Research Plan for Hydrologic Impacts

Program Definition (2007 – 2010)

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Executive Summary

Adequate water resources and hydropower generation are essential elements of the economy and foundation for urban life in British Columbia. In light of recent concerns about global climate change, climate variability, and extreme weather events, it is prudent to assess historical records and estimate future impacts. Results of current research repeatedly document increasing concern for the impacts of global climate change. There is substantial evidence from several sources that profound changes in the quantity, timing and composition of the hydrological system are already underway in BC and Pacific North America, and projections of future hydrological impacts will have important implications. A more complete understanding is needed of changes to water resources and water balance components anticipated in British Columbia.

This Research Plan is a companion document to the Letter of Agreement (January 2007) between the Pacific Climate Impacts Consortium (PCIC) and BC Hydro. The initial step is a program definition[1] that is outlined in this Research Plan. This plan must define a strategy to bring current research results to bear on our common objective: *to assess the impacts of climate change on water resources for hydroelectric power generation in BC and neighbouring watersheds*. This strategy includes a program of applied research that will be accomplished over a 4-year period by the Consortium and its staff. Four projects are described:

- Climate Overview
- Diagnostic Hydrologic Modelling
- Regional Climate Model Diagnostics
- Synthesis and Applications

The Climate Overview is a foundation for subsequent projects. This project has already been initiated with a proposal and a funded contract. A workshop was conducted and a final report was written.

The strategy for subsequent projects is to utilize existing hydrologic research models and quantitative, diagnostic tools that have been developed in a research environment, or developed in other regions or for other applications, and apply them to sub-regions and watersheds of British Columbia. As a further provision, high resolution hydrologic models may be necessary for smaller watersheds. Regarding climate modelling, however, the strategy is to utilize the output of the Canadian RCM and the diagnostic tools that are available without any intention of operating the atmospheric model. Detailed proposals for these projects will be submitted for consideration as separate contracts.

The responsibility for accomplishing the work described in this plan lies with the staff of the PCIC Consortium and will be accomplished with energetic collaboration of its member organizations and affiliates. A substantial increment in technical personnel is required—in addition to collaboration. For hydrologic modelling we intend to work with the Center for Science in the Earth System (CSES) at the University of Washington, the Water and Climate Impacts Research Center (W-CIRC) at the University of Victoria, and the River Forecast Center (RFC) in the BC Ministry of Environment. For diagnostics of the Canadian Regional Climate Model (CRCM), we intend to rely on the Consortium Ouranos, Montréal, as well as the Canadian Climate Centre for modelling and analysis (CCCma) of Environment Canada at the University of Victoria. Agreements with several of these organizations are tacit and will be developed further as a first step of this research plan.

[1] - A Program Definition was initiated with a letter-proposal to BC Hydro (4 April 2006). The first draft of this research plan was written by A.T. Werner (January 2007).

1. Introduction

Climate change is influencing the spatial and temporal distribution of water on a global scale. Changes over the last century in seasonal temperature, precipitation and streamflow patterns, and more frequent occurrences of droughts and floods have become increasingly apparent. These changes are projected to continue into the future, but with increasing intensity. Distributions of species and land cover patterns are also being altered, and these, in turn, feedback to cause changes in climate and hydrology. Although British Columbia (BC) is currently a water-rich region, these changes threaten current water resources as we have known them, and responsible management of water is paramount to secure a clean and abundant resource into the future.

The hydro-climatology of Pacific North America (Figure 1) is complex, in part due to its close proximity to the Pacific Ocean, mountainous terrain, and large latitudinal expanse. Historical changes to climate and hydrology have been documented in British Columbia (PCIC, 2007b) and are attributable to both climate change and climate variability, such as teleconnection patterns coming from El Niño/Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO). Moreover, the prevalence of snowpack and glaciers in BC and the sensitive response of these cryospheric components to climate change increases susceptibility to hydrologic impacts. Hence, effective water management strategies require understanding of the current state of the hydro-climatic system, and how the system is projected to change in the future.

Figure 1 – Pacific North America. The region of green defines all watersheds with headwaters in British Columbia.

More information on the impacts of climate change on water resources is desired by the community of water users (Swain, 2007b). Hydrologic models that quantify the impacts of regional climate change on water resources and provide future projections of hydrologic impacts are required for those water users who are struggling to plan with inadequate information. This information is necessary for mitigation, adaptation to climate change, or to plan for climate change impacts.

