required for water quality simulation.

Output can include interception, soil moisture, surface runoff, interflow, baseflow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), water temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and/or zooplankton. Streamflow hydrographs and pollutographs can be generated.

User considerations

Users can add their own modules with relatively little disruption of the existing code. The model is considered to be difficult to use without direct guidance from an experienced HSPF model user. Many parameters that control hydrologic processes are empirical and can only be determined through calibration. The model can be applied to small or large watersheds in gradual terrain in rain, snow, or mixed climatic regimes, but application to mountainous terrain is limited. Moreover, vegetation is represented as a single index, thereby, limiting the representation of variable forest cover types.

The model incorporates an internal database management system to process large amounts of simulation input and output. The model includes a graphical user interface and is integrated into a GIS environment with the development of Better Assessment Science Integrating point and Non-point Sources (BASINS). Other independent software are used to support data pre-processing and post-processing for statistical and graphical analysis. HSPF is currently distributed with BASINS and both are free.

Documentation and support

The HSPF source code, an executable version, a user's guide, and technical support are available online. Watershed Systems Modeling I and River Basin Water-Quality Modeling courses are offered annually at the USGS National Training Center and Watershed Systems Modeling II is offered upon request. EPA, Aqua Terra Consultants, and Hydrocomp Inc. occasionally offer training courses. The model can be found at: http://water.usgs.gov/software/HSPF/

WEAP (Water Evaluation and Planning System)

The Water Evaluation and Planning System (WEAP) is a surface water and groundwater simulation tool that utilizes a water balance approach and can run at a monthly time-step. It was designed as a comparative analysis tool to test alternative sets of supply and demand conditions and to project long-term changes in water demand, supply, and/or pollution to develop adaptive management strategies. Topics that can be investigated include incremental costs of water infrastructure investments, changes in operating procedures or policy scenarios, and implications of changing supply and/or demands, including an economic evaluation of these issues. The tool can be applied to agriculture practices such as crop mixes, crop water requirements, or canal linings; to reservoir operations; to water conservation strategies or efficiency programs; to management of instream flows; or to evaluating infrastructure development.

Inputs / outputs

Key inputs can include current and future spatial distributions of demographics, economics, socioeconomics, capital investments, historical water inflows, groundwater sources, water supply projections, crop water requirements, domestic water requirements, reservoir operating rules, pollution output, pollution targets, component capacities, and operating policies. The user can use GIS layers for background configuration of the system. Key outputs include mass balances, sectoral water use, cost/benefit scenario analysis, and pollution output.

User considerations

The tool is considered relatively easy to use, but requires substantial data for detailed analyses. Moderate training and experience in resource modeling is required to apply the tool effectively. It is highly transferable and can be applied to surface water and groundwater systems at municipal, Canada-wide, or international levels. A 2-year license fee costs US$1,000-$2,500 depending on the type of user.

Documentation and support

An on-line tutorial is available. Contact the Stockholm Environment Institute for details regarding available training. The model can be found at: www.weap21.org

Other semi-distributed models

- ACRU (Agricultural Catchments Research Unit)
- Aquatox
- CRHM (Cold Regions Hydrology Model)
- GAWSER (Guelph All-Weather Storm-Event Runoff)
- HBV (Hydrologiska Byråns Vattenbalansavdelning Model)
- HEC-HMS (US Army Corps of Engineers Hydrologic Engineering Centre Hydrologic Modeling System) – used in Upper Thames case study, section 3.1.
- HFAM (Hydrocomp Forecast and Analysis Modeling)
- INCA (Integrated Catchment Model)
- MIKE BASIN
- MODHMS
- OSWRM (Okanagan Sustainable Water Resources Model)
- PREVAH (Precipitation-Runoff-Evapotranspiration-Hydrotope)
- PRMS (Precipitation-Runoff Modeling System)
- RHESSys
- RIVFLOC
- SLURP (Semi-distributed Land Use-based Runoff Processes)
- SSARR (Streamflow Synthesis and Reservoir Regulation)
- SWAT (Soil and Water Assessment Tool)

- SWMM (Storm Water Management Model)
- TOPMODEL
- UBCWM (UBC Watershed Model)
- WARMF (Watershed Analysis Risk Management Framework)
- Water Balance Model by QUALHYMO
- WaterCAST
- WEPP (Water Erosion Prediction Project)

2.2.3 Fully-distributed models

MIKE SHE

MIKE SHE is an advanced, integrated hydrological modelling system that provides several approaches to modelling the land phase of the hydrologic cycle ranging from lumped conceptual approaches to fully-distributed physically-based approaches. Each hydrological process can be represented at different levels of spatial distribution and complexity. It incorporates multiple soil layers and a single vegetation layer. It can solve the governing equations for major hydrologic processes including evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow, and their interactions. Evapotranspiration is calculated analytically and snowmelt is calculated using a temperature-index (i.e. degree-day) approach with no apparent correction for rain-on-snow events. Water reaching the ground surface can either infiltrate or runoff as overland flow. The model includes three methods to simulate flow in the unsaturated zone at varying levels of complexity. The model can address solute transport, particle tracking, and geochemical reactions.

MIKE SHE’s river modelling component is the MIKE-11 modelling system for river hydraulics, which supports a range of complexity. MIKE SHE also has a full range of reservoir operation capabilities and is designed and developed to fully integrate surface water and groundwater flow. Data can be transferred between MIKE SHE and ArcGIS for pre- and post-processing. Maps of distributed parameters and digitized data are easily transferred between the two applications.

MIKE SHE has been used to model integrated catchment hydrology, conjunctive use of surface water and groundwater, irrigation and drought management, wetland management and restoration, environmental river flows, floodplain management, groundwater induced flooding, land use and climate changes, nutrient transport and management, and groundwater remediation, including point and non-point pollution. It has been applied in a large number of research and consulting studies covering a wide range of climatic and hydrologic regimes throughout the world, including the Okanagan region of British Columbia and Alberta. An example of how MIKE SHE has been used in a climate change study is a study of the Assiniboine River watershed in Saskatchewan, Manitoba and North Dakota (Stantec, 2011; available at http://www.parc.ca/rac/fileManagement/upload/2FINAL_AssiniboineRBasin_Hydrologic_Model_20120323.pdf)

Inputs/outputs

MIKE SHE can utilize input data that are readily available with agencies and authorities stored in GIS/database information systems. As a minimum, the model requires precipitation, air temperature, and soil properties as inputs. Data can be specified as constant or time varying values and can be distributed in space using stations (e.g. Thiessen polygons) or as cell-specific values.

The time series for each station can contain different time periods with uniquely varying time steps. The spatial and temporal variation of meteorological, hydrological, geological, and hydrogeological data are described in gridded format for input and output.

User considerations

MIKE SHE has a modular structure allowing the user to focus on only the processes that are important for the study and allows the user to build the model description according to the watershed conceptualization and availability of data. The model is considered complex and expensive (9,500 to16,000 Euros (2011) depending on the version). It can be applied to small or large watersheds in rain or snow regimes, but is not suitable for mixed regimes.

Documentation and support

The model is distributed by the Danish Hydrological Institute (DHI), which also provides ongoing training courses worldwide. The model can be found at:
http://mikebydhi.com/Products/WaterResources/MIKESHE.aspx

VIC (Variable Infiltration Capacity Model)

The Variable Infiltration Capacity (VIC) model is a grid-based large scale hydrologic research model that solves water and energy balances to simulate dominant land-atmosphere fluxes at a daily or sub-daily time step. It was originally developed at the University of Washington and accounts for both surface and subsurface hydrologic processes. Grid cells are large (>1km), flat, and uniform. Sub-grid heterogeneity in vegetation and soil characteristics is represented by partitioning grid cell areas to different vegetation and soil classes using statistical distributions. Up to five elevation bands can be represented in each grid cell to account for sub-grid scale variations in precipitation.

The model incorporates three soil layers and one vegetation layer with energy and water fluxes exchanged between the layers. It simulates evaporation from the soil layers, evapotranspiration from vegetation, and snowmelt processes. The snowpack is treated as a 2-layer system. The upper portion is considered separately for solving the energy balance at the snow surface. It accounts for spatially-distributed snow coverage and blowing snow sublimation, frozen soils, lakes, and wetlands. Water can only enter a grid cell from the atmosphere. Infiltration and runoff mechanisms are treated empirically. Non-channel flow between grid cells is ignored, as runoff reaching the local channel network within a grid cell is assumed to be much greater than non-channel flow crossing grid cell boundaries. Total runoff from each grid cell is the summation of surface runoff and baseflow, which are routed to simulate streamflow at points of interest. Surface runoff occurs when precipitation exceeds the variable infiltration capacity. VIC does not account for interflow. Grid cells are simulated independently of each other over the time period of interest to produce time series of surface runoff, baseflow, evapotranspiration, and snowmelt, among other variables.

The model is commonly coupled to global circulation models. It can assist with regional-scale planning and associated policy development, and can be used as a tool for assessing the effects of climate change and large-scale disturbances on hydrology. It has been applied to the Fraser River, Campbell River, Peace River, Columbia River, Ohio River, Arkansas-Red Rivers, and Upper Mississippi River, including studies addressing climate change investigations in cold mountainous terrain.

Inputs/outputs

Inputs include parameter files to describe soil and vegetation characteristics, and the distributions of elevations, lakes, and wetlands. Meteorological inputs include daily or sub-daily time series of temperature, precipitation, and wind. Solar radiation is calculated within the model. Output files describe energy fluxes, water fluxes, snowpack conditions, and soil hydrothermal conditions.

User considerations

Application of the model is limited by the low grid resolution that is used, as the model is not useful for site-specific or small watershed applications. It can only be applied to watersheds approximately 500 km^2 or larger. Streamflow routing is performed separately from the land surface simulation requiring a separate model.

VIC is a research model. It is considered highly complex and requires extensive data inputs, pre-processing, and GIS analysis. The model is easily transferable. The model is free.

Documentation and support

There is no formal documentation available beyond web pages and publications from scientific studies that have used the model. The model is always under development. The current version of the model is maintained at the University of Washington, Department of Civil and Environmental Engineering, under the direction of Dennis P. Lettenmaier. Technical support is available only through special arrangement. The model can be found at:
www.hydro.washington.edu/Lettenmaier/Models/VIC/

Other fully-distributed models

- BATS (Biosphere-Atmosphere Transfer Scheme)
- CASC2D
- CEQUEAU
- Hydrology routine coupled to CGCM
- CLASS (Canadian Land Surface Scheme)
- DHSVM (Distributed Hydrology Soil Vegetation Model)
- Hydrology routine coupled to ECHAM
- EFAS (European Flood Alert System)
- GAWSER/GRIFFS (Guelph All Weather Sequential Event Runoff / Grand River Integrated Flood Forecasting System)
- HydroGeoSphere
- HYDROTEL
- SIMGRO (Simulation of Groundwater and Surface Water Levels)
- STREAM (Spatial Tools for River Basins and Environment and Analysis of Mgmt Options)
- UBC-UF Peak Flow Model
- WaSiM-ETH (Wasserhaushalts-Simulations-Modell)
- WASP (Water Quality Analysis Simulation Program)
- WATCLASS
- WATFLOOD

2.2.4 Indicators, indices, and statistical models

This category of tools includes other useful tools that are not numerical models, and provides alternatives for organizations with insufficient resources to run complex numerical models. Each indicator, index, and statistical model tends to be unique and, thus, this category of tools encompasses a large range of approaches, structures, input requirements, and output characteristics.

Many of these tools can be useful for characterizing patterns, variability, or trends related to hydrology or climate conditions, including inferences regarding impacts (past or future) of climate change on water quantity or quality. They draw upon existing environmental monitoring programs to address water quantity or water quality metrics. While many of the tools, particularly indicators and indices, are not dynamic in terms of predicting a hydrological response to changing climate, some can be applied to spatial datasets within geographic information systems to examine the spatial distribution of watershed exposure.

Indicators and indices are generally easy to apply, are highly transferable, and free (not including costs associated with generating the necessary database). Statistical models are typically user-built, so they are highly flexible in their structure, approach, and information needs. They also are typically based on historical data, so they may not account for changing physical processes. The models often are not geographically transferable; however, the individual approaches usually are. Table 4 provides a summary of indicators and associated metrics that can be useful for assessing or inferring watershed exposure to climate change.

Hurd et al. (1999) developed several indicators for assessing the vulnerability of regional water resources and water dependent resources to climate change, including a natural variability indicator for streamflow, a dryness ratio related to the water balance, and a groundwater depletion ratio accounting for annual recharge rates. Hayhoe et al. (2006) examined changes in climate, hydrological, and biophysical indicators to assess the influence of climate change at the regional scale, including seasonal temperatures, rainfall and drought, snow cover, soil moisture, streamflow, growing season, frost days, and Spring Indices.

A relevant example of an index is the calculation of mean annual precipitation minus potential evapotranspiration (P-PET) (Marchildon et al. 2007). This index expresses the climate moisture deficit and, thus, comprises a drought index. The precipitation term represents water supply and the potential evapotranspiration term represents water demand. The index values have a physical meaning in terms of actual moisture deficit and, thus, can be used to identify land at risk of desertification, to define the boundaries between various ecosystems, and to predict the distribution of plant communities. Mapping the drought index over large areas requires an extensive climate database and a simple method of estimating PET. Evapotranspiration depends on air temperature, solar radiation, wind speed, humidity, and the soil and vegetation characteristics. The Thornthwaite equation can be used as a simple approach for estimating PET. It requires only air temperature as an input and can generate reasonable results for mid-latitude continental climates where air temperature is strongly correlated with net radiation.

Table 4: Examples of hydrology and climate indicators that can be used to assess watershed exposure. Note that the list of examples is not exhaustive (see Hurd et al. 1999; Hayhoe et al. 2006; Tiburon et al. 2010 for more examples).

Category	Sample indicators	Sample metrics
Climate	Precipitation, air temperature, solar radiation, vapour density, wind speed	Precipitation or air temperature summarized by season or time of day and by mean, median, minimum, maximum, or variance; rainfall/snowfall ratio; drought frequency
Lakes	Water level, water surface area, ice on, ice off	Maximum annual water level, minimum annual water level, timing of ice off
Snowpack	Snow accumulation or melt quantity, duration, or timing	Maximum annual snow water equivalent (SWE), April 1 SWE, snowcover duration, date of snowpack disappearance, maximum 7-day snowmelt rate
Soil	Unsaturated soil moisture, groundwater level, temperature	Pre-growing season water deficit, mean annual groundwater level, spring freshet maximum groundwater level, March 1 soil temperature
Streamflow	Discharge, water level	Maximum annual discharge, 7-day mean low flow discharge, mean annual discharge, flood frequency, low flow frequency
Water quality	Water temperature, suspended sediments, dissolved solids, nutrients, contaminants	Annual maximum stream temperature, spring freshet maximum suspended sediment concentration, days/year with nutrients or contaminants exceeding a threshold

Indicators for both physical and social analyses are used in the following case studies which appear in Chapter 3: 3.1 Upper Thames (social); 3.2 Hunter and Central Coasts (social); and 3.4 Arctic Water Resources Vulnerability Index (physical and social).

Statistical modelling approach of Isaak et al. 2010

Isaak *et al.* 2010 implemented a study for a large river network in a mountainous area of central Idaho to develop spatial regression models to predict stream temperatures across the network and to estimate climate- and wildfire-induced changes in stream temperature patterns and thermal habitat. A database was assembled of stream temperature measurements distributed across small (2350 ha), medium, and large (10 000 ha) streams and across a large range of elevations. Predictor variables representing important components of a stream heat budget were derived with many of the predictors quantified from digital map layers in ArcGIS. The data to run the spatial models included the temperature observations, predictor variables, and spatial coordinates and upstream contributing area for each location. The final models were used to make stream temperature predictions at the catchment scale and within burned areas by adjusting input values for air temperature, streamflow, and solar radiation (i.e. the dynamic variables) to match the average set of conditions at the beginning and end of the study period.

Statistical modelling approach of Swansburg et al. 2004

Swansburg et al. 2004 implemented a study to generate site-specific future climate scenarios (2010-2099) for locations across New Brunswick using regression-based statistical downscaling of GCM projections. Each scenario was compared to past climate patterns and the impacts on water resources were evaluated. Data from the Canadian Global Coupled Model in conjunction with the greenhouse gas + aerosol emission experiment (CGCM1-GA1) were used to generate site-specific scenarios in New Brunswick. The model was driven by the IPCC IS92a emissions scenario. Surface and upper-atmospheric predictor variables were interpolated to the CGCM grid. Regression-based statistical downscaling models were developed from daily time series of maximum and minimum temperatures, wet-day amounts of precipitation, stream discharge, and five other predictor variables. After calibration and validation, the final models were used to generate daily climate data for 2010-2099. Annual and seasonal trends in data were examined and long-term values of average temperature, precipitation, and river discharge were compared by analysis of variance followed by least squares difference.

Other indicators, indices, and statistical models

- Arctic Water Resource Vulnerability Index (AWRVI)
- Barnes et al. 2009
- Furniss et al. 2010
- Hayhoe et al. 2006
- Hurd et al. 1999
- Indicators of Hydrologic Alteration (IHA)
- MacMillan et al. 2005
- Modified Palmer Drought Severity Index (PDSI)
- Nestler and Long 1997
- Nixon et al. 2003
- Nolin et al. 2005
- Tiburan et al. 2010
- Turkkan et al. 2011
- UNEP 2009a
- Water Supply and Stress Index Model (WaSSI)
- Wei and Zhang 2010

2.3 Tools for Assessing Sensitivity

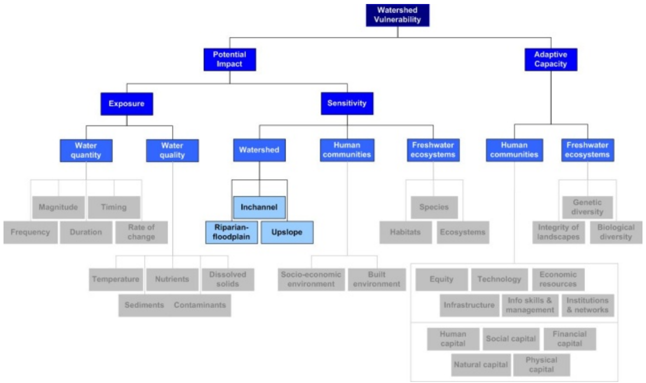
Sensitivity is defined here as *a measure of the extent to which a watershed and its reliant human communities or ecosystems will be affected by a given change in climate* (e.g., Fussel and Klein 2006; Hebb and Mortsch 2007; Glick et al. 2011). Sensitivity is a function of the *inherent properties* of the human and ecological systems (e.g., defined by a species thermal tolerance or dependence of a community's economy on water resources) and the *external drivers* acting on these systems of interest (e.g., stressors in other watersheds that have impacts on transboundary species or global / Canada-wide pressures that affect local economies and communities).

Emerging from our review of tools to assess vulnerability of watersheds are three "themes" in the way sensitivity is represented:

- sensitivity of watersheds tend to focus on the biophysical environment specifically the upslope, riparian-floodplain, and /or in-channel components.
- sensitivity of human communities tend to focus on the socio-economic and built environments of human communities.
- sensitivity of freshwater ecosystems tend to focus on freshwater species, their habitats, populations, or communities, as well as macroinvertebrate communities or other water dependent species (e.g., riparian species).

These themes are used to sort tools into the three sections that follow. However, it is recognized that tools in these sections are not usually applied in isolation of others. For instance, a tool assessing sensitivity of freshwater ecosystems will likely be informed or explicitly coupled with a tool that assesses the exposure of a watershed. Selection among tools will also depend on the end user's needs and the important endpoints for assessing vulnerability.

2.3.1 Sensitivity of Watersheds



Watersheds are the spatial units by which researchers, planners, decision makers, and resource managers tend to most often think about water resources. Watersheds integrate all features of the environment – climate, terrain, land use and land cover, human activities, human communities, and biota – across upslope, riparian-floodplain, and in-channel sub-systems. The three categories of approaches for assessing sensitivity of watersheds include:

- (i) Indicators of watershed condition or function
- (ii) Biological indicators (bioindicators)
- (iii) Coupled or integrated watershed models

These categories represent the distinct ways in which sensitivity of watersheds has been assessed. Some case studies have used the best available data as indicators of watershed condition (e.g., physical, geological, water quality, biological, and/or habitat conditions) or as indicators of the biological integrity of a watershed (e.g., macroinvertebrate diversity, fish species occurrence, habitat quantity). Other case studies have used either coupled models (outputs from one model are used as inputs to another model, linking climate, water, land, and biodiversity) or integrated watershed models (all inputs combined into a single modelling framework).

Indicators of watershed condition and biological indicators

Watersheds integrate many features – climate, terrain, land use and land cover, and biological processes. These processes include vegetation succession and natural disturbance, basin geomorphology, hydrologic patterns, chemical cycles, as well as patterns of human development and activity. This generalized framework (from Reeves et al. 2004) is useful for understanding ecological integrity of watersheds, such that those with high integrity have lateral, vertical, and longitudinal connections among its components that vary both in space and time.

Given the known complexity of relationships among these processes, indicators of watershed condition or function are used to characterize ecological integrity of watersheds as opposed to developing sophisticated models of watershed function (see below). In general terms, watersheds in "good" condition are considered as being structurally diverse with components that vary and processes that function within expected ranges of natural variation (e.g., Gallo et al. 2005).

Examples of the use of indicators to assess watershed condition in response to climate change vary widely, though this framework can be used to relate indicators to the sub-systems and processes that are important determinants of watershed function. Each application tends to tailor indicators to the components and processes of interest in a particular watershed and the availability of data to represent those indicators. Watershed indicators also tend to be reported alongside an array of other measures of vulnerability (e.g., biophysical exposure, human population characteristics, ecological sensitivity). Relevant examples of vulnerability assessments include using related indicators to characterize:

- the physical and biological vulnerability of wetlands (distribution and use by birds), streams (current health, future stream temperatures, and fish distribution), and lakes (thermal habitats and use by fish) in Lake Simcoe watershed (Chu no date)
- the existing vulnerability of a watershed in relation to its water resources (wetlands, riparian buffer, floodplain, water use and discharge), geology (bed rock, soils), land features (land use, land cover, impervious surface, road density), biological uses (fish species, macroinvertebrates), and demographics (population, housing, and income) in Pennypack Creek watershed, Pennsylvania (Meenar et al. no date)
- the overall sensitivity of watersheds to natural disturbances and human threats using an array of watershed indicators (road density, extent of forest harvesting, recreation sites, mining activities, and water diversions) in Bayesian Belief Network model (Chatel no date)
- the vulnerability of wetlands to climate change across the Southern Interior of British Columbia using a drying index comprised of a measure of snowpack (to reflect water input) and summer heat moisture (a surrogate for evapotranspiration and water output) (Bunnell et al. 2010).
- the vulnerability of watersheds in the Philippines using 21 indicators in a Geospatial based Regional Environmental Vulnerability Index for Ecosystems and Watersheds (GeoREVIEW) model. Indicators included existing indices and measures of climate (average rainfall by wet and dry season, minimum and maximum temperatures), ecosystem greenness (Normalized Difference Vegetation Index, NDVI), erosion potential (Revised Universal Soil Loss Equation, RUSLE), channel size (Strahler’s method), forest cover changes, road density, vegetation cover, and soil quality among others (Tiburan et al. 2010).

Biological indicators are related to indicators of watershed condition because freshwater macroinvertebrate and fish communities are commonly monitored to represent the ecological integrity of a watershed, specifically the condition of inchannel habitats (e.g., Bauer and Ralph 1999; 2001; Fore 2003). As integrators of all the natural and human influences in a watershed, freshwater organisms are well suited for monitoring, in some ways more so than the broader indicators of watershed condition (e.g., land and water use, pollution, discharge, nutrient concentrations). They often represent the ecosystem components that people value, either inherently or for consumptive use.

Yet by being responsive to so many influences, it is often difficult to understand the relative contributions of different drivers, including climate change. Changes in biological indicators have, however, been associated with changes in ecological condition of watersheds and as such are being recommended as a tool for representing sensitivity of watersheds to climate change (US EPA 2008). Others have also used biological indicators to assess sensitivity of freshwater ecosystems (e.g., Chu no date; Nelitz et al. 2010). Given the value of information provided, they can also be used in conjunction with other tools (e.g., developing bioclimate envelope models, evaluating species or life history susceptibility).

Inputs/outputs

Despite broad differences in watershed context, purpose, and deployment, ideal watershed monitoring programs tend to have a few common elements: (i) selection and calibration of appropriate indicators; (ii) determination of reference condition or benchmark for assessment; and (iii) use of standardized protocols that optimize data collection and minimize variability due to sampling error (Barbour et al. 2000 as cited in US EPA 2008). Table 5 provides an overview of the sub-systems within a watershed, the governing processes in these sub-systems, and some *sample* indicators that could be used to characterize processes for these sub-systems. Table 6 and Table 7 provide a comprehensive summary of macroinvertebrate and fish community indicators that are recommended and already in use in bioassessment programs. These indicators can be supplemented by other biological considerations that are known to be more responsiveness to climate change, including phenology, growing season, life stage sensitivity, thermal sensitivity, hydrologic sensitivity, and ecosystem sensitivity. Direct outputs from the collection and analysis of such indicators can be highly variable and will depend on the specific watershed context, monitoring design, and questions of interest but can include conducting time series analysis, spatial analyses, and generalized linear models among others.

Table 5: Summary of sub-systems, processes, and sample indicators that can be used to assess watershed condition (adapted from Gallo et al. 2005). Note the list of sample indicators is by no means exhaustive.

Watershed sub-systems	General process	Key process	Sample indicators
Upslope areas	Vegetative succession, growth, and mortality	Wood production and transport	Vegetation seral stage, land use, land cover, natural disturbance (e.g., fire, disease), precipitation, air temperature, degree days
	Soil cycle	Sediment production and transport	Road density, landslides, land use, land cover
	Hydrological cycle	Water storage and yield	Snowpack, glacier extent, wetlands, permafrost, impervious surfaces, equivalent clearcut area, precipitation, air temperature
Riparian-floodplain areas	Vegetative succession, growth, and mortality	Structural development and wood delivery	Vegetation seral stage, land use, land cover, natural disturbance, precipitation, air temperature, degree days
	Soil cycle	Sediment production and transport	Road density, stream crossings, landslides, land use, land cover
	Hydrological cycle	Water storage and yield	Channel connectivity, wetlands, precipitation, air temperature
Inchannel	Channel structural dynamics	Sediment and wood delivery, floodplain connectivity	Channel cross section, stream size, sinuosity, gradient, pools, wood, substrate composition, off channel habitat
	Energy exchange	Heating / cooling processes	Water temperature, riparian condition, groundwater exchange, precipitation, air temperature
	Chemical and nutrient cycles	Chemical and nutrient delivery	Water quality, non-point source pollution, precipitation
	Hydrological cycle	Water delivery	Water quantity, water use, precipitation, air temperature

Table 6: Summary of macroinvertebrate metrics (US EPA 1999).

Category	Metric	Response to perturbation
Richness measures	Total number of taxa	Decrease
	Number of EPT taxa	Decrease
	Number of Ephemeroptera taxa	Decrease
	Number of Plecoptera taxa	Decrease
	Number of Trichoptera taxa	Decrease
Composit^n measures	% EPT	Decrease
	% Ephemeroptera	Decrease
Tolerance / intolerance measures	Number of intolerant taxa	Decrease
	% Tolerant organisms	Increase
	% Dominant taxon	Increase
Feeding measures	% Filterers	Variable
	% Grazers and scrapers	Decrease
Habit measures	Number of clinger taxa	Decrease
	% Clingers	Decrease

Table 7: Summary of fish metrics (US EPA 1999).

Category	**Metric**	**Response to perturbation**
Richness measures	Total number of species	Decrease
	Number of native fish species	Decrease
	Number of salmonid age classes	Decrease
	Number of darter species	Decrease
	Number of sculpin species	Decrease
	Number of benthic insectivore species	Decrease
	Number of darter and sculpin species	Decrease
	Number of darter, sculpin, and madtom species	Decrease
	Number of salmonid juveniles (individuals)	Decrease
	% round-bodied suckers	Decrease
	Number of benthic species	Decrease
	Number of sunfish species	Decrease
	Number of cyprinid species	Decrease
	Number of water column species	Decrease
	Number of sunfish and trout species	Decrease
	Number of salmonid species	Decrease
	Number of headwater species	Decrease
	Number of sucker species	Decrease
	Number of sucker and catfish species	Decrease
Tolerance / intolerance measures	Number of intolerant/sensitive species	Decrease
	Presence of brook trout	Decrease
	% stenothermal cool and cold water species	Decrease
	% of salmonid individuals as brook trout	Decrease
	Number of green sunfish	Increase
	% common carp	Increase
	% white sucker	Increase
	% tolerant species	Increase
	% creek chub	Increase
	% dace species	Increase
	% eastern mudminnow	Increase
Trophic measures	% omnivores	Increase
	% generalist feeders	Increase
	% insectivorous cyprinids	Decrease
	% insectivores	Decrease
	% specialized insectivores	Decrease
	% juvenile trout	Decrease
	% insectivorous species	Decrease
	% top carnivores	Decrease
	% pioneering species	Increase
Effort measures	Number of individuals (or catch per effort)	Decrease
	Density of individuals	Variable
	% abundance of dominant species	Increase
	Biomass (per m^2)	Variable
Reproduct^n measures	% hybrids	Increase
	% introduced species	Increase
	% simple lithophills	Decrease
	% simple lithophills species	Decrease
	% native wild individuals	Decrease
	% silt-intolerant spawners	Decrease
Disease measures	% Diseased individuals (deformities, eroded fins, lesions, and tumors)	Increase

User considerations

There are at least five important user considerations that are beyond the scope of this compendium and can require significant time and energy to resolve. Resolution of these issues will likely vary widely across jurisdictions and physiographic settings. First, the purpose of monitoring and related monitoring questions that need to be answered will have important implications on the other issues below (e.g., sampling design and selection of indicators). Alternative purposes for monitoring include status and trends, validation, effectiveness, or implementation monitoring (Kershner 1997). Each purpose can serve a different role in a vulnerability assessment – to track *status and trends* in watershed condition, to *validate* relationships between climate and watershed processes, to understanding the *effectiveness* of adaptation strategies in mitigating the effects of climate change, or to assess whether adaptation strategies have been *implemented* as intended.

Second, significant considerations are needed to establish an appropriate sampling design that adheres to the principles of experimental design as much as possible (e.g., randomization, replication, stratification, control sites, see Hurlbert 1984; Hairston 1989; Eberhardt and Thomas 1991; Schmitt and Osenberg 1996; Sit and Taylor 1998; Stevens and Olsen 2004). Next, sampling protocols, site access, and cost will weigh heavily in selecting appropriate indicators and affect the number of samples collected across space and time.

Fourth, a rigorous application of indicators requires the use of reference conditions or control sites that can be used as a basis for evaluating disturbance in other areas. Noteworthy is that climate change will affect these reference sites, so it is unrealistic to expect stable conditions at these sites. Lastly, once the data are collected and analyzed, an indicator needs to be compared to a benchmark, threshold, or reference condition so as to assess whether some undesirable change has occurred (e.g., Gallo et al. 2005). Benchmarks can vary widely depending on the indicator, region of application, and level of risk of a decision maker (e.g., Nelitz et al. 2007). Moreover, the sensitivity of the above indicators to climate change is largely untested / unknown, in part because there is complex pathway of effects leading from changes in climate to changes in the indicators of interest. Other factors (e.g., covariates or other human stressors) are important to tease the climate signal out of the unexplained variation.

Coupled or integrated watershed models

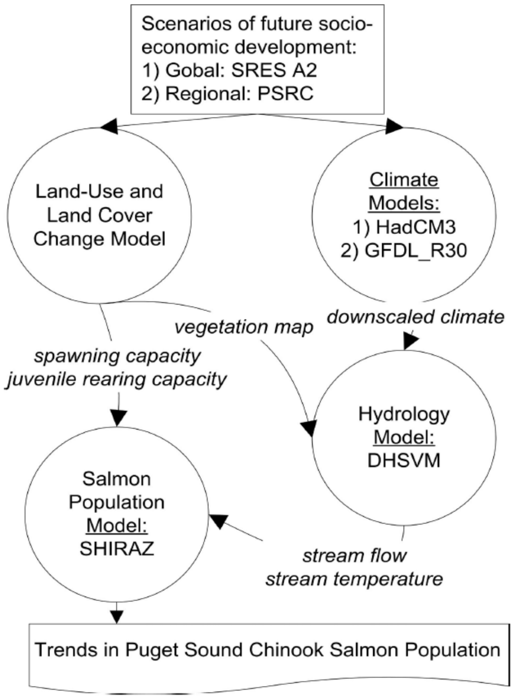
As described above, a watershed's existing form and function represent an integration of many factors – climate, terrain, land use and land cover, natural disturbance, geomorphology, as well as patterns of biological activity and human development, among others. As an alternative to an indicator approach, a more rigorous way of representing an integrated understanding of watersheds is to develop quantitative models that explicitly represent the functional relationships among important variables.

Two general approaches are used that quantitatively model links between climate and watershed response in vulnerability assessments. A first approach involves linked or coupled modelling. With this approach watershed components and/or processes of interest are separated into distinct sub-models, where each sub-model is built relatively independently of the others. Each sub-model, however, is designed with the intent that the predictions or *outputs* from one sub-model will serve as *inputs* to another sub-model. For example, in the Snohomish River basin in Washington State, U.S.A. (Battin et al. 2007) researchers used air temperature and precipitation outputs from Global Circulation Models and downscaling tools as inputs to a land use and land cover change sub model. Climate, forest cover, and land use were then used as inputs into a hydrology sub-model to predict water flows and water temperatures which in turn were used as inputs into a fish habitat and population dynamics sub-model (see Figure 6). A similar approach was applied in the Central Interior of British Columbia (Nelitz et al. 2010). In the Rouge River watershed in southern Ontario a set of mathematical models, empirical relationships, and professional judgements were used to link hydrology and water quality, groundwater, aquatic system, terrestrial system, cultural heritage, and recreation sub-models to assess the watershed's response to a set of future scenarios of climate and human development (TRCA 2007).

A second modelling approach includes integrated watershed models, some of which are described in Section 2.2 and listed in Appendices B and C. These models are different from the above approach such that the watershed form and function are represented in an integrated modelling framework that can simulate feedback responses and process interactions. This approach has similarities, however, in that distinct components are programmed as separate sub-routines, like the sub-models discussed above. Several standardized frameworks are available to assess the vulnerability of watersheds to climate change (e.g., SWAT, Nunes et al. 2007; Ficklin et al. 2009 and BASINS CAT, Johnson and Weaver 2009). In particular, the Soil and Water Assessment Tool (SWAT) is a spatially explicit tool that integrates weather, soil properties, plant growth, snow, and land management to assess impacts on the hydrological cycle, as well as sediment, pollutant, and nutrient transport across a watershed.

SWAT has been applied to the San Joaquin River watershed in California, U.S.A. to assess the impacts of climate change on agricultural activities as influenced by changes in the hydrological cycle, irrigation timing, and plant growth (Ficklin et al. 2009), and was used to assess the impacts of climate change on runoff, wheat production, and erosion potential in 18 large watersheds in Portugal (Nunes et al. 2007).

Figure 6: Example of a series of linked sub-models in the Snohomish River basin in Washington State, U.S.A. (Battin et al. 2007)



Inputs/outputs

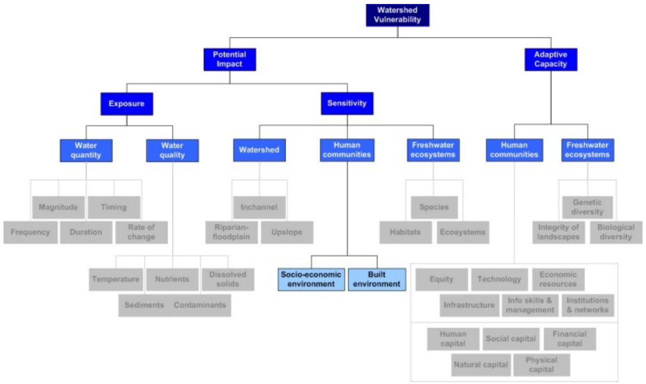
The specific data needs for the above approaches will largely depend on the specific sub-models and routines of relevance. Substantial amounts of data are required, however, which can include spatial representations of topography, stream networks, land use, forest cover, soil type, as well historic climate data, discharge measurements, and projections of future climate change. Given the number and complexity of relationships in these models, a high level of parameterization is usually required to ensure models are relevant to a local watershed. Outputs will depend on the modelling structure and approach, but often result in both spatial and numerical representations of results.

User considerations

The approaches discussed above represent some of the most sophisticated approaches to assessing vulnerability of watersheds to climate change. The coupled or linked modelling approaches are generally not transferable because applications tend to be developed for particular watersheds of interest. The frameworks for some integrated watershed models can be transferred, however, if the model's needs for data, parameterization, and technical support can be satisfied (e.g., SWAT, BASINS CAT). Given their sophistication, these approaches are likely to be among the most costly tools to develop.

2.3.2 Sensitivity of Human Communities

It can be difficult to clearly distinguish between assessments of the sensitivity of human communities and the adaptive capacity of human communities (Preston and Stafford-Smith 2009). This difficulty arises because each assessment can use the same indicators, although how they are used is inversely related. For example, household income could be an indicator for both sensitivity and adaptive capacity as illustrated here:



> "*…those with lower household incomes may be vulnerable both because cheaper housing was available in flood prone areas* [high sensitivity, or high "situational" exposure] *and because they do not have the financial resources to adapt their houses to reduce damage in times of flood* [low adaptive capacity]*."* (Brunkhorst et al. 2011)

In fact, many studies have used indicators of both sensitivity and adaptive capacity to cumulatively assess what has been termed "social vulnerability" or "socio-economic vulnerability". According to one study, use of "social vulnerability" has been considered the same as "sensitivity of human communities" (as characteristics of a community that can positively or negatively influence the impacts of the hazard; see ABARE-BRS 2010, Appendix D).

Other studies relate sensitivity of human communities to that of the biophysical environment as it relates to providing ecosystem services (Mohan and Sinha, 2010; ABARE-BRS 2010). For example, in a study of the Murray-Darling Basin in Australia, the authors define sensitivity as a "*measure of how dependent a community is upon the thing that is changing*", specifically reductions in water availability (ABARE-BRS 2010). Using this approach, sensitivity-related indicators are thus related to the dependence of the local economy on climate sensitive economic activities (agriculture in the case of the Australian example), and the dependence of local communities on identified ecosystem services (e.g., water for irrigation).

The following section includes a discussion of tools and approaches used to assess the sensitivity of the socio-economic environment and the built environment to the impacts of climate change. The tools and approaches include:

(i) Social vulnerability analysis
(ii) Engineering vulnerability assessment
(iii) Risk assessment

Given the diversity of definitions and interpretations, this section also clarifies some of the language around human sensitivity and adaptive capacity.

Social Vulnerability Analysis

Due to the challenges of distinguishing indicators of community sensitivity and adaptive capacity, a useful approach that requires the consideration of both is a Social Vulnerability Analysis (SVA). A SVA is an indicator-based approach that has emerged from the political economy literature highlighting the sociopolitical, cultural and economic factors that together may result in differential vulnerability to the same climate-induced hazard. As vulnerability is often expressed as fundamentally a "social construct" (Fussel 2007), concerned with issues of "ethics and equity" (Eakin and Luers 2006), the consideration of the social response within a geographic location is equally as important as the analysis of the risk to the biophysical environment (Wu et al. 2002). Using indicators of social and socio-economic vulnerability, a SVA is often used in combination with an exposure tool or hazard analysis.

The key to implementing a successful indicator-based approach, and also one of the greatest challenges, is ensuring the selection of the most relevant and appropriate indicators. Some indicators appear consistently throughout the literature albeit with sometimes different proxies (selected based on the nature of the hazard, as well as data availability within the identified study area). For example, common social vulnerability indicators may include poverty, gender, race and ethnicity, language (particularly in Canada given higher proportions of immigrant families), age, disabilities and mobility, family structure and social networks, housing and the built environment, income and material resources, access to services (including transportation, communication, utilities), occupation, and education. For a complete discussion of each, see Rygel et al. (2006) and Clark et al. (1998). Table 8 summarizes the socio-economic indicators selected for a vulnerability assessment recently completed for the Murray-Darling Basin in Australia and captures the diversity of indicators and indices which can be used.

Data to populate social vulnerability indicator selection can be a mixture of both quantitative and qualitative data from a variety of primary and secondary sources. Census data is generally a good place to start collecting data on general population demographics including age, gender, family structure, income, literacy/education, and others (see Box 3). Time and resource permitting, gaps in data or more qualitative data (e.g. risk perceptions) can be supplemented through random household or stakeholder surveys, interviews, or focus group discussions.

As is common with indicator-based approaches, long lists of potentially relevant indicators can be reduced using statistical techniques such as factor analysis, principal component analysis (PCA), Monte Carlo tests, and Delphi surveys. The result is a subset of relatively independent groups of indicators that can then be used to develop a more robust, manageable, and uncorrelated set of composite indices to better explain social vulnerability. Once the relevant composite indices have been identified, typically the value for each proxy is standardized on a scale from zero to one to facilitate the calculation of the indicator or index score (the higher the value the higher the vulnerability). Outputs are often communicated using maps and/or profiles of social vulnerability and its component determinants (Figure 7).

Table 8: Indicators used to assess adaptive capacity in Murray-Darling Basin, Australia
(adapted from ABARE-BRS 2010)

Index	Sub-index (if applicable)	Indicator	Census data used
Adaptive capacity (human capital)	Education advantage	% Graduates	Total bachelor degree + total graduate diploma/certificate + total postgraduate degree / total persons 15+
		% employed in public sector	Total employed in public admin sector / total employed persons 15+
		% over 15 no qualifications	% of persons 15+ with no qualifications: certificate, diploma, undergraduate degree, postgraduate degree
		Median weekly rent as a fraction of the Australian median	Medium weekly rent as proportion of the 2006 Australian median
		Median household income as fraction of Australian median	Median household income as proportion of the 2006 Australian median
		Income / mortgage differential	(Median household weekly income * 52 / 12) – median monthly housing loan repayment
	Socio-economic advantage	% one parent	Total single parent families / total families
		% couple families	Total couples without children + total couples with children / total families
		% single parent with children < 15 only	Total single parent families with children < 15 years old / total families
		Total unemployment	Total unemployed / total labour force
	Age advantage	% 65 over	Total persons aged 65 and over / total persons
		Average no. persons per household	Average household size
		% lone person households	Total one persons households / total occupied dwellings
	Mobility advantage	% dwellings rented	Rented properties / total dwelling structures
		% different address to1 yr ago	Lived at different address 1 year ago / lived at different address 1 year ago + lived at same address 1 year ago
Adaptive capacity (social capital)	Proportion of females in non-routine occupations	Women in non-routine occupations	Female managers + female professionals + female technicians + female community and personal / total female employed persons
	Participation in voluntary groups	% Voluntary work	Total volunteers / total persons 15+
Adaptive capacity (local economic diversity)	Economic Diversity Index (EDI)	Economic Diversity Index (EDI)	Diversity of local economy relative to Australian/MDB economy, calculated using employment by sector data

Table 9: Indicators used to assess adaptive capacity in Murray-Darling Basin, Australia (Con't)

Index	Sub-index (if applicable)	Indicator	Census data used
Sensitivity (SLA water dependence)		SLA irrigation intensity	Megalitres of water applied divided by number of irrigated farm establishments
		SLA irrigation incidence	% of agricultural businesses irrigating
Sensitivity (local economy agricultural dependence)		% work in agriculture	Total working in agriculture/mining/forestry sector / total employed persons 15+
		Ratio of agriculture and agri-industry employment to total employment	Ratio of persons employed in agriculture to total employment
		Proportion of households with agricultural and/or agri-industry employment	Households with at least one member employed in Agriculture and/or Food Beverage and Tobacco as a % of all households
		Ratio of employment in agriculture to downstream agri-industries employment	Ratio of persons employed in Agriculture to persons employed in Food Beverage and Tobacco.

Box 3: Census data in Canada

Every 5 years Statistics Canada issues a nation-wide census, as well as a Census of Agriculture. The 2011 census data (expected to be available in 2012) will contain information on age, sex, marital and common-law status, and language. Comparatively, the results from the voluntary National Household Survey released for the first time in 2011 will contain information previously requested on the census long form including immigration, ethnic origin, mobility, education, income, house, place of work and labour market activities.

One inherent challenge in using census data to understand socio-economic vulnerability is that changes in indicator values cannot be measured on an ongoing basis. By definition, a census can only produce a ‘snapshot’ of data for a specific point in time which for Canada is every 5 years. As highlighted by Smit and Wandel (2006), a system’s adaptive capacity is not static. The same could be said for a system’s sensitivity and exposure to hazards. Thus, to monitor changes in components of vulnerability or overall vulnerability, it is preferable to supplement census data with primary data as collected through household surveys, questionnaires, key informant interviews, and focus group discussions.

Figure 7: Overall social vulnerability to storm surge in Hampton Roads, Virginia, U.S.A. Based on component scores for indicators of poverty, immigrants, and old age / disabilities; darker areas indicate higher social vulnerability (Rygel et al. 2006).

Risk Assessment

A targeted risk assessment of vulnerable infrastructure is a means to prioritize structures that are more sensitive to specific climate stressors given a set of specific criteria such as age, service area, location, and other structural characteristics that can help inform the magnitude, or severity, of consequences.

The Privy Council Office (PCO 2002) and Treasury Board of Canada define risk as "*a function of the probability (chance, likelihood) of an adverse or unwanted event, and the severity or magnitude of the consequences of that event.*" Risk-based approaches to understanding vulnerability originated in the natural hazards and disaster response literature and are reflected in the work of the International Panel on Climate Change (Eakin and Luers 2006). Risk assessment as it applies to climate change vulnerability analysis is a popular tool with a "relatively linear analysis" that moves through the process of characterizing a hazard, assessing impact, and identifying adjustments (or adaptations) to evaluate both the structural and economic sensitivity[3] of the built environment to the risks of climate change.

A relevant application of such a risk-based approach can be found in the Chicago Climate Change Action Plan. In 2006, the city of Chicago completed a risk assessment to evaluate the likelihood of occurrence of identified climate change impacts and the consequences of such occurrences in response to rising weather related catastrophes and insurance claims. Impacts were categorized according to four general themes including water, health, ecosystems, and infrastructure. Risk scores were assigned by multiplying a consequence score for each identified impact by the associated likelihood score (Figure 8). Table 9 provides a more detailed summary of the impacts on infrastructure with moderate (scores between 9 and 14) to high risks (scores of 15 and greater).

Simplified risk assessment approaches have been developed by Nesbitt (2010) for the Northwest Territories and Black et al. (2010a) for communities across northern Canada. Black et al. (2010b) includes worked examples for Eastern Arctic, Western Arctic, and the Yukon/Mackenzie Region. These northern risk assessment approaches are designed to be used by communities with limited capacity.

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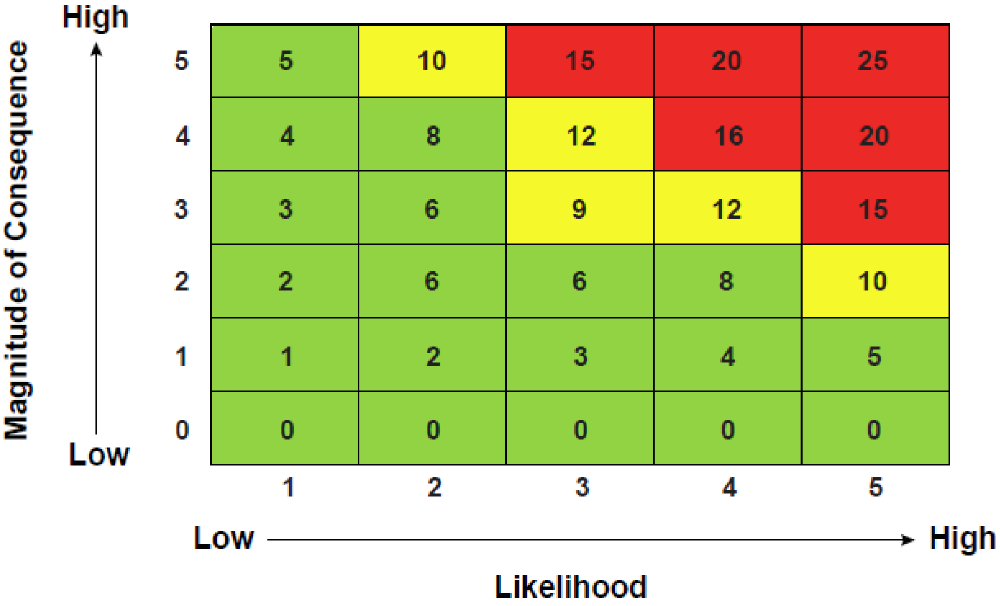
[3] Brunckhorst et al (2011) use the term "economic vulnerability" to characterize the impact of sea level rise and storm intensity on built capital, including houses, offices, roads, water and stormwater systems, electricity and telecommunications networks.

Figure 8: Matrix of risk ratings along axes of likelihood and consequence associated with projected effects of climate change (Parzen 2008)



Magnitude of Consequence	1	2	3	4	5
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	6	6	8	10
1	1	2	3	4	5
0	0	0	0	0	0

Table 10: Impacts on infrastructure ranked as moderate or high
(Parzen 2008)

Sub-theme	Impact	Risk	Timing
Heating and cooling	Increased annual energy costs	High	Near
	Increased demand for A/C to residential units	Moderate	Near
Operation and maintenance	Increase in replacement and maintenance costs for fleets	Moderate	Mid
	Damage to key infrastructure (pump stations, electricity distribution equipment, etc.)	High	Mid
Other	Lower revenue from summer events	Moderate	Mid
	Damage to property and increasing cost of insurance due to stormwater	Moderate	Mid
	Increase in insurance premiums, deductibles, exclusions, and/or no. of underinsured properties	Moderate	Now
	Damage to property and increasing cost of insurance due to overbank flooding in area rivers	Moderate	Near

Engineering Vulnerability Assessment

Design standards for the built environment (including residences, offices, industrial and community buildings, roads, rail, ports, water and wastewater systems, telecommunications and electricity networks) are often based on historical climate data. Given the anticipated effects of climate change, there is a risk that such systems may fail as standards based on historical trends will no longer be appropriate. Additionally, the design of new infrastructure must have the capacity to perform under climate conditions ranging from current climate norms and extremes to projected future climate extremes (PIEVC 2008). According to the Harvard Business Review, physical assets are as vulnerable to the effect of heat, drought, floods, and storms as the biophysical environment (Lash and Wellington 2007).

In 2008 the Public Infrastructure Engineering Vulnerability Committee (PIEVC) of the Canadian Council of Professional Engineers led the development and validation of a Canada-wide engineering assessment protocol for assessing the vulnerability of Canadian infrastructure to the impacts of climate change. The protocol is a five step process (Figure 9) where the third step is risk (vulnerability) assessment determined from the multiplication of probabilities by severities. Results from the design and validation of the Protocol[4] to the four infrastructure examples listed below highlighted key vulnerabilities according to possible climate stressors (see example in Table 10).

<u>Buildings:</u> Tunney's Pasture Campus (Ottawa Ontario) and Thermosyphon Foundations in Warm Permafrost (Inuvik, Northwest Territories)

<u>Roads and associated structures:</u> Quesnell Bridge Rehabilitation (Edmonton, Alberta) and Road Pavement Assessment (Sudbury, Ontario)

<u>Stormwater and wastewater systems:</u> Vancouver Sewage Infrastructure Assessment (Vancouver, British Columbia)

<u>Water resources:</u> Water treatment and supply system (Portage-la-Prairie, Manitoba) and Water resources assessment (Placentia, Newfoundland and Labrador).

The use and application of the Protocol generally requires a multidisciplinary team of professionals. The output from the application of the Protocol can provide civil engineers, city planners and decision-makers with a better idea for the sensitivity of the built environment within a particular watershed. Additionally, applying the PIEVC Protocol can inform the design of sensitivity maps by isolating and highlighting sensitive infrastructure located within a watershed.

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[4] Of potential interest to readers, recommendations from the final PIEVC report suggested that ongoing validation of the Protocol was warranted, particularly for power infrastructure systems and coastal infrastructure (e.g., ports). Furthermore, the report recommended development of an electronic database of results from infrastructure vulnerability assessments to aid in more national and regional analysis.

Figure 9: Protocol for assessing vulnerability of infrastructure in response to climate change events (PIEVC 2008)

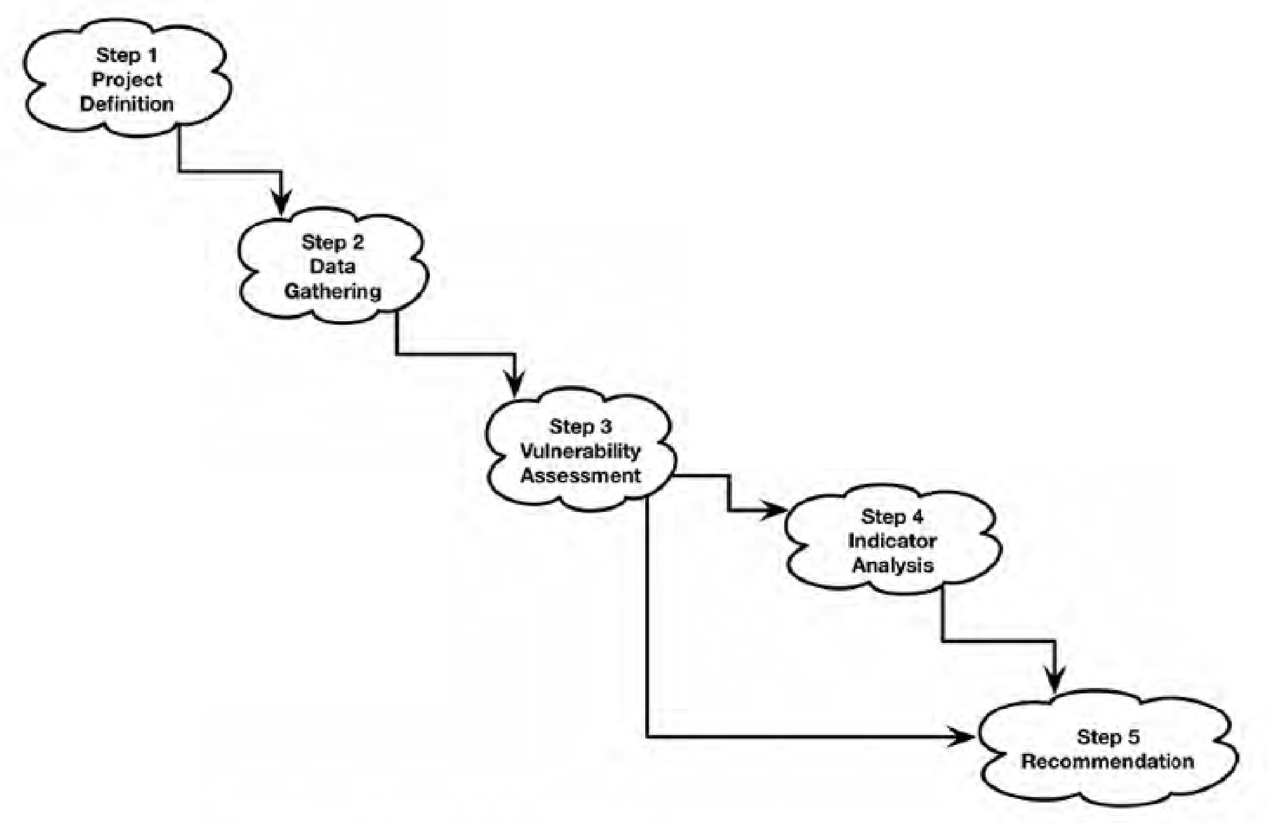

Table 11: Vulnerability ratings for water resource infrastructure[5]. Numbers indicate cases observed. Red denotes high vulnerability, yellow denotes medium vulnerability (PIEVC 2008)

	Climate and Other Environmental Factors													
	Flooding	**High Temp**	**Low Temp**	**Intense Rain**	**Drought**	**Ice Storm**	**Blizzard**	**Intense Wind**	**Hail**	**Frost**	**Ground Water**	**Sea Level**	**Storm surge**	**Sea Level + Storm Surge**
Infrast Components														
Admin & Operations														
Personnel	🟨 1					🟨 1	🟨 1	🟥 1						
Facilities Equipment	🟥 1	🟨 1	🟨 1	🟨 1		🟥 1	🟨 1	🟥 1						
Dams														
Reservoir					🟨 1									
River System	🟥 1				🟨 1									
Dam Structure	🟥 1											🟨 1	🟨 1	🟨 1
Intake Well Pumps	🟥 1			🟥 1	🟥 1									
Breakwater												🟨 1	🟨 1	🟨 1
Water Treatment														
Pre-treatment	🟨 1	🟨 1	🟨 1	🟨	🟨 1									
Softening Clarification		🟨 1	🟨 1		🟨 1									
Disinfection			🟨 1											
Storage					🟨 1									
Chemical storage	🟥 1							🟥 1						
Valves & Pipes	🟨 1		🟨 1		🟨 1		🟨 1			🟨 1	🟨 1			
Water Distribution														
Pump Stations	🟨 1	🟨 1					🟨 1	🟥 1						
Pipelines & Valves	🟨 1		🟨 1		🟨 1		🟨 1			🟨 1	🟨 1			
Pipe Materials					🟨 1					🟨 1	🟨 1			
Electric Power														
Substations	🟨 1					🟥 1	🟨 1	🟥 1						
Transmission						🟥 1	🟨 1	🟨 1						
Standby Generators	🟨 1	🟨 1				🟨 1	🟨 1	🟨 1						
Transportation														
Vehicle						🟨 1	🟨 1	🟥 1						
Maintenance Facilities						🟨 1		🟥 1						
Supplies						🟨 1	🟨 1	🟨 1						
Roadway Infrastructure	🟨 2			🟨 1			🟨 1	🟨 1						
Communication														
Telephone						🟨 1	🟨 1	🟨 1	🟨 1					
Telemetry						🟨 1	🟨 1	🟨 1	🟨 1					

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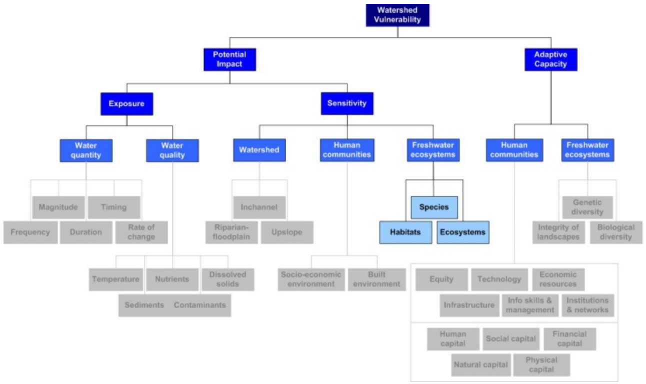
[5] Water resource case studies included i) the city of Portage la Prairie (Manitoba) waterworks and related infrastructure; and ii) the town of Placentia (Newfoundland and Labrador) which included a breakwater, a floodwall, a building in a floodplain, and a stretch of highway susceptible to flooding and washouts.

2.3.3 *Sensitivity of Freshwater Ecosystems*

The biological components of watersheds are sensitive to the impacts of climate change on water resources (e.g., Hauer et al. 1997; Schindler 1997; Schindler 2001; Lemmen et al. 2008; CCSP 2008b; US EPA 2008; Campbell et al. 2009; CCSP 2009b; Glick et al. 2011). Observed impacts on freshwater ecosystems include changes in *species* (changes in physiology, phenology, and reproductive strategies), *habitat* (habitat dependence and specialization, species range and distribution), and/or *ecosystem* responses (components, structure, and processes). The sensitivity of an ecosystem will depend on the degree of exposure to local climate change, resulting impact on water resources, distribution of the organisms of interest, range of their habitats, and degree to which inherent watershed features buffer habitats against, or reduce exposure to, the effects of climate change (e.g., Williams et al. 2008).



Impacts on freshwater ecosystems are known to be consequential to provincial, territorial, and federal jurisdictions because the protection of ecosystem values are embedded within the laws, regulations, policies, and management practices governing development and conservation in watersheds across Canada. For instance, decisions related to the use and allocation of natural resources, land use planning, and design of development projects are typically adjusted on the basis of their ability to protect, mitigate, compensate, or restore valued components and processes within freshwater ecosystems. Accompanying these choices are costs or constraints on human activities which demonstrates the inherent value that Canadians place on ecosystems.

Few “off the shelf” tools are readily available to assess vulnerability of ecosystems (Glick et al. 2011) that are also broadly transferrable across watersheds. Approaches to assessing vulnerability tend to be developed for specific purposes in response to the unique social and environmental conditions in a watershed. For this reason, we have grouped examples from the literature into broader categories that are more generally transferrable. The three categories of tools for assessing sensitivity of freshwater ecosystems include:

(i) Bioclimate envelope models
(ii) Species or life history susceptibility
(iii)Habitat or species models

These approaches include methods that integrate external exposure to climate change either *explicitly* by quantitatively linking future climate predictions to water resource models to ecosystem models or *implicitly* by qualitatively inferring how ecosystems will respond.

Bioclimate envelope models

A core underpinning of bioclimate envelope models is that climate has a dominant influence on the distribution of species. This understanding is fundamental in the study of biogeography and is supported by the fossil record. Bioclimate envelope approaches also tend to ignore the role of other abiotic and biotic interactions on species distributions, including the influence of human activities.

Models can be *empirically-based*, drawing upon correlations between species observations and climate conditions (e.g., using logistic regression), or *mechanistically-based*, which incorporate the physiological mechanisms or limits that explain relations between species distributions and climate (Pearson and Dawson 2003). Once an empirically- or mechanistically-based model has been developed, projections of future climate conditions can be used to map the potential impact on regional and local species distribution across watersheds. Bioclimate models have been used to estimate the broad-scale impacts of climate change on biodiversity in Europe (Harrison et al. 2006; Bertzky et al. 2010), and on fish habitats and species distribution across the continental U.S. (Eaton and Scheller 1996; O'Neal 2002).

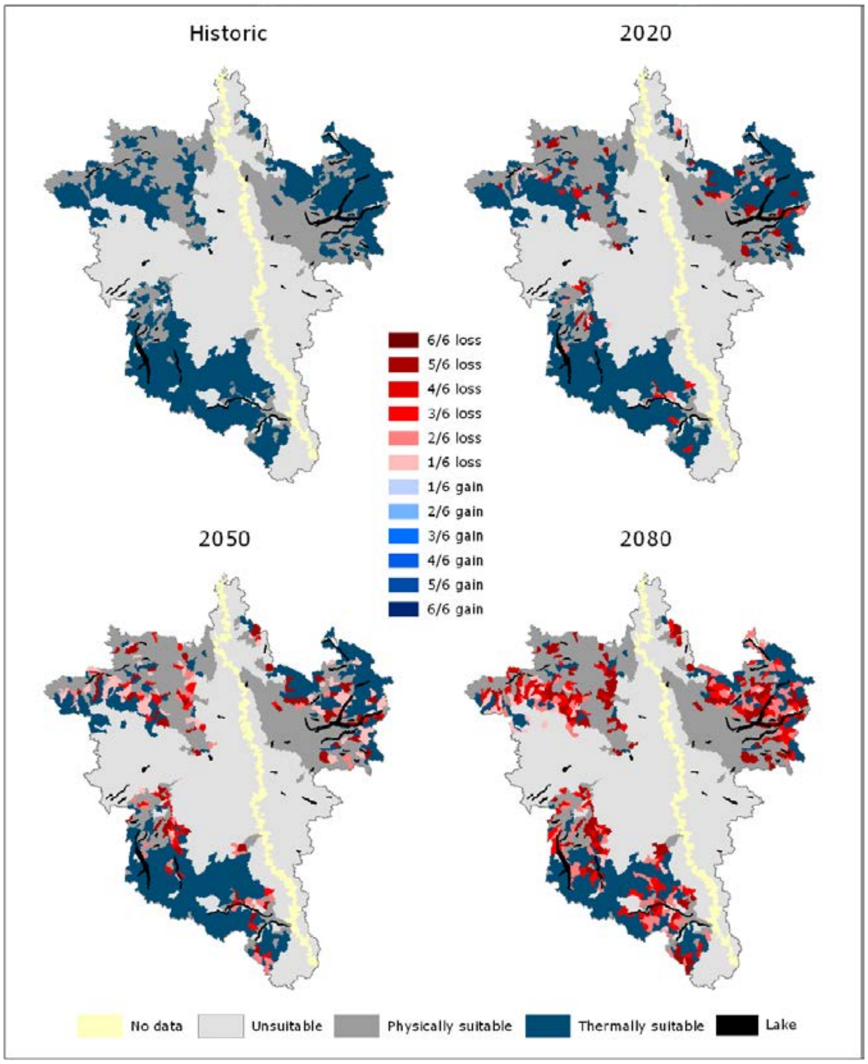
Inputs/outputs

The specific methods for developing a bioclimate envelope model and applying it to a vulnerability assessment will vary according to the specific species and locations of interest (Pearson and Dawson 2003). Regardless of the method, however, four distinct sources of data / information are required to develop a bioclimate model:

- a first requirement is an understanding of thermal tolerances or physiological limits for the species of interest
- second, field observations of the species of interest aligned with measurements of climate and other important environmental variables are needed for model development
- from these observations, a third requirement is an empirical relationship that relates the occurrence or distribution of a species to a climate variable, such as air temperature
- finally, spatially explicit representations of current and future climate are needed to evaluate the effect of climate change on expansion / contraction of species ranges.

These data are overlaid onto a baseline distribution using the empirical relationship to assess how climate change will affect species ranges. Maps representing species distribution for a historic reference and future time periods are common outputs (e.g., Figure 10). Quantifiable measures of change in the areal or linear extent of habitats over time can also be generated (e.g., Eaton and Scheller 1996; O'Neal 2002; Nelitz et al. 2010).

Figure 10: Representation of accessible and thermally suitable 3rd order watersheds for bull trout across the Cariboo Plateau of the Fraser River basin in British Columbia. Polygons with increasingly deeper shades of red denote the number out of 6 climate scenarios that predict the loss of this area as thermally suitable to bull trout (Nelitz et al. 2010).



User considerations

Stand alone and transportable bioclimate envelope models are generally not available. Thus, these tools need to be developed for a species / freshwater community of interest or the results borrowed from other studies. If these tools are developed for a specific watershed, they can be more intensive and costly relative to some options (e.g., species or life history susceptibility), though likely less intensive and costly compared to others (e.g., habitat or species models). Biological and technical expertise is required, as well as having sufficient observational data.

The most important user considerations are limitations in the approach, of which there are three main criticisms (Pearson and Dawson 2003).

First, bioclimate models tend to oversimplify the relationship between a species and its environment by focusing on climate as the main influencing variable, thus ignoring many other variables important for describing species and habitat requirements.

Second, bioclimate models ignore the evolutionary potential, genetic adaptation, and phenotypic plasticity of species which have developed in constantly changing environments and will likely adjust, to some degree, to climate change (e.g., Gottard and Nylin 1995; Bernardo et al. 2007; Skelly et al. 2007; Berg et al. 2010).

Finally, bioclimate models do not sufficiently account for the mobility and movement of species in response to climate change. In some cases, human activities and structures may obstruct movement, while in other cases natural rates of movement may not be able to keep up with the pace of climate change. Despite these limitations, bioclimate envelope models are still deemed as useful for providing a first approximation of the impacts of climate change on the distribution of species of interest (Pearson and Dawson 2003).

Species or life history susceptibility

As described above, some of the first and ongoing assessments of the impacts of climate change on ecosystems used species-climate relationships to evaluate changes in their range and distribution. This approach tends to ignore the evolutionary potential, plasticity, or adaptability of the inherent life history characteristics (reproduction, physiology, phenology), as well as the ecosystem interactions (trophic relationships, habitat requirements) of species which are potentially more important regulators of the effects of climate change (e.g., Gottard and Nylin 1995; Bernardo et al. 2007; Berg et al. 2010).

Leading conservation organizations have recognized this weakness and have begun developing general frameworks for incorporating a broader range of consideration in climate change assessments (Williams et al. 2008; Foden et al. 2008; US EPA 2009a; MDFW 2010; McDaniels et al. 2010; Bagne et al. 2011; Kittel et al. 2011; Young et al. 2011). These alternative approaches tend to use expert opinions to quantitatively score or rank the vulnerability of life history characteristics. Kittel et al. (2011) describes these techniques as “bottom-up” approaches to assessing vulnerability to inform climate change adaptation (see Dessai and Hulme 2004, Box 1).

Four tools were identified that are informative illustrations of this approach. A first example was developed by the US EPA (2009a) which categorizes the relative vulnerability of threatened and endangered species to climate change in four steps: (i) categorizing baseline vulnerability; (ii) evaluating future vulnerability to climate change based on physiological, behavioral, demographic, and ecological response; (iii) producing an overall score of a species’ vulnerability; and (iv) determining the level of uncertainty in overall vulnerability. This approach has been applied to both terrestrial and freshwater species (US EPA 2009a; MDFW 2010).

A second example, the NatureServe Climate Change Vulnerability Index[6], was developed by The Nature Conservancy (Groves et al. 2010; Young et al. 2011; Young et al. in press). This index assigns terrestrial and freshwater species to categories of vulnerability based on a consideration of: (i) exposure to climate change; (ii) indirect effects including barriers to movement; (iii) species-specific sensitivities; and (iv) documented responses to climate change for a species.

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[6] NatureServe. The NatureServe Climate Change Vulnerability Index. Available online: http://www.natureserve.org/prodServices/climatechange/ccvi.jsp

A third example (Foden et al. 2008) was developed by the International Union for Conservation of Nature (IUCN). With this framework, expert opinions were used to perform a one-time assessment of the susceptibility to climate change of 9,856 birds and 6,222 amphibians. This approach is generally not relevant to Canadian watersheds because it applies to many species that have a global distribution. However, the approach is consistent with other methods that use expert opinions and rankings of susceptibility to climate change.

A fourth example is the System for Assessing Vulnerability of Species (SAVS), an advanced model for assessing the relative vulnerability or resilience of vertebrate species to climate change (Bagne and Finch 2008; Bagne et al. 2011). SAVS was developed by the US Forest Service and is available as an online tool. It is designed for fish and wildlife managers and uses an online questionnaire[7] with fixed questions and fixed categories of response to develop a score of vulnerability for an individual species based on four factors – habitat, physiology, phenology, and biotic interaction. Basic ecological principles and the current state of knowledge are used to identify which characteristics of survival, growth, and reproduction are sensitive to the effects of climate change. This knowledge is then used as the basis for scoring a set of criteria representing each of these factors. The tool generates six scores for a species in a given location: a score for overall vulnerability, a score for each of four contributing factors, and an uncertainty score representing confidence in these results.

Inputs/outputs

The factors, criteria, and information needs for answering questions in SAVS are summarized in Table 11 with sources suggested by Bagne et al. (2011). Although numeric climate data are not explicitly used in scoring, a general understanding of the influence of climate change on a species is necessary, including an understanding of the effects of:

- change in total annual precipitation
- change in seasonal precipitation
- change in average temperatures
- maximum summer / winter temperatures
- changes to snowpack duration, amount
- change to number of frost days
- projected drought duration and frequency
- changes in potential, frequency and timing of flooding
- changes in frequency, severity, extent or timing of fire disturbances
- changes in frequency, duration, extent or timing of extreme weather events (e.g., storms, heat waves).

The web accessible data portal, “Climate Wizard”[8], is recommended as a relatively low resolution source for these climate data. When all questions are answered, scores for each of the four factors will be generated on a normalized scale from -5 to 5 for each individual factor, and from -20 to 20 for the overall score combining all factors with an equal weighting. Positive scores indicate vulnerability and negative scores indicate resilience for a species. An uncertainty score is also calculated as a percent of uncertainty associated with the scores for each factor and overall vulnerability.

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[7] USDA Forest Services. SAVS Climate Change Tool. Available from: http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/savs-climate-change-tool/

[8] The Nature Conservancy. Climate Wizard. Available from: www.climatewizard.org

Table 12: Summary of criteria, dimension(s) of vulnerability, and data needs for scoring vulnerability of species to climate change using the System for Assessing Vulnerability of Species (SAVS) (Bagne et al. 2011)

Factors and criteria	Dimension(s) of vulnerability	Data / information needs
Habitat		
Breeding habitat area and distribution	Exposure, Sensitivity	• Climate projections related to vegetation type for breeding and non-breeding habitats including disturbance processes • Habitat/associated vegetation type: Breeding and nonbreeding habitats, vegetation type associations • Habitat components required for breeding or survival • Any aspect of the breeding or nonbreeding habitat associated with habitat quality (improved breeding or survival) • Dispersal ability and sex biased dispersal • Migration habits/requirements
Non-breeding habitat area and distribution	Exposure, Sensitivity	
Habitat components required for breeding	Exposure, Sensitivity	
Habitat components required outside breeding	Exposure, Sensitivity	
Habitat quality	Exposure, Sensitivity	
Ability to colonize new areas	Adaptive Capacity	
Reliance on migratory or transitional habitats	Sensitivity	
Physiology		
Physiological thresholds	Sensitivity, Adaptive Capacity	• Threshold or sensitivity to moisture or temperature extremes (Alternative: species range relative to area under assessment) • Sex ratio/temperature relationships (some reptiles) • Potential exposure of species to extreme weather condition / Known cases of mortality of failed reproduction related to weather • Climate or weather-mediated limitations to active periods • Endothermic or exothermic • Variable life history strategies / Able to postpone reproductive output
Sex ratio related to temperature	Sensitivity	
Exposure to weather-related disturbance	Sensitivity, Exposure	
Changes to daily activity period	Sensitivity, Adaptive Capacity	
Survival during resource fluctuation	Adaptive Capacity	
Energy requirements	Sensitivity	
Phenology		
Mismatch potential: Cues	Sensitivity	• Temperature or moisture variables used as cues • Events that need to be timed to coincide with reproduction/survival (insect emergence, etc.) • Proximity (in time / space) of cues, activities, and essential resources • Number of breeding attempts per year
Mismatch potential: Event timing	Sensitivity	
Mismatch potential: Proximity	Sensitivity	
Resilience to timing mismatch	Sensitivity, Adaptive Capacity	
Biotic Interactions		
Food resources	Exposure, Sensitivity	• Identify primary food resources, expected changes to resources • Identify primary predators and expected changes to predators • Identify symbionts and expected changes to symbiont populations • Identify significant pathogen entities, disease risk factors, and expected changes to these issues • Identify major competitors and expected changes to competitors
Predators	Exposure, Sensitivity	
Symbionts	Exposure, Sensitivity	
Disease	Exposure, Sensitivity	
Competitors	Exposure, Sensitivity	

Scores can be used to assess the relative vulnerabilities (i.e., ranking) of a suite of species, or applied for an individual species across multiple watersheds to assess relative vulnerability across space, which can then be used to prioritize deployment of conservation resources. Scores for individual factors can also be used to identify the most important contributions to vulnerability (i.e., habitat, physiology, phenology, or biotic interactions), thus forming the basis for targeting adaptation.

User considerations

The System for Assessing Vulnerability of Species (SAVS) is relatively easy to use, readily transferable across watersheds and taxa, and is available online as a free resource. The tool does, however, require respondents to have a strong understanding of ecology, and specific knowledge / data about the requirements of and the impacts of climate change on an individual species of interest. The tool has been designed for terrestrial species, though the factors and criteria are generally transferrable, which could theoretically be applied to freshwater fish species (though no freshwater examples were identified).

Given the equal weighting and breadth of criteria in the scoring, caution should be applied when used for a species with a narrow set of life history or habitat constraints that are highly vulnerable to climate change. In these cases, the tool might underestimate vulnerability. As the tool is focused on understanding the effects of climate change, it does not consider the effect of other stressors on populations. Care should also be taken to standardize the use of consistent climate scenarios when using the tool to evaluate multiple species. Lastly, the use of normalized scores assumes a linear response for each criterion which is unrealistic given the nonlinear responses that are often observed in ecosystems (e.g., nonlinear contractions in range or changes in community composition).

Habitat or species models

Changes in air temperature and precipitation will affect water quantity and water quality, and these changes are expected to have a broader range of impacts on freshwater species, habitats, and ecosystems (e.g., Hauer et al. 1997; Schindler 1997; 2001). Researchers have tried to explicitly account for these effects by developing species or habitat models that have included a wide range of approaches. Common among them is that in their simplest form they attempt to account for the dynamic relationship among key variables to represent how species or habitats will respond to changes in driving factors. Given the strength of the relationship between climate (air temperature and precipitation) and habitat conditions (water temperature and water flow), and relevance to productivity of freshwater species, most of these models tend to focus on examining the influence of climate change on water temperature and flow.

Methods used to model habitat or species relationships fit along a continuum ranging from qualitative to quantitative approaches. At the qualitative end are conceptual models that draw upon the existing body of literature to develop box and arrow diagrams representing the form and function of a system of interest, in particular the web of cause-effect relationships among key variables, including climate (Fischenich 2008; Glick et al. 2011). Conceptual models are useful for: (i) synthesizing the state of science or understanding about how a system functions; (ii) representing the mental model by which a group of scientists envision the way a system functions; and (iii) tracing cause and effect linkages to qualitatively predict response to changes in key drivers, such as climate. Model development can also be informative as a learning process about the important drivers and relationships in a watershed. Such an approach can also be used as a step in the development of quantitative models as described below.

A more quantitative technique includes what can generally be described as an indicator-threshold approach to estimate the biological sensitivity of habitats to climate change, specifically changes in water temperature and water flow. To assess the sensitivity of biota to changes in water temperature, several have synthesized the literature and data to establish "*water temperature guidelines*" or thresholds for protection of freshwater fish species in Canada (e.g., Oliver and Fidler 2001; Hasnain et al. 2010 summarize preferred / optimal temperatures for growth, spawning, egg development, and survival). These thresholds can be used as benchmarks against which to compare current or estimated future thermal conditions so as to understand the implications of climate change on freshwater fish species. Such thresholds can also be used in the functional relationships of more sophisticated models (see below).

Another relevant indicator-threshold approach includes the use of tools to assess environmental flow needs for a stream (also termed ecological flows or instream flows, see Annear et al. 2004; Bradford 2008; Bradford and Heinonen 2008; Petts 2009). These "*standard setting*" approaches require applying one of a wide range of desktop or rule of thumb tools to calculate the amount of water required to support ecosystem needs by relating flow availability to habitat suitability curves, for instance. Thresholds can then be derived below which additional water diversions or water losses are presumed to impair ecological function. Ideally these thresholds are based on an assessment of instream needs for water that consider the magnitude, timing, and/or frequency of flow (e.g., % of mean annual discharge).

Next, these thresholds can be compared to existing or forecast conditions to assess the suitability of flows in a stream for fish (e.g., Nelitz et al. 2010). This category of tools includes methods that can generate one-dimensional (i.e., flow magnitude), two-dimensional (i.e., flow and stage relationships for a channel cross section), or three dimensional (i.e., channel / floodplain inundation maps according to flow) representations of the suitability of habitats for fish.

No method is universally applied; application of a tool will depend on local watershed conditions and needs of decision makers. Annear et al. (2004) review 34 related tools which includes Indicators of Hydraulic Alteration (IHA), Physical Habitat Simulation (PHABSIM), Tennant Method, and Instream Flow Incremental Methodology (IFIM), as well as a range of other hydrology models (some of which are described in Section 2.2 or listed in Appendices B and C).

Lastly, dynamic systems models use sophisticated functional relationships to explicitly represent linkages between system drivers (including climate variables, such air temperature and precipitation) and species / habitat responses. Similar to bioclimate envelope models these models can be empirically (e.g., using statistical correlations to predict fish distribution based on watershed characteristics) or mechanistically based (e.g., bioenergetics relationships to predict individual and population level responses to habitat conditions). Various applications to climate change are available in the literature which have been developed for distinct needs unique to the particular regions of application (e.g., Mangel 1994; Melville 1997; Battin et al. 2007; Rieman et al. 2007; USGS 2008; Nelitz et al. 2010; Wenger et al. 2011).

These tools are generally not transferrable to other locales. Such models are, however, advantageous over the approaches discussed above because they have the potential to more explicitly account for fish population behaviour and other factors that influence species / habitat responses (e.g., wildfire, insect disturbance, land use, water use). Examples from the literature tend to have been developed by academics or government research scientists, apply across broad spatial scales (likely to best serve needs for conservation assessment and planning), and focus on modelling the effects of climate change on salmonids (i.e., trout, char, and salmon). Specific examples include:

- a generalized life history model for Atlantic salmon to predicts the effect of climate change (due to potential changes in water temperature, migration timing, and food availability) on patterns of development, such as maturation and smoltification, and feeding behaviour (Mangel 1994)
- attempts to predict changes in yields for lake trout in the MacKenzie Great Lakes (Great Bear Lake, Great Slave Lake, and Lake Athabasca) using a regression model to estimate changes in summer thermal habitat volume of these lakes (Melville 1997)
- a model of population dynamics for Atlantic salmon to estimate the effect of climate-induced changes in summer low flows, groundwater discharge, and stream temperature on number and size of outmigrating smolts, number of adult spawners, as well as measures of population growth and survival for watersheds in the northeastern U.S. draining into the Gulf of Maine (USGS 2008)
- various empirical and spatially explicit models to predict the thermal suitability of bull trout habitats and their corresponding distribution in the Columbia River basin of the U.S. The effects of climate change are assessed using anticipated changes in air temperature to provide predictions of change in fish distribution at regional and watershed scales (e.g., Chatel no date; Rieman et al. 2007; Isaak et al. 2009; Rieman and Isaak 2010)
- an empirical model of fish distribution based on field surveys and correlations with land use, water availability, and climate variables for cutthroat trout, brook trout, brown trout, and rainbow trout across watersheds in the interior western United States. Predictions of climate-induced changes in distribution of these fish species were assessed using predictions of downscaled climate data and a hydrologic model as drivers in the statistical model (Wenger et al. 2011)
- an existing model of salmon population dynamics (SHIRAZ, see Scheuerell et al. 2006) to predict impacts on habitat capacity for juvenile and adult Chinook salmon in Snohomish River basin in Washington State. The effects of climate change were assessed using emissions scenarios in a distributed hydrology model to predict changes in water temperature and flow variables, and then use these predictions, among other variables, as inputs in the salmon model (Battin et al. 2007)
- an empirical stream temperature, macro-scale hydrologic, and habitat access models, as well as habitat benchmarks were used to estimate potential changes in water temperature and flow and the corresponding suitability and distribution of habitats for bull trout, Chinook salmon, and coho salmon in British Columbia (Nelitz et al. 2010)

Input/outputs

Across approaches a minimum requirement will include basic information on life history requirements and habitat needs to ensure models provide an appropriate representation of the interaction among relevant variables. All approaches will also require a qualitative or quantitative understanding of climate change in a form that can be used as a meaningful input into a model – either directly as a climate variable (e.g., air temperature and precipitation) or indirectly as a climate-mediated habitat variable (e.g., water temperature and flow).

More specific information / data needs will depend on the modelling approach, species of interest, its distribution, life history requirements, and important drivers of response (Glick et al. 2011).

A qualitative conceptual modelling approach will require a more intensive review of the literature and a strong summary of the state of knowledge for a particular species.

Indicator-threshold approaches will require water temperature and/or flow observations, future predictions of these variables, and benchmarks against which to compare current and future conditions. Benchmarks can be based on existing water temperature or flow guidelines (e.g., Hasnain et al. 2010), or derived using desktop approaches as necessary to derive instream flow needs (e.g., Annear et al. 2004).

Other models will require specific and tailored data needs which will depend on the specific model. These data can include field observations of habitat conditions and fish abundance by life stage (egg, juvenile, or adult) that are needed to establish functional relationships in the model or validate predictions. Functional relationships are also needed to represent the quantitative associations among interacting variables. These relationships can be drawn from existing literature, expert opinions, or field observations.

Outputs will vary widely across approaches but can include box and arrow diagrams illustrating relationships among variables that influence species or habitats, graphs that quantify changes in habitat conditions, maps that show changes in fish distribution, or estimates of the probability of occurrence or population survival for a species.

User considerations

The broad group of modelling approaches discussed above are generally not transferable to other regions because they are normally developed for a particular species of watersheds of interest (though some models are generally applicable to a species or group of species; see Shiraz salmon model from Scheuerell et al. 2006). Development of these kinds of models also requires involvement of biologists with expertise in both the species / habitats of interest and quantitative modelling. As a result, they generally have more intensive and broader data needs than the other tools discussed above, meaning they are potentially more costly to develop in both time and money (unless data and functional relationships are readily available). Such data requirements are typically only available for species with high commercial or societal value (e.g., salmonids), which implies that these approaches may have limited application across species (Rosenfeld 2003). In those cases, a more qualitative approach, such as conceptual modeling, may be the only option available.

Given the breadth of approaches discussed above it will be very important to have a clear purpose or goal for developing a habitat or species model (Glick et al. 2011). This clarity is essential for guiding selection of the species or habitat endpoints of interest, choice of modelling approach, and development of model structure.

Another important consideration is that the functional relationships between habitats and species across these models are normally based on correlations between habitat use and abundance by life stage which often lack validation (Rosenfeld 2003). Lastly, these models do not explicitly account for the plasticity and adaptive capacity of fish species, which will be an important factor in determining a species response to climate change (see Section 2.4.2).

2.4 Tools for Assessing Adaptive Capacity

Throughout the literature, adaptive capacity has been synonymous with adaptability, coping ability, management capacity, stability, robustness, flexibility, and resilience (Smit and Wandel 2006; Engle 2011). **Adaptive capacity** is defined as *a system's ability to accommodate, adapt, or cope with the effects of climate change by either reducing exposure or ameliorating the sensitivity of a watershed to climate change* (e.g., Glick et al. 2011). It is the ability of a system to prepare for stressors or changes in advance (*a priori*) and/or adjust and respond to the effects caused by the stressors (*ex ante*) (Smit et al. 2001).

Across many climate change studies, adaptive capacity tends to be focused on assessments of human communities. In the ecological literature, however, a comparable term is referred to as resilience (Gunderson 2000). For our purposes a "system" within a watershed can include both human communities and ecosystems because each has an inherent capacity to cope with climate change – neither will remain static in the face of climate change.

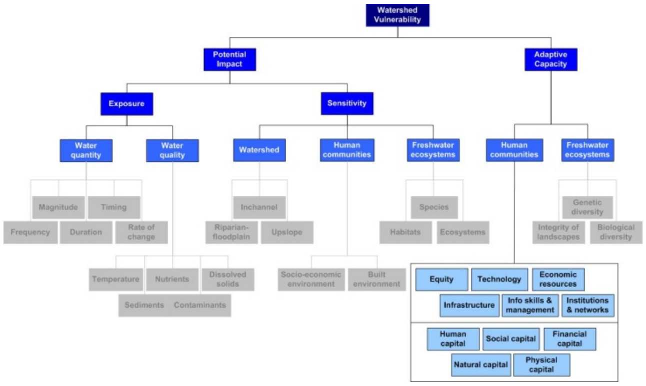
Adaptive capacity is distinct from adaptation because it is a pre-existing condition of a system, as opposed to adaptation which would be pursued in response to or in anticipation of the impacts of climate change (Glick et al. 2011). It is related, however, because it can be described as a measure of the potential or ability to implement adaptation (Metzger 2005). Adaptive capacity is affected by the *internal characteristics* of a system (e.g., ability of a individuals – human or non-human – to physically move in response to an adverse change in water quantity or water quality, such as flooding) and the *external drivers* that have a regulating influence (e.g., terrain features or physical barriers that constrain movement of individuals). Furthermore, adaptive capacity tends to be described in terms of its fundamental characteristics (e.g., economic resources, infrastructure, technology or genetic diversity, integrity of landscapes, biological diversity) and assessed using generalized frameworks as described below (see Box 4). The following sections describe these frameworks / approaches as related to assessing the adaptive capacity of human communities and resilience of freshwater ecosystems.

Box 4: Measuring versus characterizing adaptive capacity (adapted from Engle 2011)

Measuring adaptive capacity is an attempt to directly assess the adaptive capacity of a system by evaluating the system's response to a recent event, or hazard (e.g., flood, drought, wind storm). By empirically investigating and understanding the structures, relationships, processes, and other variables that either helped or hindered adaptation to previous events, researchers can then use this understanding and knowledge as a proxy for how systems may respond to future events that occur gradually over time. Measuring adaptive capacity is difficult as it can only be measured *ex-ante*, or after it has already been realized or mobilized within a system. Assessing adaptive capacity *a priori* is also difficult but is done instead by characterizing its theoretical determinants. Characterizing adaptive capacity uses the attributes, mechanisms, or indicators of social-ecological systems that play a role in facilitating adaptation as outlined in the literature (Ellis 2000; Smit 2001; Brooks et al. 2005; Smit and Wandel 2006).

2.4.1 Adaptive Capacity of Human Communities

The adaptive capacity of communities is considered fundamentally dependent on the magnitude of *resources* available to the system to cope, or adapt, in addition to the system's capacity to use such *resources* efficiently and effectively (Easterling et al. 2004; Adger et al. 2004; Brooks and Adger 2005; Wall and Marzall 2006). As it is strongly considered a localised phenomenon that will vary from system to system, sector to sector, and region to region, the adaptive capacity of communities is noted to be difficult to assess, measure, or quantify (IPCC 2001; Yohe and Tol 2002; Brooks and Adger 2005).



Instead, adaptive capacity is generally "characterized" by key components or key determinants (see Box 4). Furthermore, key determinants will be dependent on the nature of the hazard, as well as the characteristics of the system or populations in question. To date, most studies characterizing adaptive capacity (also known as Adaptive Capacity Assessments, see below) have used aggregated indices or composite indices developed from a set of assumptions highlighted in the literature regarding the key determinants of adaptive capacity.

Because of the localised nature of adaptive capacity, there is no universal list of indicators to capture or characterize adaptive capacity of a system. Rather, indicators must be identified and tailored to each study, project, or vulnerability assessment. Some guiding questions to help identify appropriate indicators have been identified by Brooks and Adger (2005) and may include:

1. What is the nature of the system/population being assessed?
2. What are the principal hazards faced by this system/population?
3. What are the major impacts of these hazards and which elements/groups of the system/population are most vulnerable to these hazards?
4. Why are these elements/groups particularly vulnerable?
5. What measures would reduce the vulnerability of these elements/groups?
6. What are the factors that determine whether these measures are taken?
7. Can we assess these factors in order to measure the capacity of the system population to implement these measures?
8. What are the external and internal barriers to the implementation of these measures?
9. How can capacity constraints be removed from key barriers to adaptation?

In addition to these questions, there are a number of general frameworks commonly used to help categorize determinants of adaptive capacity and structure an assessment of adaptive capacity. Two of the more commonly used frameworks for completing an adaptive capacity assessment are described in greater detail below and examples from Canada provided.

The first framework has its origins in the IPCC Third Assessment Report (Smit and Pilifosova 2001) where some of the earliest determinants of adaptive capacity were identified. These determinants have since spawned a new generation of determinants and frameworks based on our evolution of thinking in this area however most of the underlying concepts remain the same. Key determinants of adaptive capacity as identified by the IPCC include:

- the range of available technological options for adaptation
- the availability of resources and their distribution across the population
- the structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed
- the stock of human capital including education and personal security
- the stock of social capital including the definition of property rights
- the system's access to risk spreading processes
- the ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers, themselves and
- the public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

A number of studies have used some form of the above determinants to identify indicators of adaptive capacity. A Canadian example includes the Prairie Climate Resilience Project where the project team identified 20 indicators of adaptive capacity of agriculturally based Prairie communities (Smit et al. 2001). Indicators were organized by determinants which included: (i) economic resources; (ii) technology; (iii) infrastructure; (iv) information, skills, and management; (v) institutions and networks; and (vi) equity (see Table 12). Data sources for generating indicators included the 2001 Census of Agriculture and the 2001 Census of Population (available by census division from the Statistics Canada website). Composite indicators were then calculated by determinant to produce an overall Adaptive Capacity Index for each census division (Figure 11).

A second widely-accepted framework that provides the basis for a number of adaptive capacity assessments is one which has emerged from the global livelihoods literature, which identifies various forms of capital, or "endowments of resources" as key determinants of adaptive capacity. The types of capital most often considered include human, social, physical, financial and natural (Ellis 2000) (Table 13). A recent study applied a variation of the above framework on four rural Canadian communities to assess adaptive capacity of a community (Wall and Marzall 2006) (Table 14). Using census data, key informant interviews, and a review of publicly available reports, the authors identified indicators using previous studies and converted them to a common score based on a Likert scale. Likert scales enable overall adaptive capacity to be represented using 'amoeba' profiles, or radar charts, a tool that presents information to stakeholders in an easily understandable format (Figure 12). Section 2.5.1 discusses other tools for profiling vulnerability, its dimensions, and underlying components.

In summary, assessing the adaptive capacity of communities within a watershed is an activity specific to the nature of the hazard and the conceptual framework used to understand the structure and relationship between determinants of vulnerability. Although indicators of adaptive capacity abound throughout the literature, they are informed mostly by a few theoretical frameworks that have been developed to better facilitate our knowledge and understanding of the relationship between key determinants of adaptive capacity. It is for this reason that it is said that adaptive capacity is better "characterized" than it is "measured". The output of an adaptive capacity assessment is generally a summary of the availability, access and use of endowments of resources to help cope, adjust or adapt to hazardous events.

Table 13: Framework for representing determinants and indicators of adaptive capacity (Smit et al. 2001)

Determinant	Aspect	Indicator
Economic Resources	Income generation relative to capital investment	Ratio of gross farm receipts to total capital investment. Higher is better.
	Income generation relative to summary expenses	Ratio of income to expenses. Higher is better.
	Off-farm earnings	Off-farm earnings as a percent of total family income where families have at least one farm operator. Higher is better.
	Diversity of employment opportunities	Ratio of off-farm contribution of time to on-farm contribution of time. Not available with current dataset. Alternative was the ratio of employment in agriculture to employment in other industries within Census Division. Lower is better.
Technology	Water access technology	Ratio of value of irrigation equipment to value of all other farm equipment. Higher is better.
	Computer technology	Ratio of farms reporting use of computer to all other farms. Higher is better.
	Technological flexibility	Ratio of value in tractors under 100 hp to total value of all other tractors. Lower is better.
	Technological exposure	Ratio of technologically-demanding to less demanding farm types. Higher is better.
Information, Skills, and Management	Enterprise information management	Ratio of farms reporting computer livestock and crop record keeping to all other farms. Higher is better.
	Sustainable soil resource management practices	Ratio of area of no-till or zero till seeding to tilled area. Higher is better.
	Sustainable environmental management practices	Ratio of farms reporting windbreaks and shelter belts to all other farms. Higher is better.
	Human resources management	Ratio of total farms reporting paid agricultural labour to all other farms. Higher is better.
Infrastructure	Informal operating arrangements	Ratio of total farms reporting formal agreements to total no. of farms reporting sole proprietorships and partnerships without written agreement minus miscellaneous category. Lower is better.
	Email use	Ratio of total farms reporting email use to all other farms. Higher is better.
	Internet access	Ratio of farms reporting internet use to all other farms. Higher is better.
	Opportunity to access agricultural education institutions	Distance between centroids of each Census Division and the nearest regionally significant agricultural institution. Lower is better.
Equity	Employment opportunities	Unemployment rate from Statistics Canada’s 2001 Census of Population 20% sample data for population of 15 years and over. Lower is better.
	Opportunity to access health and social services	Ratio of labour force in health and social service occupations to all other occupations. Statistics Canada’s 2001 Census of Population 20% sample data for population. Higher is better.
	Distribution of income – general population	Rating by Alessandro’s work as published in Catalogue no. 21-006-X1E (Rural/urban divide is not changing: income disparities persist).
	Distribution of income – agricultural producers	Ratio of farms reporting sales in excess of 250k to all other farms. Lower is better.

Figure 11: Adaptive capacity index by Prairie census divisions. Dark green census divisions indicate highest adaptive capacity, while red indicates lowest adaptive capacity (Swanson et al. 2007).

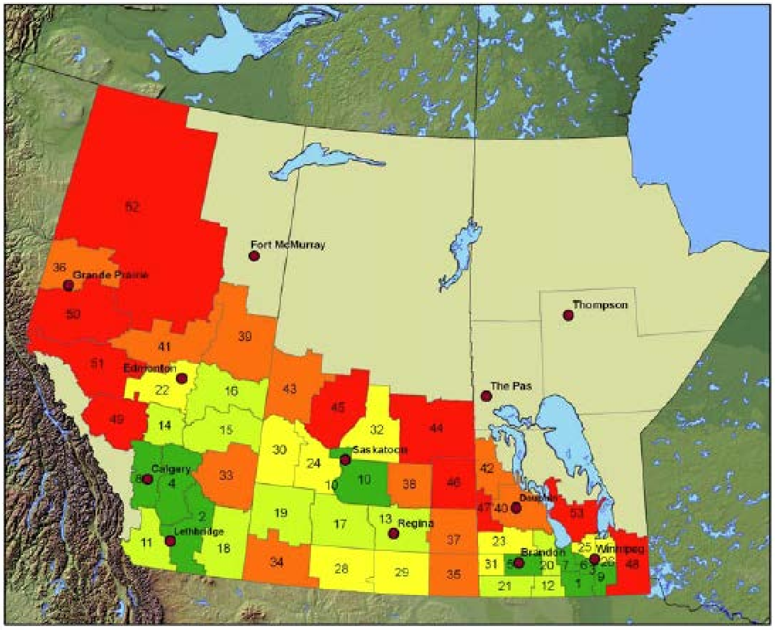


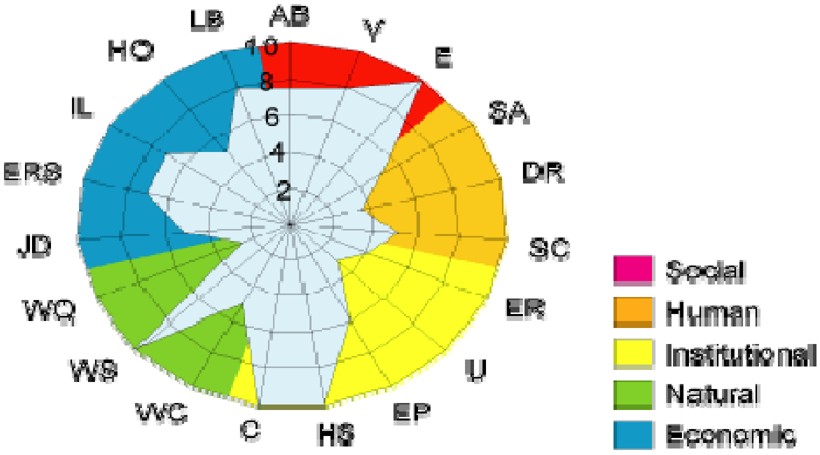
Table 14: A commonly accepted framework for representing adaptive capacity (adapted from Ellis 2000)

Asset Category	Description
Human	The skills, health, age and education of individuals that contribute to the productivity of labour and capacity to manage land
Social	Reciprocal claims on others by virtue of social relationships, the close social bonds that facilitate, cooperative action and the social bridging, and linking via which ideas and resources are accessed. Includes organizational and institutional capacity.
Natural	The productivity of land, and actions to sustain productivity, as well as the water and biological resources from which rural livelihoods are derived
Physical	Capital items produced by economic activity from other types of capital that can include infrastructure, equipment, and technology, including improvements in genetic resources (crops, livestock)
Financial	The level, variability and diversity of income sources, and access to other financial resources (credit and savings) that together contribute to wealth.

Table 15: Framework for adaptive capacity as applied to four rural Canadian communities (Wall and Marzall 2006)

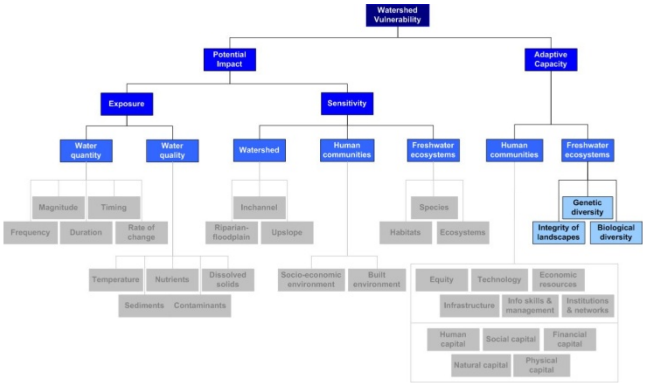
Resource Determinant (or "Capital")	Variable	Indicator (CODE)	Data source
Social	Community attachment	Buckner scale (AB)	Household survey
	Social cohesion	Trends in mobility rates (MR)	Census data
		Number of community events (E)	Local communication report
Human	Education Infrastructure	School / institutional availability measure (SA)	Site profiles
	Productive population	Trends in dependency ratios (DR)	Census data
	Education levels	Trends in years of schooling completed (SC)	Census data
Institutional	Political action	Elected representation (PR)	Published reports
	Utilities infrastructure	Age and condition (U)	Interviews with municipal personnel
	Emergency preparedness	Number of emergency programs available (EP)	Primary research on-site; community profiles
	Health services	Services available (HS)	Local services report
	Communication services	Availability of local radio/TV/ ARES (Amateur Radio Emergency Service) (C)	Local communication report
Natural	Potable water quality	Frequency of contamination (WC)	Local annual report
	Potable water quantity	Frequency of shortage measure (WS)	Local annual report
	Surface water	Quality/quantity assessment (WQ)	Local annual report and other local reports
	Soil conditions	Erosion/quality measure (S)	
	Hardiness	Plant hardiness measure (H)	
	Forest reserve	Diversity / age measure (TS/FP)	
	Fish reserves	Quality/quantity measure (FA/FS)	
	Coastal erosion	Assessment for potential (CE)	
Economic	Employment levels and opportunities	Trends in job diversity (JD)	Census data
	Economic assets	Trends in employment rates (ER)	Census data
		Trends in income level (IL)	Census data
		Trends in home ownership rates (HO)	Census data
		Local business ownership rates (LB)	Local business retention and expansion survey report

Figure 12: An ‘amoeba’ diagram representing adaptive capacity for the community of Tweed, Ontario using 19 proxy indicators (Wall and Marzall 2004)



2.4.2 *Resilience of Freshwater Ecosystems*

The term resilience emerged in the ecological literature in the 1970s and over the past decades has been described and interpreted in many different ways (Gunderson 2000). For the purposes of understanding vulnerability of ecosystems, resilience is defined as:



> *“…the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes. A resilient ecosystem can withstand shocks and rebuild itself when necessary*[9]*”*

This definition is informative because it helps distinguish adaptive capacity in ecosystems from that in human communities, such that the capacity in ecosystems is only used in response to a disturbance event such as climate change, while the capacity in human communities is deployed both in response to and in anticipation of climate change. This definition is further informative because it illustrates that adaptive capacity in ecosystems is generally viewed through a lens of resilience, which does not tend to be represented in this way when assessing the capacity of human communities (Engle 2011). Several others have made the link between resilience, adaptive capacity, and vulnerability despite having different origins, definitions, and interpretations, largely due to the recognition that the sensitivity of ecosystems to climate change will be mediated by resilience and/or adaptive capacity

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[9] See Resilience Alliance. Available from: http://www.resalliance.org/index.php/resilience.

(e.g., Gunderson 2000; Elmqvist et al. 2003; Williams et al. 2008; Miller et al. 2010; Fraser et al. 2011; Engle 2011).

The concept of resilience is important for scientists and decision makers to consider in a vulnerability assessment because it improves our understanding and management of complex social-ecological systems, especially in light of climate change. There is substantial evidence that illustrates how *species* (Gotthard and Nylin 1995; Bagley et al. 2002; Skelly et al. 2007; Bradshaw and Holzapfel 2006), *habitats / landscapes* (Gustafson 1998; Vos et al. 2002; Bengtsson et al. 2003; Chapin et al. 2004; Alberti et al. 2007), and *ecosystems* (Elmqvist et al. 2003; Chapin et al. 2004; Petchey and Gaston 2009; Berg et al. 2010) have an inherent resilience or capacity to adapt to climate change. This potential for evolutionary adaptation tends to be ignored when trying to predict the impacts of climate change. This omission can lead to overestimating the adverse effects of climate change.

There is also evidence which shows that human behaviour and actions can maintain or hinder an ecosystem's ability to adapt or maintain its capacity for renewal (e.g., Gunderson 2000; Hansen et al. 2003; Glick et al. 2011). For instance, broad strategies for maintaining / enhancing resilience include: (a) protecting intact systems, (b) restoring systems to pristine states, and (c) preventing further degradation (CCSP 2008a).

Despite its importance, the science, theory, and development of tools for assessing, measuring, or predicting resilience of ecosystems is nascent. Thus, our ability to measure resilience is relatively weak, making prediction and management for resilience "*more an art than a science*" (CCSP 2008a). There is, however, a generally robust view on the core aspects of resilience which can be informative for characterizing resilience (see Box 4). Across the literature resilience is consistently viewed as being described according to the intrinsic characteristics of species, habitats, or ecosystems (Peterson et al. 1998; Carpenter et al. 2001; Bengtsson et al. 2003; CCSP 2008a; Thompson et al. 2009; Glick et al. 2011) because ecosystems that are resilient across these levels are believed to exhibit faster recovery after a disturbance or perturbation (CCSP 2008a). Thus, ecosystem resilience can be described using the following aspects:

- <u>Genetic diversity</u> as a representation of the genetic signature, behavioural, morphometric, and physiological plasticity, and overall evolutionary potential of a species to respond to changes in the environmental conditions associated with climate change
- <u>Integrity of landscape mosaics</u> as a representation of the ability of habitats to sustain the distribution and connectivity of populations thereby allowing for their movement across landscapes in response to climate change
- <u>Biological diversity</u> as a representation of the ability of communities and ecosystems to maintain their form (i.e., biodiversity) and function (i.e., trophic interactions).

These aspects of resilience provide useful guidance for reviewing existing tools or approaches that could be used, though have not been specifically applied, in vulnerability assessment of watersheds in relation to climate change. For instance, the changes in distribution and timing of life history activities associated with climate change have been termed "phenotypic plasticity" which relates to an individual's ability to change its behaviour, morphology, and physiology in response to altered environmental conditions such as climate change (Gotthard and Nylin 1995; Skelly et al. 2007; Bradshaw and Holzapfel 2006). Such species level adaptations have a genetic signature which is considered a heritable trait in populations of animals. Thus, <u>genetic diversity</u> has been proposed as a means to provide insights into the consequences of environmental change which can be used in conjunction with other ecological indicators related to landscapes and biodiversity (Bagley et al. 2002). Many different molecular technologies are available for measuring genetic diversity such as using genetic markers to provide precise estimates of overall levels of genetic diversity within and among populations of a species (e.g., Bagley et al. 2002).

Landscape patterns (i.e., intensity, composition, configuration, and connectivity) and processes (e.g., succession, fluvial geomorphology) are important characteristics of resilience of terrestrial and freshwater ecosystems (Vos et al. 2002; Bengtsson et al. 2003; Chapin et al. 2004). Human development can affect these natural landscape patterns and processes by altering the connectivity of habitats and disrupting natural processes which can affect the dispersal, migration, and overall resilience of species, habitats, and ecosystems (Glick et al. 2011). Landscape patterns matter to ecosystems and these patterns are quantifiable beyond simple measures of watershed development, such as impervious cover or population density (Haines-Young and Chopping 1996; Gustafson 1998; Alberti et al. 2007). Such measures are relevant for understanding the integrity of landscape mosaics which tend to relate to metrics of intensity (e.g., density or percent of different types of human development), composition (e.g., percent of different habitat types), configuration (e.g., contagion, patch size, adjacency, aggregation), and connectivity (e.g., fragmentation, crossings, and distance of connections between habitats) of habitats (Haines-Young and Chopping 1996; Gustafson 1998; Alberti et al. 2007).

Multiple authors demonstrate that resilience is influenced by both the form (i.e., species composition and diversity) and function (i.e., trophic interactions) of an ecosystem (Elmqvist et al. 2003; Chapin et al. 2004; Petchey and Gaston 2009; Berg et al. 2010). For instance, fish species composition can affect the thermal tolerance of individual species, such that in the presence of a competitor a species can be excluded from suitable habitats along a thermal gradient before it reaches its thermal limit (Nelitz et al. 2008). Thus, in some cases it can be important to understand community composition and species interactions to properly assess the effects of climate change and overall ecosystem resilience. Another example includes a consideration of the redundancy of species within functional groupings of animals within an ecosystem (e.g., primary producers, herbivores, carnivores, decomposers, competitors, predators).

Species redundancies can maintain ecosystem functioning in the event of a loss of a species due to climate change, for instance, thus increasing overall functional resilience (Petchey and Gaston 2009). Existing measures for representing biological diversity include the Simpson Index (richness and composition of different species, Simpson 1949; Krebs 1989), Shannon-Weiner Index (richness and composition of different species, Krebs 1989), Morisita Index (species similarity, Morisita 1962; Krebs 1989), and the Index of Biological Integrity (composition and structure of fish, macroinvertebrate, and other communities, Karr 1981; Whittier et al. 2007). Examples describing the diversity of individuals within a functional grouping of species (i.e., “functional diversity” as termed by Petchey and Gaston 2009) were not identified, though the above diversity indices could be used in conjunction with existing approaches to classifying species into functional groupings (e.g., reviewed by Wilson 1999).

2.5 Tools for Supporting Vulnerability Assessment of Watersheds

2.5.1 Aggregating Dimensions of Vulnerability

Referred to as the "holy grail" of vulnerability assessment (Alwang et al. 2001), the process of aggregating components and individual indicators of vulnerability into an overall score, or index, is a valuable yet contentious task. As illustrated by Figure 1, one can imagine the added value of being able to summarize all of the underlying dimensions, components, and sub-components of vulnerability into a single value, while at the same time understanding the contention of the underlying decisions which must be made to do so. Aggregation itself is a tool for multicriteria decision analysis which systematically reduces all values into a single number that is comparable across both time and space. The challenge is that the end result must be accepted and agreeable to a variety of interests including decision-makers, stakeholders, adaptation planners, and practitioners alike.

As with the use of an indicator approach, the challenges of aggregating data across indicators are numerous. Of primary importance is understanding and acknowledging that aggregate, or composite, indices are only as good as the data from which they were created. This is dependent both upon the identification of appropriate and relevant indicators, as well as the completeness, quality, and integrity of data that are used to develop the indicators. Additional challenges are inherent in the calculation, interpretation, and communication of aggregations, particularly where the composite index may appear deceivingly simple and homogenous as a single value. In reality, a composite index can mask the importance of a single vulnerability factor by averaging across all variables (Adger et al. 2004). For example, an area with a high vulnerability score may be vulnerable due to high risk of exposure, high sensitivity (due to the local soil conditions, deforestation rates, and erosion potential of the watershed), or low adaptive capacity of communities residing in the watershed (due to low economic diversity or awareness of climate risks). A single aggregate score may diminish the significance of any one of the contributing variables and make it unclear which components need to be addressed moving forward as part of the adaptation planning process.

In general, methods for developing aggregate, or composite, indices of vulnerability are not technically complex, though they can be highly contentious due to a number of subjective and underlying assumptions which must be made. Below we present six methods for representing the many dimensions, components, and sub-components of vulnerability in a more digestible format for decision makers and stakeholders. These approaches represent a distinct core of alternatives, yet do not represent a comprehensive summary of all possible approaches. The methods described below include:

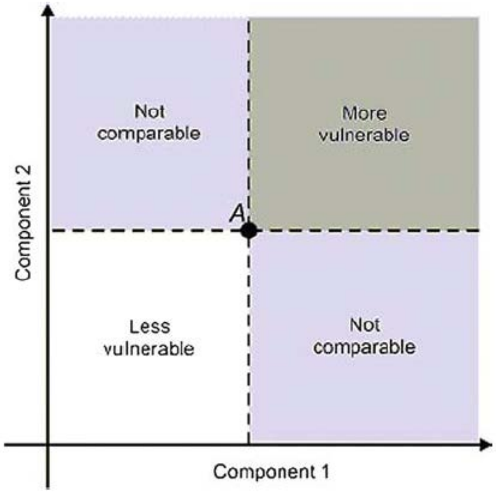
(i) Simple averaging technique
(ii) Weighted averaging technique
(iii) Pareto ranking
(iv) Data Envelopment Analysis (DEA)
(v) Vulnerability maps
(vi) Vulnerability profile

The most common method for calculating an aggregate index is a simple averaging technique. Averaging assumes equal value, or weight, assigned across all indicators – the underlying assumption being that all components contribute equally to vulnerability. Conversely, weighted averaging techniques assign arbitrary weights to each indicator using either statistical means (e.g., z-scores, Principal Component Analysis, factor analysis, Monte Carlo, Kolmogorov-Smirnov) or stakeholder values and judgements (see Lasco et al. 2010). Statistical methods are useful tools in identifying relatively independent groups of indicators that explain the greatest amount of variance in a dataset. Using a weighted average technique to calculate an overall vulnerability index would assign those indicators contributing the greatest amount of variance heavier weights. Although statistical methods are sometimes considered more scientifically defensible (and less resource intensive), using stakeholder, expert, local, and/or indigenous judgement can help to ensure overall legitimacy and ownership of the results and subsequent follow-up actions (Smit and Wandel 2006).

Although weighted averages acknowledge the differential contribution of each component to overall vulnerability, assigning weights requires a subjective assessment of value or importance. Furthermore, averaging techniques mask extreme values when combined with lower values. When trying to understand vulnerability to climate change and severe weather events in a watershed, such high values may be particularly important to maintain as they may reflect where resources are required most (Clark et al. 1998).

Two alternatives to simple and weighted averaging techniques that maintain these high values and share many of the same underlying concepts are Pareto ranking and Data Envelopment Analysis (DEA). Pareto ranking is a tool that has been adapted from welfare economics (Pareto 1896). Pareto ranking does not require the researcher to judge the relative importance of components and their indicators and therefore does not require assigning arbitrary weights. It is a tool based on the idea that in some cases vulnerability, as a multi-component attribute, cannot be directly compared across time or space. Rygel et al. (2006) use a simple and hypothetical two-component case to illustrate this approach whereby only those situations with both component scores higher than A, or alternatively both component scores lower than A, are clearly more or less vulnerable than the point represented by A (see Figure 13). Situations with one component score higher and one lower than A fall into a grey area of non-comparability.

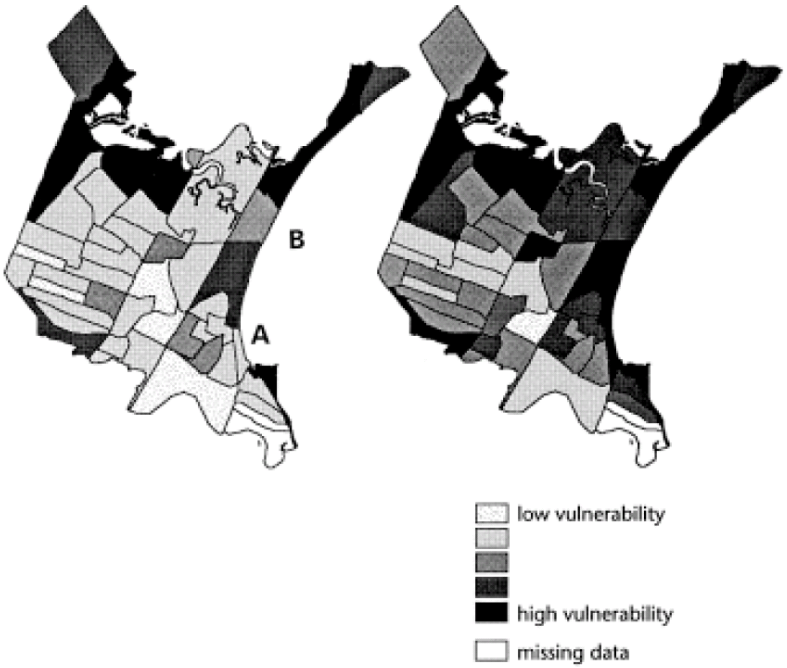
Figure 13: A simple two-component case of vulnerability, where A is a geographic unit (Rygel et al. 2006)



Using Figure 13 as a simple example, Pareto ranking is the continual process of isolating all those cases with nothing above or to the right of them (thereby identified as the “most vulnerable” situations). Once those situations scoring highest across all components of vulnerability are identified, they are lumped into block groups, removed from the dataset and assigned a vulnerability ranking or weighting accordingly. This process continues until all cases have been lumped into a block group and assigned a vulnerability rank. Rygel et al. (2006) provides a multi-dimensional example of how Pareto ranking is applied to estimate an overall social vulnerability to hurricane storm surges on the eastern shores of the United States.

Based on the same principles, a similar yet “conceptually and practically more complicated” alternative to Pareto ranking is Data Envelopment Analysis (Charnes et al. 1979; Haynes et al. 1993). Figure 14 shows a map of social vulnerability for Revere, Massachusetts using a simple averaging technique on the left and a DEA on the right. The authors of this study note that there are more areas of “high vulnerability” using the DEA approach because of the dampening of high values in the equally weighted approach (Clark et al. 1998).

Figure 14: Map of overall vulnerability in Revere, Massachusetts using simple averaging (left) and Data Envelopment Analysis (right) (Clark et al. 1998)



Once vulnerability scores, or ranks, have been calculated using one of the aggregation tools discussed above, Geographic Information Systems (GIS) provide a common and effective way to subsequently map the spatial distribution of exposure, sensitivity, adaptive capacity, and/or overall vulnerability. Most vulnerability assessments use GIS as a means to input, store, manage, analyze, integrate, aggregate, and communicate data related to risk, exposure, and socio-economic vulnerability across both time and space. In some studies, maps are used as an output of an exposure, or hazard, assessment to identify areas at highest risk of exposure. GIS layers built from proxies for sensitivity and adaptive capacity can then be overlaid to help understand overall vulnerability and identify ‘hot spots’ where adaptation planning and investment could be prioritized.

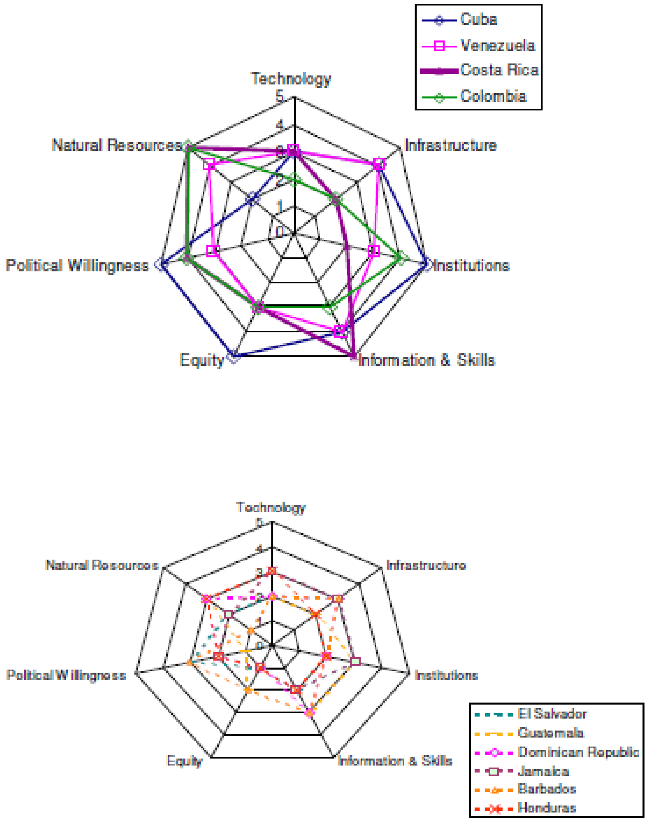
While the strength in calculating and communicating overall vulnerability using GIS is well established, challenges exist. Common challenges of using maps to display differences in vulnerability across spatial units actually stems from the challenges inherent in the underlying aggregated data, namely that aggregated data masks the internal characteristics and structure of vulnerability. For example, in Figure 14 on the left, Dissemination Area (DA) A is less vulnerable than B however how to reduce the vulnerability of B is not clear. Is it a matter that the sensitivity to sea level rise and storm surge is greater for B than it is for A in which case adaptation investments may include sea walls, polders and dikes? Alternatively, is it the case that Area A is wealthier and the population has a higher level of education in which case adaptation planning would include efforts to improve access to economic and financial resources for Area B? In some studies, multiple maps are used to express aggregated results for the identified component parts of vulnerability (exposure, sensitivity and adaptive capacity) such that decisions regarding adaptation planning and investments can be better informed.

Additionally, vulnerability maps in particular can propagate the illusion of hard spatial boundaries of vulnerability rather than the more realistic permeable, or fluid, boundaries (Eakin and Luers 2006). Maps too are only representative of a ‘snapshot’ in time thus inferring hard temporal boundaries. As a result, GIS maps are often used as a baseline and subsequent monitoring tool, to monitor changes in vulnerability across both time and space.

A final alternative to aggregating data on vulnerability that resolves some of the challenges of using maps, is to create a vulnerability profile. Vulnerability profiles allow analysts to understand the internal structure and characteristics of vulnerability, which is important when managing for vulnerability or planning for adaptation. Whereas aggregation may result in the identification of geographically vulnerable areas, a single score or value may not provide enough information to determine the cause or structure of the vulnerability and therefore how to best manage for it in future. Thus, “*Vulnerability profiles enable a quick assessment of [an area’s] strengths and weaknesses in terms in terms of the structural causes of vulnerability, and tell us where to concentrate in terms of vulnerability reduction and capacity building*” (Adger et al. 2004).

Vulnerability profiles are generally presented as graphical representations known as radar diagrams (Figure 15) or ‘amoeba’ profiles (used to profile adaptive capacity in Figure 12). In this way, profiles enable stakeholders and decision-makers to focus discussions, research efforts and investments on those indicators or proxies most poorly represented. Furthermore, profiles of vulnerability can provide a baseline diagram against which future progress in the identified areas can be measured and monitored. A challenge, however, is that each indicator, or variable, must be normalized or converted to a common scale (0 – 5 in Figure 15, and 0 – 10 in Figure 12).

Figure 15: A radar diagram representing the profile of water resource vulnerability in Latin America (adapted from Downing et al. 2006)



2.5.2 *Understanding the Effect of Uncertainties*

It is unrealistic to expect that a vulnerability assessment will be able to accurately and precisely trace the pathways of effect among changes in climate to changes in water resources, watersheds, human communities, and freshwater ecosystems. Uncertainties are pervasive because imperfect knowledge will be embedded within all components of a vulnerability assessment. For instance, potential sources of uncertainty include:

- disparity among predictions from Global Climate Models and emissions scenarios
- differences in local climate predictions from regional climate models and statistical downscaling approaches
- difficulties in tracing effects through a complex pathway of cause and effect relationships due to varying assumptions and understandings about how these components interact (e.g., linking climate drivers to changes in the biophysical environment to changes in the water cycle to changes in human communities and ecosystems)
- natural variation in water supplies across watersheds, seasons, and years
- errors in observing, measuring, and modelling values for the dimensions of vulnerability

- imperfect knowledge about which indicators and metrics most appropriately represent the true state of nature for a vulnerable watershed
- imperfect knowledge about the relative importance or weighting of different dimensions in determining overall watershed vulnerability
- differences among decision makers and the societal values associated with the targets or endpoints being evaluated through a vulnerability assessment
- imperfect knowledge about the effectiveness of capacity and behavioural changes available to respond to climate change.

Despite the uncertainties, analysts can still perform useful vulnerability assessments and decision makers can still use them to make informed decisions. In other words, a lack of certainty should not paralyze an analyst from developing an understanding of watershed vulnerability or a decision maker from taking action in response to climate change (Saerwitz et al. 2000).

Assessments or decisions which ignore uncertainty usually lead to different outcomes than when they are considered (Morgan and Henrion 1990; Clemen 1996). An explicit consideration of uncertainties commonly leads to more comprehensive analyses and more robust decision making. A few basic tools are available to analysts and decision makers for addressing uncertainties. Where possible and appropriate it will be valuable to apply these tools in the assessment of vulnerability of watersheds across Canada. CCSP (2009a) provide an excellent summary and guidance on considerations for estimating, incorporating, communicating, and making decisions in the face of the large uncertainties associated with climate change. Below we describe two tools for understanding the effect of uncertainties on projections from vulnerability assessments:

(i) Sensitivity Analysis
(ii) Scenario Analysis

Sensitivity Analysis

Sensitivity analysis represents a systematic and explicit approach to exploring the effect of uncertainties in key drivers on a model’s or formula’s predictions (Morgan and Henrion 1990; Clemen 1996). This approach is commonly used by quantitative modellers, using a fixed model structure or formula and then targeting inputs with the highest level of uncertainty so they can be varied by informed, though arbitrary, amounts through repeated calculations. For instance, if a sensitivity analysis targets three levels for one input variable (e.g., existing values ±10%) a model’s predictions would be generated across a manageable number of iterations (e.g., 3 levels of 1 variable = 3*1 = 3 iterations).

Alternatively, if a sensitivity analysis targets multiple inputs and ranges for those inputs, model predictions or calculations would ideally be generated across all possible combinations of input variables and ranges of values. Such an analysis would lead to many iterations and many possible outcomes, which leads to challenges in managing and interpreting the results (e.g., 3 levels for 5 variables = 3*3*3*3*3 = 243 iterations). The results from a sensitivity analysis are useful because they can be analyzed to examine the variation in model predictions associated with the change in one of the key model inputs. This variation can then be compared across multiple inputs to come to a determination on the relative importance of uncertain variables and their relative influence on model predictions. For vulnerability assessment of watersheds, such information would provide valuable insights to help:

- evaluate the robustness of a watershed's vulnerability to key uncertainties (i.e., errors in data, assumptions, and models), which in turn can help analysts / decision makers gauge a level of confidence in the results from a vulnerability assessment
- identify the most influential sources of uncertainty in a vulnerability assessment, which in turn can inform future research priorities and ultimately reduce uncertainties over time.

The value of this approach has been recognized and recommended as part of a general framework for assessing climate change impacts on water and watershed systems (Johnson and Weaver 2009). In particular, such an approach could be used to target uncertainty in the underlying data, model structure (i.e., alternative tools), or key assumptions within an individual tool.

Examples of sensitivity analyses appear in vulnerability assessments of watersheds in varying though somewhat similar ways. For instance, Prudhomme and Davies (2009a; 2009b) used three GCMs, two downscaling techniques, and different hydrological model structure and model parameters to examine the effect of these uncertainties on river flows. Their results showed that uncertainty in GCMs was larger than the uncertainty associated with the downscaling approaches, and both were generally greater than the uncertainties associated with hydrological modelling or natural variability. Imhoff et al. (2007) examined a wide range of changes in precipitation and air temperature to assess the effect of climate change on nitrogen loadings using a modelling framework that integrates climate, terrain, land use, hydrology, and pollutant loadings. Lastly, Tarekegn and Tadege (no date) varied air temperature and precipitation by fixed amounts to examine the vulnerability of runoff and agricultural production in watersheds in Africa (e.g., increased air temperature by 2˚C and 4˚C and altered amount of rainfall by ±10% and ±20%). Though these studies tended to focus their sensitivity analyses on climate variables, a sensitivity analysis can target any other important tool or model drivers being used in a vulnerability assessment.

Scenario analysis

Put simply, a scenario can be defined as a structured account of a possible, probable, or desirable future for a system of interest (e.g., watershed, community, or ecosystem). It represents a dynamic story generated using a specific development pathway and key assumptions about how the future might unfold which typically includes a description of demography, economics, natural resource use, governance/policy, and culture (UNFCCC 2008).

Scenario analysis is a futuring exercise where multiple scenarios about the future are used to represent a range of uncertainties in development pathways and related assumptions, and then used as inputs or considerations in an assessment framework to better understand the range of plausible outcomes. Similar to a sensitivity analysis, scenario analysis is useful for understanding the effect of key uncertainties on an analyst's predictions and ultimately decision making. Thus, scenario analysis is most relevant in situations with large and potentially irreducible uncertainties that cannot easily be quantified in probabilistic terms and in situations that might be minimally controllable (Peterson et al. 2003).

Where a more sophisticated sensitivity analysis attempts to examine uncertainty across an entire response surface, a scenario analysis is more constrained in that it tends to represent the outer boundaries of a response surface (Morgan and Henrion 1990). Scenario analysis is a highly transferable approach having been considered in a range of domains, including environmental assessments (Alcamo 2001; Duinker and Greig 2007), conservation planning (Peterson et al. 2003), business management (Goodwin and Wright 2009), and climate changes studies (Dessai and Hulme 2004, see Box 1; Johnson and Weaver 2009; CDM 2011).

Other studies provide useful and detailed guidance on developing plausible and meaningful scenarios for scenario analysis (Alcamo 2001; Peterson et al. 2003; CDM 2011). Several other resources are described in UNFCCC (2008) which provide more specific guidance and description of approaches for developing socioeconomic scenarios in climate change studies. Across these sources we summarize a few common steps:

1. Identify the issue: Focus a scenario analysis on relevant issues by framing the analysis to address a fundamental question of interest.
2. Assess the system: Develop an understanding of the system of interest, (e.g., watershed), its components, and its driving forces (i.e., variables).
3. Identify alternatives: Identify alternative development pathways for the system, determine key uncertain variables affecting those development pathways (e.g., air temperature, precipitation, water demand, land use development, population growth), define the range of conditions worth exploring for these uncertainties, and then rank the variables according to their importance.
4. Build scenarios: Use the most important uncertainties to define a manageable number of scenarios and combine them to create a scenario table or scenario tree (Figure 16). Develop a storyline or narrative describing the pathway from the current baseline to each scenario endpoint.
5. Test scenarios: Evaluate the scenarios to ensure they are plausible and consistent with the perspectives of alternative stakeholders, yet push the boundaries to current thinking about development pathways for the system.

Scenario development tends to be an inclusive process that includes a diverse group of people (e.g., scientists, managers, policymakers, stakeholders) and often require multiple iterations.

The most notable example of scenario development related to climate change is the Special Report on Emissions Scenarios (SRES) developed by the IPCC (Nakicenovic et al. 2000). SRES scenarios are distinguished by different assumptions about demography and social, economic, technical, and environmental development. Though these emissions scenarios have been developed for the specific purpose of understanding changes in climate forcing, scenarios for vulnerability assessment of watersheds can be tailored more specifically to address the particular needs of tools being used in such an assessment. A relevant example includes the Willamette Water 2100 study[10] currently under development. This approach integrates socioeconomic, hydrological, and ecological considerations to assess the water system in the Willamette River basin, Oregon.

Future scenarios are defined by alternative climate change scenarios, landscape change, and human population growth which are in turn being used to assess the vulnerabilities of the water system and identify opportunities for adaptation. In the Rouge River watershed in southern Ontario, eight land use and management scenarios, including alternative pathways of urban development, stormwater

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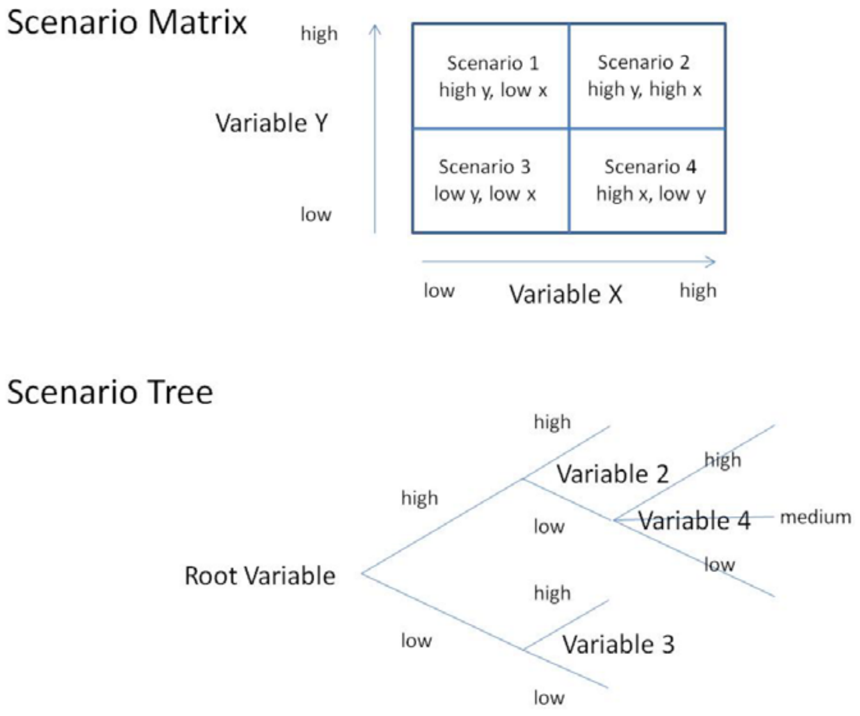
[10] Willamette Water 2100. See: http://envision.bioe.orst.edu/StudyAreas/WW2100/WW2100.htm

systems, natural cover, and climate change, were developed to depict the alternative futures for the watershed and predict the potential range of responses (TRCA 2007).

Another example relates to the First World Water Forum in Morocco which identified a need to develop a world water vision to communicate the urgency of global water problems and need for taking action (Alcamo 2001). The resulting scenario process developed three storylines to serve this purpose – a "Business as usual (BAU)" scenario, "Technology, economy, and private sector" (TEC) scenario, and a "Values and lifestyle" scenario as alternative representations of how individual nations and collective action might resolve current, emerging, and future water crises.

Figure 16: Classification of scenarios according to the uncertain variables being used to develop the range of plausible futures. The scenario matrix represents a categorization of four scenarios, while the scenario tree represents classification of six scenarios (endpoints of the branches, CDM 2011).



2.5.3 Communicating Uncertainty

Another important consideration when dealing with uncertainty is to acknowledge it and to be as clear as possible in communicating with others about the magnitude of uncertainty wherever possible. The Intergovernmental Panel on Climate Change (IPCC) has developed and used some standardized language to communicate uncertainty in the context of climate change (IPCC 2005). This language has been adopted by others (e.g., CCSP 2008a; 2008b; 2009; Glick et al. 2011) even though some have identified opportunities for misinterpretation due to nonlinear interpretations of probability (e.g., Patt and Schrag 2003; Patt and Dessai 2005).

The IPPC’s treatment of uncertainty relates to two distinct concepts: likelihood and confidence in scientific predictions. Likelihood is used to describe the probability of occurrence of a defined outcome in the future (e.g., a change in flood frequency) which could be based on a quantitative analysis or elicitation of expert opinions (Table 15). Confidence is used to express the level of confidence in judgements, statements, findings, or conclusions (e.g., conclusion about an impact on a vulnerable human community or fish species) based on the current state of knowledge (Table 16). Confidence is further defined in terms of the *amount of evidence* available to support a statement and the *level of agreement* or consensus around the evidence. Where possible and appropriate this language can be informed by and associated with quantitative modelling results or qualitative interpretations of findings from vulnerability assessments of watersheds.

Table 16: Language used by the IPCC to describe likelihood of occurrence of a defined future outcome (Parry et al. 2007)

Terminology	**Likelihood of the occurrence / outcome**
Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

Table 17: Language used by IPCC to describe confidence in statements based on an understanding of current knowledge (Parry et al. 2007)

Terminology	**Degree of confidence in being correct**
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

3. CASE STUDIES OF VULNERABILITY ASSESSMENT

This section reviews case studies of assessments from the Thames River watershed in Ontario, Canada, the Hunter and Central Coasts, New South Wales, Australia, Alpine Watersheds in the Alps Region of Europe and the Arctic Water Resource Vulnerability Index in Alaska, U.S.A. to illustrate how others have assessed vulnerability of watersheds to climate change. Case study tools that are described in this compendium are noted with a cross-reference to the appropriate section.

3.1 Upper Thames River Watershed, Ontario, Canada

Hebb, A. and L. Mortsch. 2007. Floods: Mapping Vulnerability in the Upper Thames Watershed under a Changing Climate - CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions - Project Report XI. 53 pp.

Study Area: The Upper Thames watershed in south-western Ontario is predominantly an agricultural basin with 78% of the total land area considered agricultural (12% forest, 9% urban, 1% quarries and water). The study area is located at the Forks of the Thames, where north and south branches of the river meet near the city of London.

Methodology: To assess the vulnerability of the Forks of the Thames River, a variety of methods were applied. These included scenario development and the development of a semi-distributed rainfall-runoff model (these models are described in Section 2.2.2), as well as a natural hazards and social vulnerability analysis (see Section 2.3.2).

Scenario development: Scenarios were developed using historical data as collected from meteorological station observations from between the years of 1964 and 2001. Additionally, two Global Climate Model (GCM) simulations were selected to explore the impact of two alternative future scenarios, one based on wetter conditions with risk of more extreme and frequent flooding events and the other based on drier conditions with risk of more extreme and frequent drought events. Historical and GCM data were run through a non-parametric weather generator to determine annual maximum daily rainfall. This data was in turn run through a semi-distributed event-based rainfall-runoff model developed for the project and based on HEC-HMS, to determine corresponding peak flows and return periods. Peak flows were then run through a HEC-2 hydraulic model to determine changes in water elevation and estimate floodlines for 6 different return periods (2-, 5-, 10-, 25-, 50-, and 100-year).

Natural Hazard Analysis: Natural hazards were analyzed using GIS and intersecting each floodline scenario with layers of infrastructure, services and economic and recreational activities. The result provided an overview of affected areas (including number of people and private dwellings), structures, services and activities in the Forks of the Thames area.

Social Vulnerability Analysis: Based on a review of existing literature, the authors identified three thematic areas relevant to the adaptive capacity of the affected communities under scenarios of future climate change. Thematic areas and their associated indicators included:

1. Ability to cope and respond

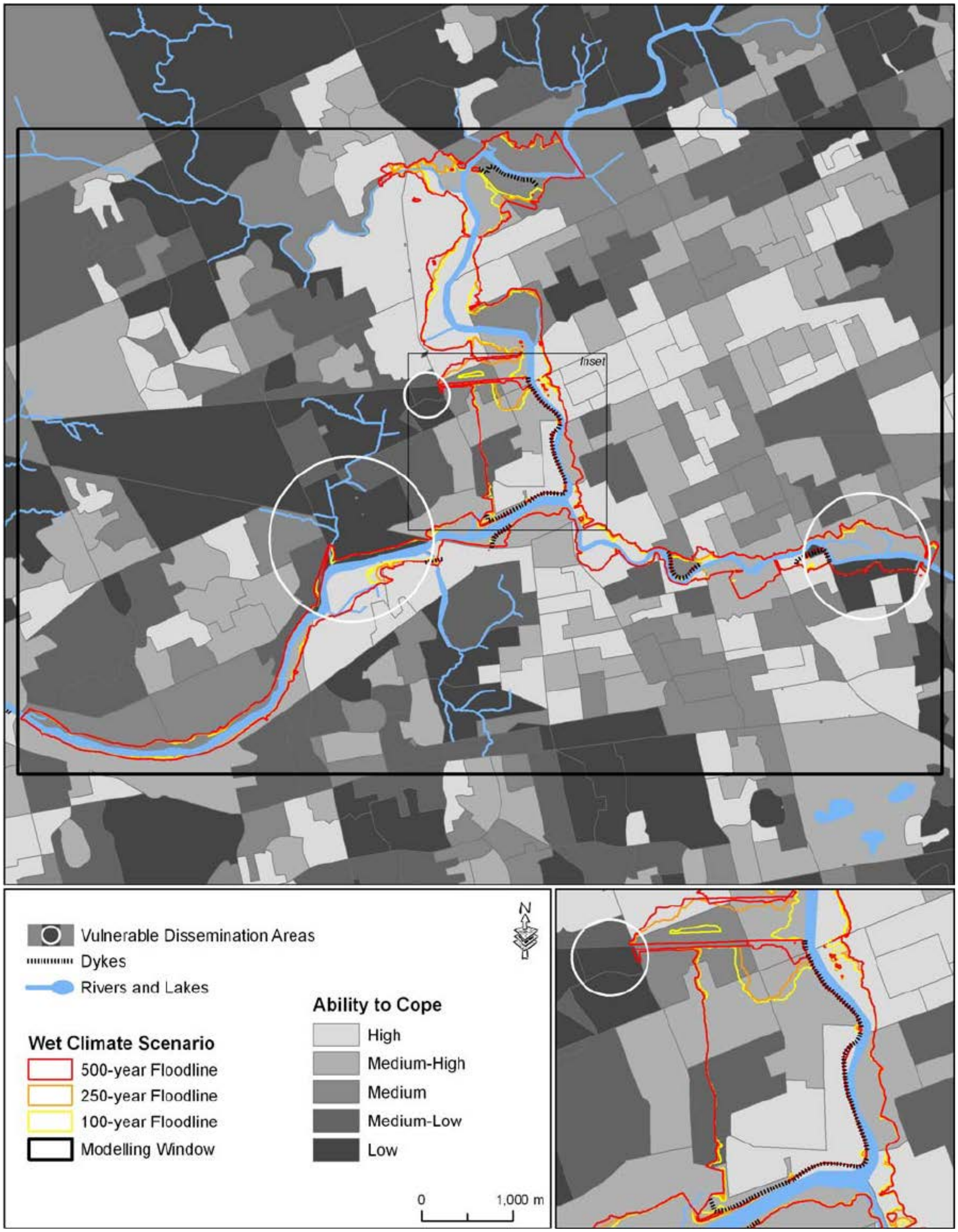
    i. >65 years of age
    ii. <19 years of age
    iii. No knowledge of official languages
    iv. Females
2. Differential access to resources
    i. Low income households
    ii. Single parent families
    iii. Rely on public transit
    iv. Renters
3. Level of “situational” exposure
    i. Housing type
    ii. Period of construction

Data to calculate indicator scores for each Dissemination Area (DA) was collected using the publicly available census data from Statistics Canada 2001. Scores were standardized to a value between 0 and 1.0 using the following equation (Wu et al. 2002):

Index Value = Actual Value for the Dissemination Area (DA) / Maximum Value of all DAs

One vulnerability score per thematic category per DA was calculated using simple averaging and a total overall vulnerability score for the DA was calculated by summing the resulting scores for each of the three thematic areas (maximum value 3.0). All vulnerability scores for a DA were then linked to their geographic boundary coverage in GIS and mapped according to quintiles (e.g., low vulnerability ≤ 20th percentile, high vulnerability between 81st and 100th percentiles). Floodline scenarios were then superimposed on the social vulnerability maps to highlight key areas of vulnerability in the basin (see Figure 17).

Figure 17: Total vulnerability in the Forks of the Thames River, Ontario (Hebb and Mortsch 2007)



3.2 Hunter and Central Coasts, New South Wales, Australia

Brunckhorst, D., I. Reeve, P. Morley, M. Coleman, E. Barclay, J. McNeill, R. Stayner, R. Glencross-Grant, J. Thompson, and L. Thompson. 2011. Hunter & Central Coasts New South Wales – Vulnerability to climate change impacts. Report to the Department of Climate Change and Energy Efficiency, Australia.

Study Area: The Hunter Coast in New South Wales (Australia) is a mostly residential and tourist-friendly basin. A major tourist destination for city dwellers in Sydney, it is an area of beaches, lakes, and vineyards and is known for its water activities, including sailing, canoeing, water skiing and fishing. Migration from the Sidney basin has resulted in significant urban growth and development in the Hunter and Central Coasts (HCC) basin since the 1990's.

Methodology: Using scenarios in combination with landscape ecology, biophysical modeling, social science, and GIS, this vulnerability assessment consisted of three major components:

1. Ecological vulnerability analysis (vulnerability of landscapes)
2. Economic vulnerability analysis (vulnerability of the regional economy)
3. Social vulnerability analysis (vulnerability of people and communities) (see Section 2.3.2)

The HCC case study used the IPCC's maximum A1F1 emission scenarios (95th percentile maxima projections) to inform the development of scenarios of sea level rise (SLR) and resulting flood extent in the 2030s and 2070s respectively. Maximum percentile projections were used as it was noted that IPCC predictions do not account for regional variability and maximum projections were of common use to the NSW government.

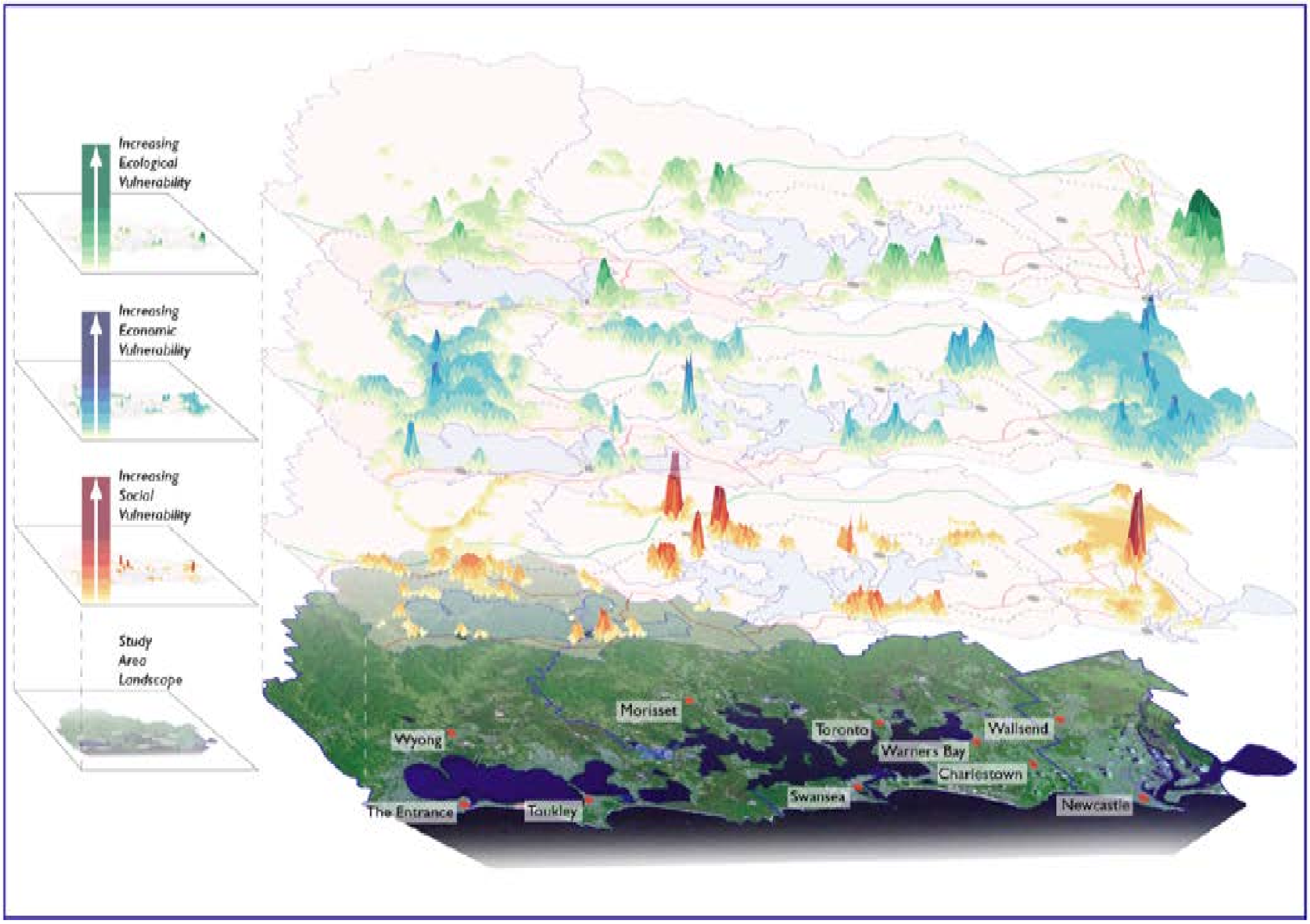
Landscape and Ecological Vulnerability: Historical data on maximum flood extents were used in combination with estimates of future rainfall intensity to identify land use classes of potential change in response to projections of sea-level rise. Seventeen socio-economic and ecological land-use / land cover (LULC) classes were derived based on current attributes to produce a model representing the current landscape (2007-08). Based on the assumption that future urban development and sprawl tend to follow historical trends, a future landscape model was developed using a combination of historical LULC change patterns and historical socio-economic and demographic change (namely, population, urban infrastructure, and industry growth) to develop emergent trajectories for the 2030s and 2070s. Spatial representation of ecological vulnerability was mapped as a 3D surface.

Economic Vulnerability: In this case study, economic vulnerability was defined as the sensitivity of the built environment to the impacts of sea level rise. For the purposes of the HCC case study, a risk assessment framework was used to assess the vulnerability of various types of built capital – port infrastructure, telecommunications systems, etc. To determine economic vulnerability, SLR projections together with flood extent data were superimposed on a digital elevation map (DEM) of infrastructure within the area.

Social Vulnerability Analysis: Social vulnerability of the HCC was determined first by using census data to construct social profiles of the study region, and secondly, by using both census data and household surveys to estimate social indicators of community sensitivity and adaptive capacity. Overall social vulnerability was calculated as an index aggregated from indicators of short- and long-term vulnerability, in addition to attitudinal predisposition to vulnerability. Short-term vulnerability was defined as a function of socio-economic disadvantage; physical capacity; family formation; ethnicity; visitors and caravans; and social isolation. Long-term vulnerability on the other had was defined as a function of socio-economic disadvantage; residential stability; relative disinclination to re-locate; satisfaction with neighbourhood; intention to remain in neighbourhood. Attitudinal predisposition was constructed from survey responses. Spatial representation of overall social vulnerability was mapped as a 3D surface.

The resulting 3D surface, or DEM, from each of the analysis above were spatially integrated to provide a useful overview of where the different types of vulnerabilities overlap geographically and therefore where particular attention is required when developing adaptation policies, plans, and disaster preparedness procedures (see Figure 18).

Figure 18: Graphical representation of ecological, economic, and social vulnerability to climate change in the Hunter and Central Coasts, Australia (Brunckhorst et al. 2011).



3.3 Alpine Watersheds in the Alps Region, Europe

European Environmental Agency (EEA). 2005b. Vulnerability and adaptation to climate change in Europe. EEA Technical Report No. 7 (2005), Copenhagen, Denmark. 84 pp.

Study Area: The Alps region covers a total land area of 190,000 km^2 and eight countries (Austria, France, Germany, Italy, Liechtenstein, Monaco, Slovenia, and Switzerland) with a range of 1,100 km long and 170 km wide. The average elevation is 2,500 m (max up to 4,800 m) above sea level with the ridges forming a barrier between maritime temperate and Mediterranean climates, thus creating a unique and complex regional climate.

The Alps provide a continuous and important source of water supply to the region, as well as ecosystem goods and services including wood products and hydro-power. The Alps region is also rich in biological diversity with 2,500 high alpine species living above the tree line alone.

Tourism in the Alps generates 50 billion euros annually. In some areas of the Alps, tourism represents the single most important source of income, and throughout the region, provides 10-12% of jobs.

As a mountainous, sub-arctic region, the Alps are particularly vulnerable to climate change and are already experiencing higher than average increases in temperature. Increasing temperatures are impacting snow-cover, snow pack and biodiversity in the region, while changes in precipitation patterns are resulting in more landslides and flash floods with consequences for infrastructure and settlements.

Methodology: This case study employed the collection, synthesis and consolidation of secondary data from a variety of initiatives, activities and assessments on risk, natural hazards, and climate change across the region (from Bavaria, Switzerland, Austria, etc). Given the importance of tourism to the local economy of the Alps region, the focus for assessing vulnerability and adaptation in this case study was on tourism and natural hazards.

A large-scale review of international, Canada-wide and regional activities, as well as hazard and risk assessments previously completed in the region was undertaken. Although such activities may not have addressed vulnerability or adaptation to climate change explicitly, the objectives of these studies included risk reduction and sustainable economic development through tourism. Some studies reviewed analysed climate data to detect trends in climate and extreme events (historical exposure), others had created detailed regional climate change scenarios for various time periods (future exposure), while other studies addressed impacts of climate change on winter tourism (potential impacts and sensitivity of the local economy).

The results of the review of secondary sources identified five vulnerability issues for the Alps region:

- increasing risk of economic losses during the winter tourism season
- increasing risk to settlements and infrastructure from natural hazards
- changing species richness (biodiversity) and ecosystem stability
- changing water balance (with direct impacts on hydro power, water supply, thermal and nuclear power station cooling facilites, and navigation)
- increasing risk to human health and tourism due to heat waves, flashfloods, and higher air pollution from increased traffic and energy consumption

3.4 The Arctic Water Resource Vulnerability Index, Alaska, U.S.A.

Alessa, L., A. Kliskey, R. Lammers, C. Arp, D. White, L. Hinzman, and R. Busey. 2008. The Arctic Water Resource Vulnerability Index: An integrated assessment tool for community resilience and vulnerability with respect to freshwater. Environmental Management. 42 (3): 523-541.

Study Area: The three Alaskan communities and associated watersheds of Eagle River, White Mountain, and Wales span a range of latitudes, environmental settings, and levels of human development (Figure 19). These communities range from several hundred (White Mountain and Wales) to several thousand people (Eagle River). All are situated in relatively undisturbed watersheds, as compared southern latitudes, though Eagle River is more urbanized than the others being located just outside of the major centre of Anchorage. All are situated in proximity to the coastline, though Wales is the only community located on the ocean. The watershed of Eagle River contains several large glaciers and receives high annual snowfall, while the watersheds around White Mountain and Wales are considered cold desserts and receive little snowfall.

Methodology: The Arctic Water Resource Vulnerability Index (AWRVI) was developed to address the lack of availability of an index for describing the vulnerability of water in Arctic conditions at the community level. This index characterizes vulnerability of a community and its watersheds as a function of two sub-indices: the surrounding physical conditions related to water supply and water quality, as well as the social conditions related to a community's social network and capacity to respond to disturbance (described below). These sub-indices are characterized by a set of constituent indices and related indicators, which are further informed by the best available and largely public data for these indicators. Though the north is highly sensitive to the effects of climate change, this index does not explicitly account for the effects of climate change by integrating future projections of changes in air temperature or precipitation.

Physical sub-index: This sub-index is defined by indicators that reflect the natural supply, municipal supply, water quality, permafrost, and subsistence habitat in a watershed. Specific indicators include measures of precipitation, surface water storage, and river runoff (to characterize natural supply), yield from water sources, diversity of water sources, water treatment technology, hydraulic gradient, and infrastructure reliant on permafrost (to characterize municipal supply), amount of upstream development and number of streams with water quality data (to characterize water quality), distribution of permafrost (to characterize permafrost), as well as the proportion of a watershed with fish recruiting streams and level of forest cover (to characterize subsistence habitats) (see Section

2.2.4 for descriptions of physical indicators for exposure and Section 2.3.1 for descriptions of physical and biological indicators for sensitivity).

Social sub-index: This sub-index is defined by indicators of knowledge, economics, informational capacity, and sensitivity to change. Specific indicators include measures of traditional and western knowledge, residency time of people in community (to characterize knowledge), average household income (to characterize economics), amount of land as a protected area (to characterize informational capacity), as well as importance of subsistence living, diversity of the social network, and the perception of water planning activities in the community (to characterize sensitivity to change) (see Section 2.3.2 for descriptions of sensitivity indicators for human communities and Section 2.4.1 for indicators for adaptive capacity).

A Delphi technique was used to reach consensus among water experts to define five categories of values for each indicator to reflect distinctions in the physical and social dimensions of vulnerability / resilience for a community and its watershed (i.e., highly vulnerable, moderately vulnerable, threshold, moderately resilient, highly resilient). These five categories are assigned scores between 0 and 1 to provide a common framework for comparing the very disparate types of indicators. All indicators are weighted equally in the final calculation to avoid the value judgements required for such weightings. The constituent indices, sub-indices, and overall index is calculated using a simple averaging technique based on the following generic formula:

AWRVI = (Physical sub-index + Social sub-index) / 2

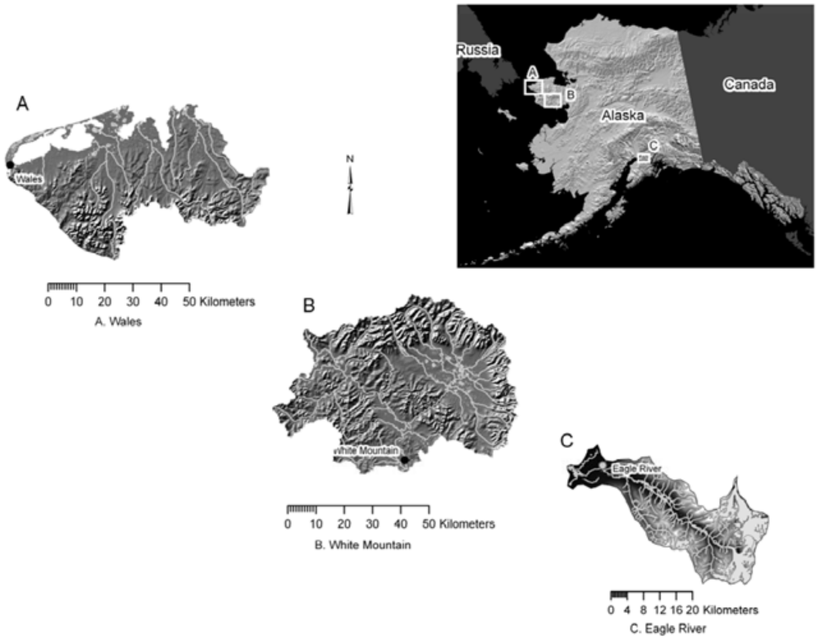
Physical sub-index = (natural supply indicators + municipal supply indicators + water quality indicators + permafrost indicator + subsistence habitat indicators) / 5

Social sub-index = (knowledge indicators + economic indicator + information capacity indicator + sensitivity change indicators) / 4

Indicators with missing data are removed from this calculation and a lack of data score is calculated to provide a level of confidence in the AWRVI score.

Overall, the index provided a useful and informative relative ranking of the overall vulnerability of communities and watersheds, the results of which were corroborated by independent experts. Importantly, its constituent components were further useful as a diagnostic tool to understand which parts of the social-ecological system was most vulnerable or most resilient to disturbance.

Figure 19: Location of the communities and watersheds (A – Wales, B – White Mountain, and C – Eagle River) for which the Arctic Water Resource Vulnerability Index has been applied in Alaska, U.S.A. (Alessa et al. 2008)



3.5 Drought and Excessive Moisture Preparedness Plan, Saskatchewan, Canada

Rowan, K., J. Pittman, V. Wittrock, and A. Unvoas, 2011. Swift Current Creek Watershed Drought and Excessive Moisture Preparedness Plan. Saskatchewan Watershed Authority, 40 pp.

Study Area: The Swift Current Creek Watershed is located in southwestern Saskatchewan. It begins in the Cypress Hills, a high plateau that contains a mix of forests, wetlands and grasslands and then winds across 160 km of prairie to flow into the South Saskatchewan River. Most of the watershed is typically very dry with an annual precipitation of 350 mm and residents rely on the creek for water supply, irrigation, livestock production and recreation. Threats to water quality and quantity include climate change, growth in water demand, drought and floods (excessive moisture).

Methodology: Three workshops involving watershed stakeholders were held to identify their vulnerability and resilience to drought and excessive moisture. The stakeholders participated in five activities and the results of these activities were used to determine exposure, sensitivity and adaptive capacity of the community. The five activities are described below.

1. Participatory Mapping: Workshop participants were asked to identify on a map of the watershed the areas and infrastructure previously affected by drought and flooding.
2. Timeline: The impacts and adaptation from past drought and flood events was constructed through group discussion.

3. Drought and Excessive Moisture Characterization: The basis of this activity is a scientific analysis that identified the top ten extreme drought and excessive moisture events between 1901 and 2005. The two methods used to do this included The Palmer Drought Severity Index and the Standardized Precipitation Index. The results for the wettest and driest years from each of the methods were placed on a map on the watershed to show how impacts vary across the watershed. An exercise for the workshop participants was to overlay these maps on the map developed in the first activity to determine more about potential impacts. It was found that the potential impacts of drought may have been greater in the southwestern portion of the watershed.
4. Scenario Planning: The results from the mapping and timeline exercises were used to develop various scenarios that were considered and addressed by workshop participants. The three scenarios were:
    1. A wet year like 2010 happened twice in 5 years;
    2. A long-term drought (lasting longer than previously experienced) occurred; and
    3. A wet year alternated with a dry year in a continuing cycle.

5. Information Requirements: During the third workshop, participants were asked to complete a questionnaire to determine the information that is relevant to them.

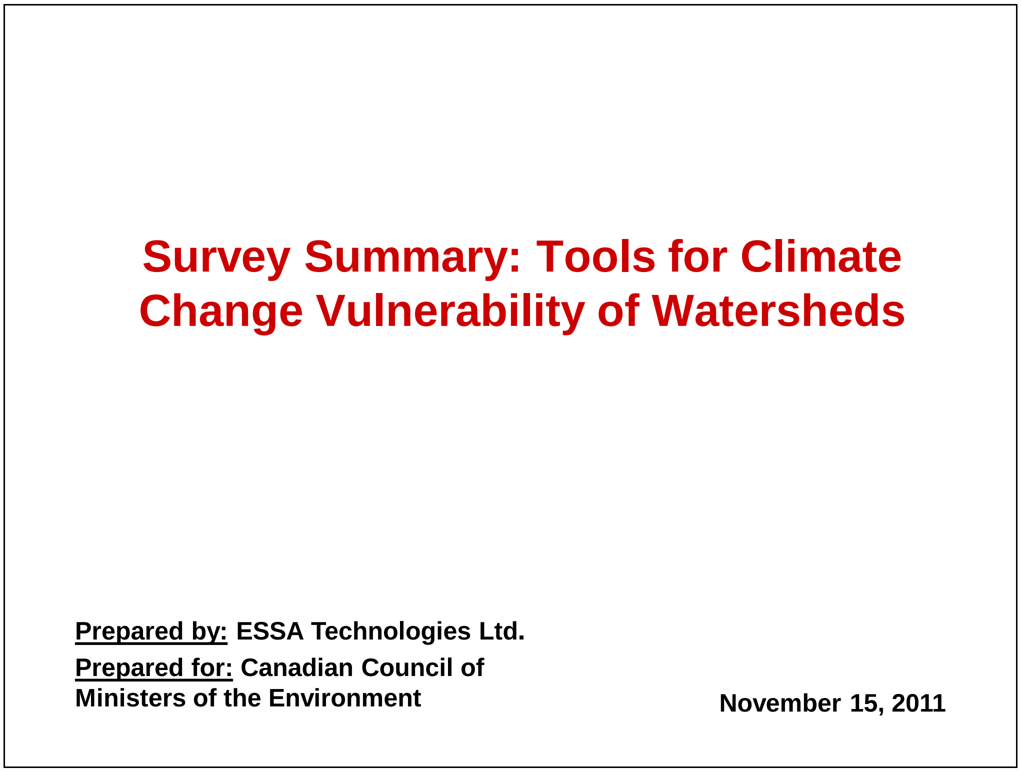
Potential adaptive responses were also identified by workshop participants who discussed three vulnerability issues that were identified as relevant to the watershed:

1. Municipal Preparedness;
2. Awareness/Education on benefits of being proactive; and
3. Agriculture.

Action items were identified for each vulnerability issue and the stakeholders rated the actions items as either low, medium or high priority. Then the items were categorized as being applicable to preparedness, response, or recovery for drought or flood.

Since the climate, technology, scientific understanding and the community are changing, adaptive planning and responses will need to be periodically assessed.

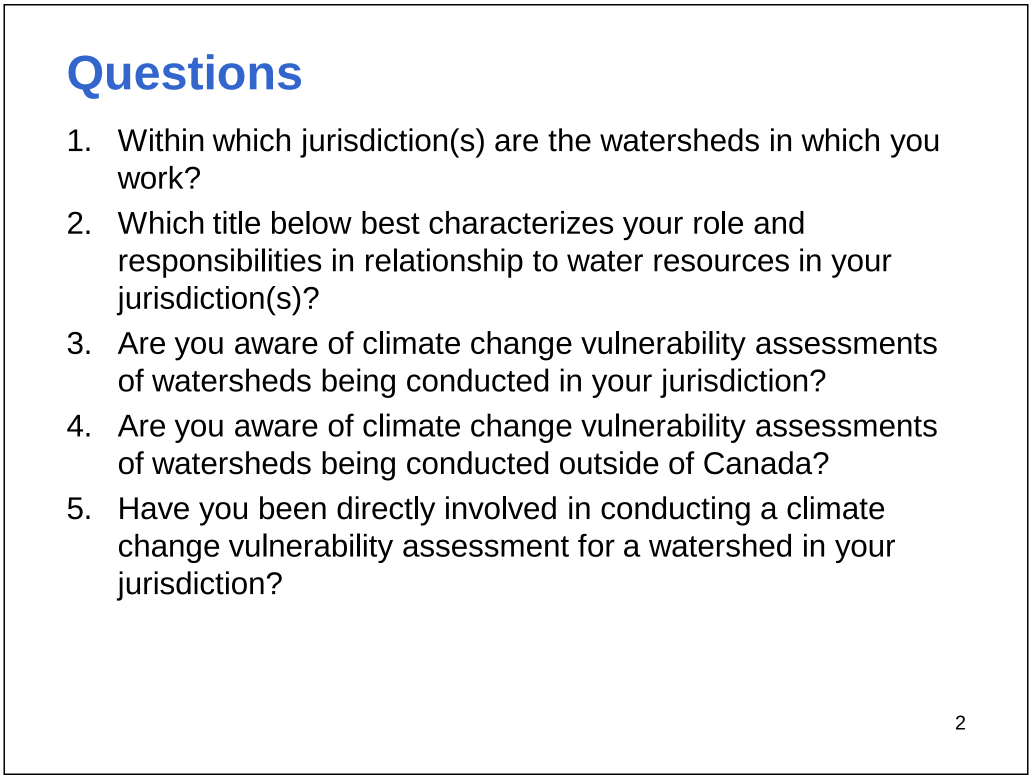
APPENDIX A: SUMMARY OF JURISDICTIONAL SURVEY



Survey Summary: Tools for Climate Change Vulnerability of Watersheds

Prepared by: ESSA Technologies Ltd.
Prepared for: Canadian Council of Ministers of the Environment

November 15, 2011

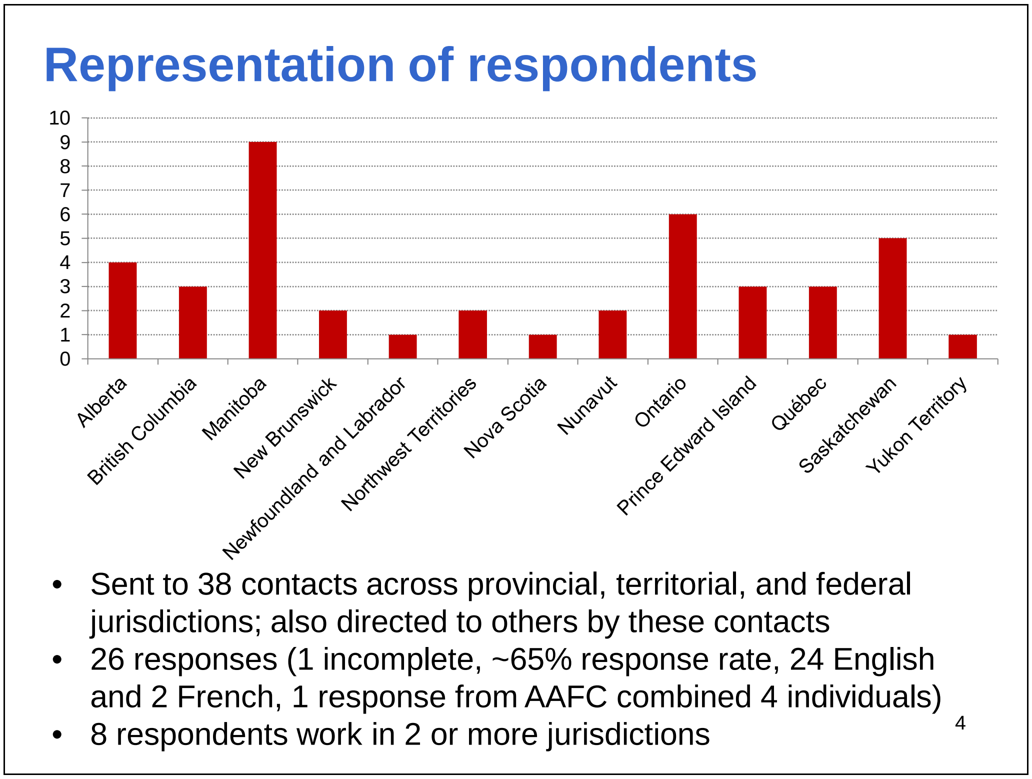


Questions

1. Within which jurisdiction(s) are the watersheds in which you work?
2. Which title below best characterizes your role and responsibilities in relationship to water resources in your jurisdiction(s)?
3. Are you aware of climate change vulnerability assessments of watersheds being conducted in your jurisdiction?
4. Are you aware of climate change vulnerability assessments of watersheds being conducted outside of Canada?
5. Have you been directly involved in conducting a climate change vulnerability assessment for a watershed in your jurisdiction?

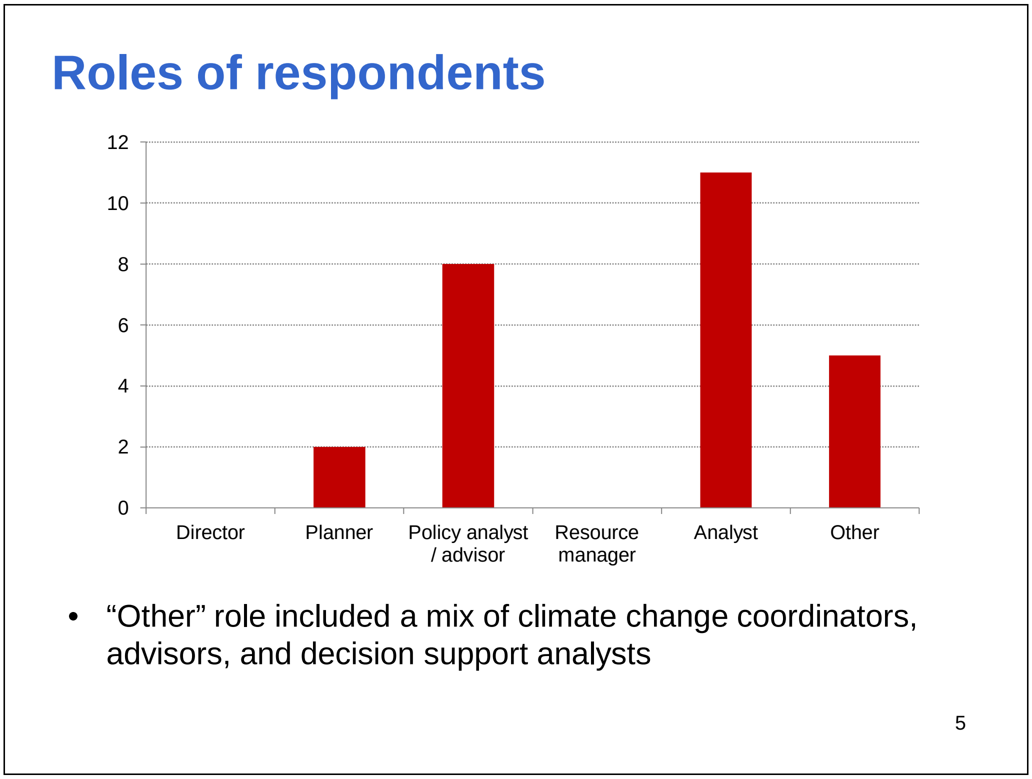
Questions

6. Please provide a brief description of examples of climate change vulnerability assessments of watersheds in your jurisdiction(s).
7. Please provide a brief description of any tools / methods to assess vulnerability of watersheds to climate change in your jurisdiction(s).
8. Please direct us to any readily available documentation that we can use to gain more information about the vulnerability assessments or tools / methods described above.
9. Which statement(s) below best describe your specific needs for information to understand the vulnerability of watersheds to climate change in your jurisdiction(s)?



Representation of respondents

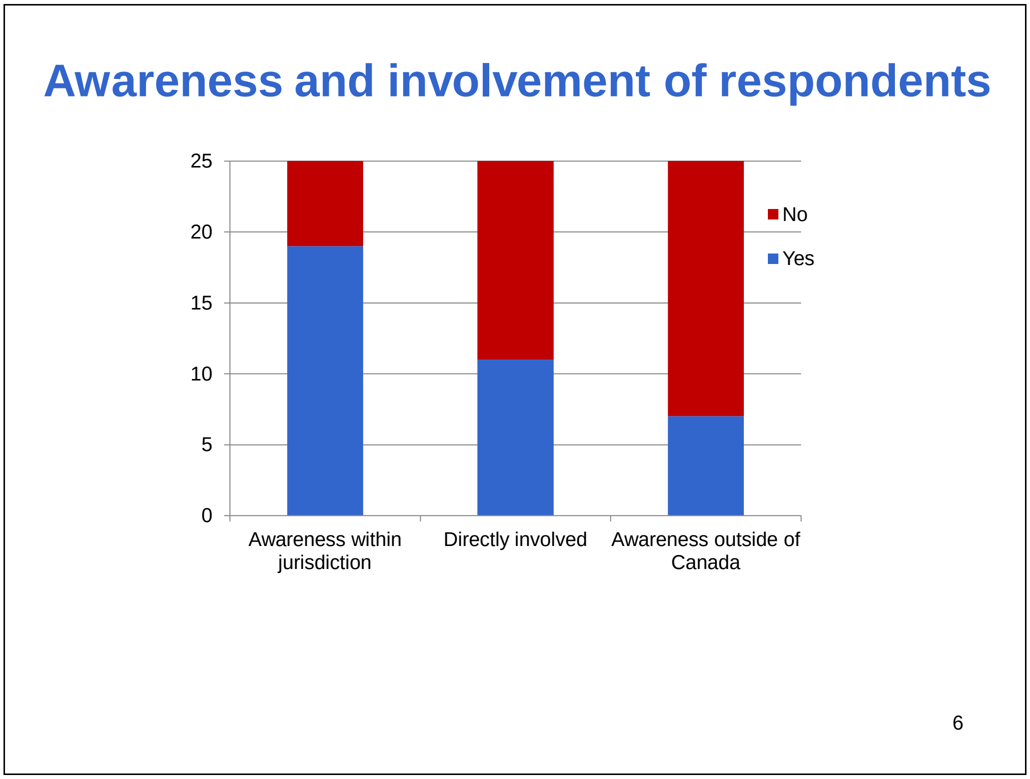
- Sent to 38 contacts across provincial, territorial, and federal jurisdictions; also directed to others by these contacts
- 26 responses (1 incomplete, ~65% response rate, 24 English and 2 French, 1 response from AAFC combined 4 individuals)
- 8 respondents work in 2 or more jurisdictions



Roles of respondents

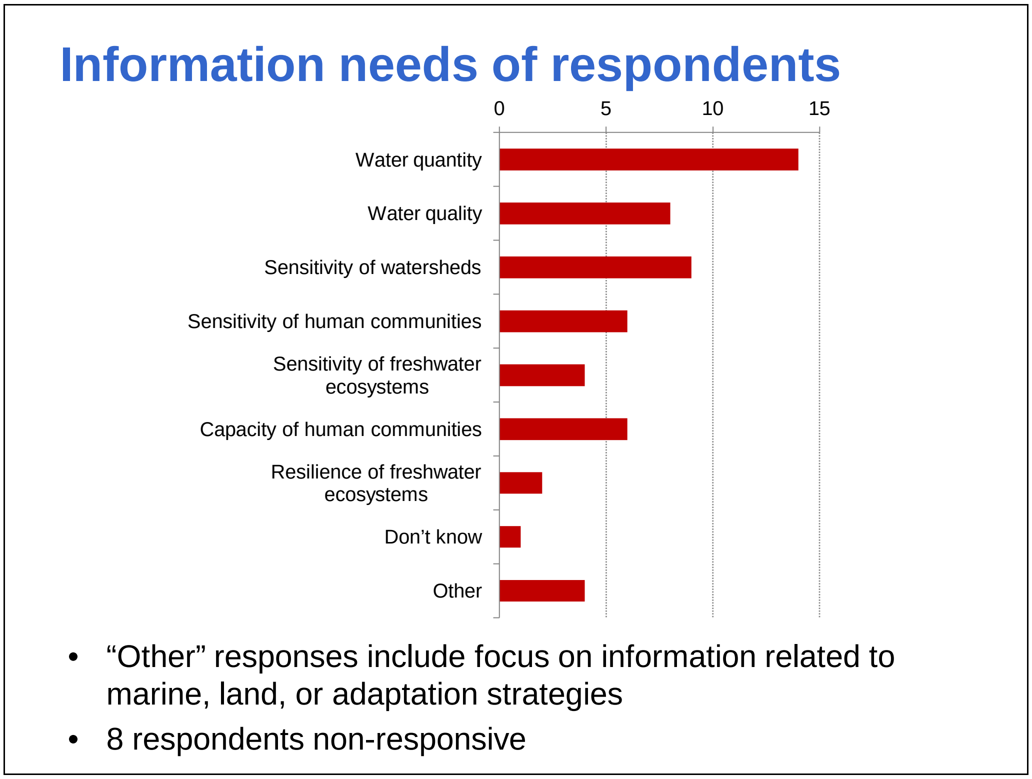
- “Other” role included a mix of climate change coordinators, advisors, and decision support analysts

5



Awareness and involvement of respondents

6



Information needs of respondents

- “Other” responses include focus on information related to marine, land, or adaptation strategies
- 8 respondents non-responsive

International case studies

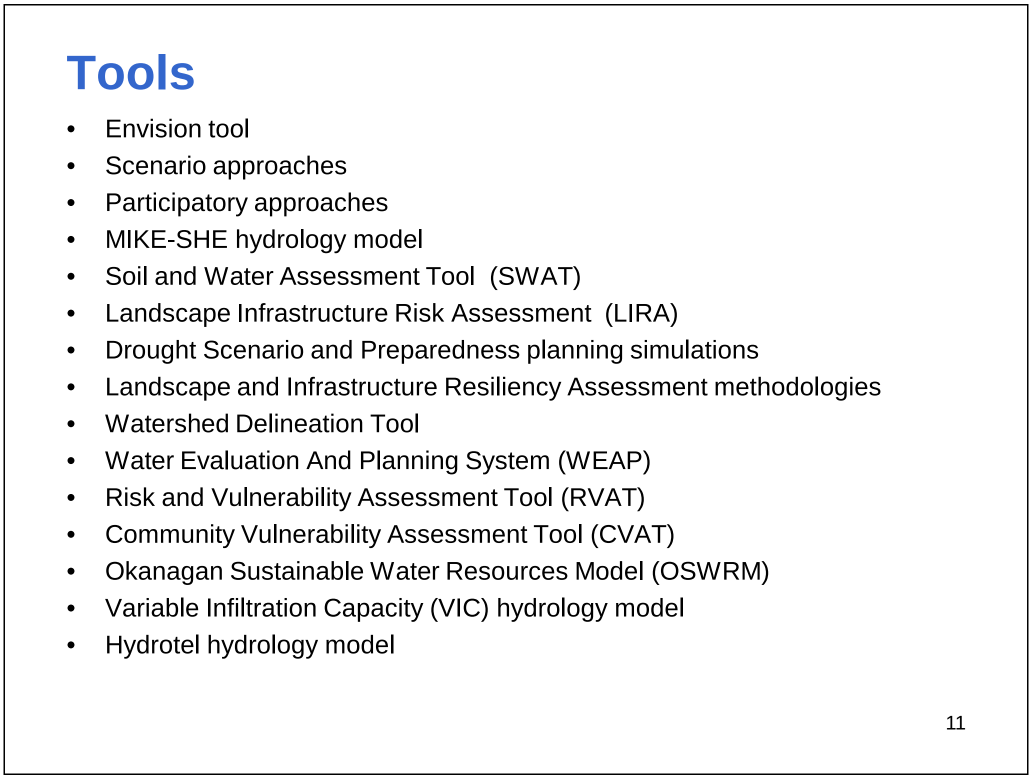
- Skagit Climate Science Consortium: http://www.skagitclimatescience.org/
- UKCIP: http://www.ukcip.org.uk/
- Partnership for Canada-Caribbean Community Climate Change Adaptation (ParCA): http://www.bulletin.uwaterloo.ca/2011/jul/19tu.html
- Coastal Climate Adaptation Strategies, North America: http://www.coastalchange.ca/
- Willamette Water 2100 (Oregon, USA): http://envision.bioe.orst.edu/StudyAreas/WW2100/WW2100.htm
- Vulnerability assessment of Lake Balaton, Hungary: http://www.iisd.org/measure/tools/assessment/balaton.asp
- Institutional Adaptations to Climate Change Project (Canada-Chile): http://www.parc.ca/mcri/
- Vulnerability and Adaptation to Climate Extremes in the Americas (VACEA) http://www.parc.ca/vacea/
- Various Canadian and international scenario based approaches: http://www.iisd.org/adaptation/research/

Canadian case studies

- **North:**
  - Mackenzie River Basin
  - City of Whitehorse
  - Vulnerability of Cryospheric and Socio-Economic Systems
  - Yukon Colleges Northern Climate Exchange
- **British Columbia:**
  - Okanagan River Basin Supply / Demand Study
- **Prairies:**
  - Assiniboine River Water Demand Impact Study
  - Red River-Assiniboine integrated watershed modeling
  - South Saskatchewan River Basin Study
  - Vermilion River watershed
  - Prairie Adaptation Research Collaborative
  - Prairies Regional Adaptation Collaborative
  - Drought Research Initiative

Canadian case studies

- **Ontario:**
  - Various Conservation Authorities
  - International Upper Great Lakes Study
  - Lake Simcoe Climate Change Project
  - Rideau Valley watershed
- **Québec:**
  - Châteauguay river basin
  - Eastern Townships
- **Atlantic:**
  - Towns of Souris, Rustico, Victoria, Mount Stewart
  - Hillsborough River watershed
  - North Shore ws -- Lennox Island to Savage Harbour
  - Bras d'Or lakes
- **National:**
  - NRCAN Regional Adaptation Collaboratives
  - AAFC Watershed Evaluation of Beneficial Management Practices
  - AAFC / EC Land Use Modeling Decision Support Unit



Tools

- Envision tool
- Scenario approaches
- Participatory approaches
- MIKE-SHE hydrology model
- Soil and Water Assessment Tool (SWAT)
- Landscape Infrastructure Risk Assessment (LIRA)
- Drought Scenario and Preparedness planning simulations
- Landscape and Infrastructure Resiliency Assessment methodologies
- Watershed Delineation Tool
- Water Evaluation And Planning System (WEAP)
- Risk and Vulnerability Assessment Tool (RVAT)
- Community Vulnerability Assessment Tool (CVAT)
- Okanagan Sustainable Water Resources Model (OSWRM)
- Variable Infiltration Capacity (VIC) hydrology model
- Hydrotel hydrology model

APPENDIX B: SUMMARY OF WATER QUANTITY TOOLS

Note the use of the following abbreviations in the table below: LM (site level, one dimensional, or lumped numerical model), SD (semi-distributed numerical model), FD (fully-distributed numerical model), SM (statistical model), or I (index). In some cases these tools also address water quality issues and are denoted as such using WL (water quality tool).

Model name	LM	SD	FD	SM	I	WL	Example Regions	Citation	Comments
ACRU (Agricultural Catchments Research Unit)		X				X	-Africa -Alberta -New Zealand	-Beckers et al. 2009c	-Multi-purpose -Flexible spatial structure
BATS (Biosphere-Atmosphere Transfer Scheme)			X				-California	-Snyder et al. 2004	-Land surface model
BROOK90	X						-Alberta -Arizona -Germany	-Beckers et al. 2009a -Beckers et al. 2009c	-Site level water balance model
CANWET (Canadian Water Evaluation Tool)	X					X	-Ontario	-Walters 2011 -Greenland Technologies Group Ltd.	
CASC2D			X			X		-Cunderlink 2003	
CATCHMOD	X						-UK	-Lopez et al. 2009	
CEQUEAU			X				-Quebec	-Cunderlink 2003	
Hydrology routine coupled to CGCM (Canadian Centre for Climate Modeling and Analysis Coupled General Circulation Model)			X				-Globally	-Arora and Boer 2001	-Macro-scale -Coupled with flow routing algorithm
CLASS (Canadian Land Surface Scheme)			X					-Beckers et al. 2009c	
CRHM (Cold Regions Hydrology Model)		X					-Canada	-Beckers et al. 2009a -Pomeroy et al. 2007 -Beckers et al. 2009c	
DHSVM (Distributed Hydrology Soil Vegetation Model)			X			X	-US Pacific Northwest -British Columbia	-Water Management Consultants 2008 -Beckers et al. 2009a -Battin et al. 2007 -US Environmental Protection Agency 2011 -Beckers et al. 2009c	

Model name	LM	SD	FD	SM	I	WL	Example Regions	Citation	Comments
Hydrology routine coupled to ECHAM			X					-Wild et al. 1995	-Runoff not addressed
EFAS (European Flood Alert System)			X					-UNFCCC 2008	-In development -Generates 3-10 day advance flood probability information
ForWaDy & ForHyM	X						-Atlantic Canada -British Columbia	-Beckers et al. 2009a -Beckers et al. 2009c -Arp & Yin 1992	
GAWSER (Guelph All-Weather Storm-Event Runoff)		X				X	-Ontario	- EBNFLO Environmental and AquaResource Inc. 2010	
GAWSER/GRIFFS (Guelph All Weather Sequential Event Runoff / Grand River Integrated Flood Forecasting System)			X					-Cunderlink 2003	
HBV (Hydrologiska Byråns Vattenbalansavdelning Model)		X				X	-Globally	-Akhtar et al. 2008 -Batimaa et al. 2011 -Cunderlink 2003 -Beckers et al. 2009c -Whitehead et al. 2011 -Water Management Consultants 2008—	-Several versions of the model, including the HBV-EC ("Environment Canada") model
HEC-HMS (US Army Corps of Engineers Hydrologic Engineering Centre Hydrologic Modeling System)		X					-Canada -US	-Hebb & Mortsch 2007 -Simonovic 2010 -Cunderlink 2003 -Beckers et al. 2009c -Cunderlik & Simonovic 2004 -Kang & Ramirez 2007 -Water Management Consultants 2008	-Event-based model -Inverse vulnerability assessment approach (Simonovic)
HELP (Hydrologic Evaluation of Landfill Performance)	X						-British Columbia	-Beckers et al. 2009c	
HFAM (Hydrocomp Forecast and Analysis Modeling)		X						-Cunderlink 2003	
HSAMI Hydrological Model	X						-Quebec	-Minville et al. 2010	
HSPF (Hydrological Simulation Program-FORTRAN Model)		X				X	-Globally	-US Environmental Protection Agency 2009;	-Available within BASINS CAT

Model name	LM	SD	FD	SM	I	WL	Example Regions	Citation	Comments
								2011 -Cunderlink 2003 -Imhoff et al. 2007 -Beckers et al. 2009c -Johnson & Weaver 2009	-Has been coupled to a climate model
HydroGeoSphere		X				X	-North America	-Beckers et al. 2009c	
HYDROTEL			X				-Canada	-Cunderlink 2003	
Indicators of Hydrologic Alteration (IHA)					X		-North Carolina	-Richter et al. 1996	-Statistical summary of hydrologic response dynamics -Not dynamic
IHACRES (Identification of Unit Hydrographs and Component Flows from Rainfalls, Evaporation and Streamflow Data Model)	X							-Cunderlink 2003	
INCA (Integrated Catchment Model)		X				X	-Globally	-Whitehead et al. 2011	
MIKE BASIN		X				X	-Globally	-UNFCCC 2008	-Advanced water resource simulation system -Rainfall-runoff only
MIKE SHE			X			X	-North America -Australia -UK -Europe	-Cunderlink 2003 -Beckers et al. 2009c -Graham & Butts 2005 -Water Management Consultants 2008	-Flexible spatial structure
MODHMS		X					-USA -Australia	-Beckers et al. 2009c	-Combines MODFLOW and HEC-HMS
OSWRM (Okanagan Sustainable Water Resources Model)		X					-British Columbia	-UNFCCC 2008	-Designed specifically for the Okanagan basin
PDM (Probability Distributed Moisture Model)	X						-UK	-Prudhomme & Davies 2009a,b	
Modified PDSI (Palmer Drought Severity Index)					X		-Globally	-Dai 2011	
P-PET drought index					X		-Canadian Prairie	-Marchildon et al. 2007	

Model name	LM	SD	FD	SM	I	WL	Example Regions	Citation	Comments
PLAN2ADAPT					X		-Canada	-Pacific Climate Impacts Consortium	
PREVAH (Precipitation-Runoff-Evapotranspiration-Hydrotope)		X					-Europe	-Beckers et al. 2009c	
PRMS (Precipitation-Runoff Modeling System)		X				X	-USA	-Cunderlink 2003 -USGS -Wilby et al. 2000 -Beckers et al. 2009c -Hay et al. 2002 -Water Management Consultants 2008	
RHESSys		X				X	-North America -Europe	-Beckers et al. 2009a -Beckers et al. 2009c	
RIVFLOC		X				X	-Northern Canada	-Cohen 1997	
SAC-SMA (Sacramento Soil Moisture Accounting Model)	X						-California	- Miller 2003	
SIMGRO (Simulation of Groundwater and Surface Water Levels)			X				-Netherlands	-Querner et al. 2007	
SLURP (Semi-distributed Land Use-based Runoff Processes)		X						-Water Management Consultants 2008	
SRM (Snowmelt-Runoff Model)	X						-Globally	-Cunderlink 2003	
SSARR (Streamflow Synthesis and Reservoir Regulation)		X					-North America	-Cunderlink 2003 -Beckers et al. 2009c	
STREAM (Spatial Tools for River Basins and Environment and Analysis of Management Options)		X					-Globally	-UNFCCC 2008 -Aerts et al. 1999	-Advanced water resource simulation system
SWAT (Soil and Water Assessment Tool)		X				X	-Globally	-Takle et al. 2006 -Zhang et al. 2011 -Parajuli 2010 -Nunes et al. 2007 -Cunderlink 2003 -Ficklin et al. 2009 -Beckers et al. 2009c -Neitsch et al. 2011	
SWMM (Storm Water Management Model)		X				X		-Cunderlink 2003	-Urban runoff
Thornthwaite Monthly Water	X							-McCabe & Markstrom	-Site level water

Model name	**LM**	**SD**	**FD**	**SM**	**I**	**WL**	**Example Regions**	**Citation**	**Comments**
Balance Model								2007	balance model
TOPMODEL		X						-Cunderlink 2003	
UBC-UF Peak Flow Model			X					-Beckers et al. 2009c	-Under development
UBCWM (UBC Watershed Model)		X					-British Columbia	-Whitfield et al. 2003 -Beckers et al. 2009a -Morrison et al. 2002 -Beckers et al. 2009c -Merritt et al. 2006 -Cohen & Neale 2006 -Water Management Consultants 2008	
Unnamed					X			-Barnes et al. 2009	
Unnamed					X			-Furniss et al. 2010	
Unnamed					X		-USA northeast	-Hayhoe et al. 2006	
Unnamed					X		-USA	-Hurd et al. 1999	
Unnamed					X		-Southern USA	-Nestler and Long 1997	
Unnamed					X		-Europe	-Nixon et al. 2003	
Unnamed				X			-Oregon	-Nolin et al. 2005	-Regression
Unnamed				X			-Atlantic Canada	Swansburg et al. 2004	-Regression
Unnamed							-Philippines	-Tiburan et al. 2010	
Unnamed				X			-Atlantic Canada	-Turkkan et al. 2011	-Artificial neural network analysis
Unnamed					X		-North America	-UNEP 2009	
Unnamed					X		-Northern BC	-Wei and Zhang 2010	
VIC (Variable Infiltration Capacity Model)			X				-North America	-Crozier et al. 2007 -Hayhoe et al. 2006 -Lasco et al. 2010 -Beckers et al. 2009c -Water Management Consultants 2008	-Macro-scale -Available within SEA BASINS
WARMF (Watershed Analysis Risk Management Framework)		X				X	-California	-US Environmental Protection Agency 2011	
WaSiM-ETH (Wasserhaushalts-Simulations-Modell)			X				-Europe	-Beckers et al. 2009a -Beckers et al. 2009c	
WaSSI (Water Supply Stress Index)					X		-USA	-Sun et al. 2008	-A demand/supply ratio
WATBAL (Hydrological Water Balance Model)	X						-Africa -Eastern Europe	-Tarekegn & Tadege 2006 -Cunderlink 2003	

Model name	LM	SD	FD	SM	I	WL	Example Regions	Citation	Comments
								-Chirila et al. 2008	
WATCLASS			X					-Beckers et al. 2009c -Kouwen et al	-Combines WATFLOOD & CLASS
Water Balance Model by QUALHYMO		X				X		-Beckers et al. 2009c	-Online decision support tool
WaterCAST		X				X	-Australia	-BMT WBM 2010 -Cook et al. 2009	
WATFLOOD			X				-Canada	-Cunderlink 2003 -Beckers et al. 2009c -Kouwen et al -Water Management Consultants 2008	
WEAP (Water Evaluation and Planning System)		X				X	-Globally	-Purkey et al. 2008 -Harris 2007 -UNFCCC 2008 -Yates et al. 2005	-Advanced water resource simulation system
WEPP (Water Erosion Prediction Project)		X				X	-Oregon -California	-Beckers et al. 2009c	
WRENSS (WinWrnsHyd and ECA-AB)	X						-Western Canada	-Beckers et al. 2009c	

APPENDIX C: SUMMARY OF WATER QUALITY TOOLS

Note the use of the following abbreviations in the table below: T (water temperature), S (sediments), DS (dissolved solids), N (nutrients), C (contaminants), LM (site level, one dimensional, or lumped numerical model), SD (semi-distributed numerical model), FD (fully-distributed numerical model), and SM (statistical model). In some cases these tools also address water quantity issues and are denoted as such using WN (water quantity tool).

Model name	T	S	DS	N	C	LM	SD	FD	SM	WN	Example Regions	Citation
ACRU (Agricultural Catchments Research Unit)	X			X			X				-Africa -Alberta -New Zealand	-Beckers et al 2009c
Aquatox	X	X		X	X						-USA	-Park & Clough 2009
CANWET (Canadian Water Evaluation Tool)		X		X	X	X				X	-Ontario	-Walters 2011 - Greenland Technologies Group Ltd.
CASC2D		X						X				-Cunderlink 2003
DHSVM (Distributed Hydrology Soil Vegetation Model)		X						X			-US Pacific Northwest -British Columbia	-Water Management Consultants 2008 -Beckers et al 2009a -Battin et al 2007 -US Environmental Protection Agency 2011 -Beckers et al 2009c
EPD-RIV1 (One Dimensional Riverine Hydrodynamic and Water Quality Model)	X			X	X	X					-USA	-US EPA http://epa.gov/athens/wwqtsc/html/epd-riv1.html
FJQHW97	X					X					-British Columbia	-Foreman et al 2001 -Morrison et al 2002
ForWaDy & ForHyM				X		X				X	-Atlantic Canada -British Columbia	-Beckers et al 2009a -Beckers et al 2009c -Arp & Yin 1992
HBV (Hydrologiska Byråns Vattenbalansavdelning Model)		X	X	X			X				-Globally	-Akhtar et al 2008 -Water Management Consultants 2008 -Batimaa et al 2010 -Cunderlink 2003 -Beckers et al 2009c

Model name	**T**	**S**	**DS**	**N**	**C**	**LM**	**SD**	**FD**	**SM**	**WN**	**Example Regions**	**Citation**
HSPF (Hydrological Simulation Program-FORTRAN Model)	X	X	X	X	X		X				-Globally	-US Environmental Protection Agency 2009b; 2011 -Cunderlink 2003 -Imhoff et al 2007 -Beckers et al 2009c -Johnson & Weaver 2009
HydroGeoSphere	X	X		X	X		X				-North America	-Beckers et al 2009c
INCA (Integrated Catchment Model)		X	X	X	X		X				-Globally	-Whitehead et al. 2011
Intragravel Temperature Diffusion Model	X					X					-New Brunswick	-Caissie & Satish 2001
MIKE BASIN				X	X		X				-Globally	-UNFCCC 2008
MIKE SHE				X	X			X			-North America -Australia -UK -Europe	-Water Management Consultants 2008 -Cunderlink 2003 -Beckers et al 2009c -Graham & Butts 2005
PRMS (Precipitation-Runoff Modeling System)		X					X				-USA	-Water Management Consultants 2008 -Cunderlink 2003 -USGS
QUAL2K (River and Stream Water Quality Model)	X	X	X	X	X	X						-US EPA http://epa.gov/athens/wwqtsc/html/qual2k.html
RHESSys				X			X				-North America -Europe	-Beckers et al 2009a -Beckers et al 2009c
RIVFLOC		X					X				-Northern Canada	-Cohen 1997
SWAT (Soil and Water Assessment Tool)	X	X		X	X		X				-Globally	-Takle et al 2006 -Zhang et al 2011 -Parajuli 2010 -Nunes et al 2007 -Cunderlink 2003 -Ficklin et al 2009 -Beckers et al 2009c -Neitsch et al 2011

Model name	T	S	DS	N	C	LM	SD	FD	SM	WN	Example Regions	Citation
SWMM (Storm Water Management Model)					X		X				-Urban runoff	-Cunderlink 2003
Unnamed	X								X		-Idaho	-Isaak et al 2010a
Unnamed	X								X		-Nova Scotia	-MacMillan et al 2005
WARMF (Watershed Analysis Risk Management Framework)	X	X		X	X		X				-California	-US Environmental Protection Agency 2011
WASP (Water Quality Analysis Simulation Program)	X			X	X			X			-USA	-US EPA http://epa.gov/athens/wwqtsc/html/wasp.html
Water Balance Model by QUALHYMO		X					X					-Beckers et al 2009c
WaterCAST		X		X	X		X				-Australia	-BMT WBM 2010 -Cook et al 2009
WEAP (Water Evaluation and Planning System)	X			X	X		X				-Globally	-Purkey et al 2008 -Harris 2007 -UNFCCC 2008 -Yates et al 2005
WEPP (Water Erosion Prediction Project)		X					X				-Oregon -California	-Beckers et al 2009c

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