There are substantial challenges in constructing projections of the future climate change influences on water resources in BC. The scope of work to create a hydrologic model and to project impacts of climate change on water resources is beyond the capability of most water users or any single community. Moreover, within BC there are limited observational data available in a complex terrain. Additionally, it is difficult to estimate some of the data which is critical to setting the parameters of a physical model. Although hydrologic models have been developed for research investigations, the results are specialized, uncertain, or not widely applied. Secondly, climate change scenarios from global climate models (GCMs) are needed, and these results must be downscaled to regional watersheds. Finally, a physical model of the watershed is needed that incorporates all of the components of the hydrologic system such as glaciers, accumulated snowpack, runoff, changes in soil moisture, and evapotransporation. These challenges further substantiate the need for collaboration between government, academics and industry to develop hydrologic models to estimate climate change impacts on water resources.

To address these challenges, the Pacific Climate Impacts Consortium (PCIC; Attachment A1) was conceived. The mission of PCIC is to assess climate impacts and stimulate collaboration of government, academe, and industry; bridge the gaps between climate research and climate applications; and make practical information available to government, industry, and the public. Consequently, PCIC at the University of Victoria and BC Hydro (BCH) have agreed to a joint Letter of Agreement (Attachment A2). The first task is *Program Definition*. Both the Letter of Agreement and this Research Plan define a cooperative effort that will address the consequences of climate variability and change on water resources in selected watersheds of British Columbia.

1.1. Hydrological Modelling and Regional Climate Modelling

Some hydrologic modelling in BC has focused on issues pertaining to forest management, operational forecasting, and land-cover change (including glaciers). Recently, modelling applications have addressed the future response of streamflow to climate change (Merritt et al., 2006; Pietroniro et al., 2006; Stahl et al., 2007; Toth et al., 2006; Whitfield et al., 2002b). Specifically, five hydrologic models have been applied in the Province, UBCWM[2], HBV-EC[3], DHSVM[4], WATFLOOD[5] and VIC[6]. Several different empirical models, including UBCWM are used operationally by RFC and BCH. The description of models detailed in this research plan is not exhaustive or exclusive.

Although these models each have their own special capability and their applications have provided valuable results, they lack the versatility that is required within the complex hydro-climate of BC to project streamflow conditions in the future. An ideal model would accommodate changes in land-cover, changing hydrologic regimes, or regions of steep terrain, and will be compatible with hydropower reservoir inflow models. A suitable model should also be able to incorporate the effects of climate variability such as ENSO and PDO and output results for specific water balance parameters, especially streamflow.

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[2] - UBC Watershed model, UBCWM (Quick, 1995)
[3] - Hydrologiska Byråns Vattenbalansavdelning-Environment Canada, HBV-EC (Bergstrom, (1973, 1995); Moore et al., 1993)
[4] - Distributed Hydrology Soil Vegetation Model, DHSVM (Wigmosta, et.al., 1994)
[5] - Waterloo flood forecasting system, WATFLOOD (Kouwen, 1988)
[6] - Variable Infiltration Capacity model, VIC (Liang, et.al., 1994)

The macro-scale hydrologic model, VIC, has been used extensively by the Center for Science in the Earth System (CSES) at the University of Washington to study climate change in the Columbia River Basin. CSES has set a standard for hydrologic modeling and assessment of impacts. For these reasons, we propose to extend the VIC model to address climate change impacts in other regions of BC. For applications in smaller basins, the DHSVM model may be used at sites which require high-resolution analysis. This plan would permit intercomparison of model results using DHSVM (or results from other modeling studies) with the VIC modelling results. This work also invites intercomparison studies between different model formulations.

Another approach for projecting hydrologic impacts is the use of regional climate models (RCMs) of the atmosphere. RCMs provide a systematic approach for resolving global climate change on a regional scale. Current RCMs in development incorporate a macro-scale hydrologic model explicitly, however, there are some practical challenges involving the RCM approach that include: experimental design, massive data output, unresolved physical processes, and insufficient resolution of topographic features. The Consortium Ouranos, the Canadian Climate Centre for modelling and analysis (CCCma), and the CRCM[7] network have developed and validated a successful climate model that is useful for regional studies—the Canadian Regional Climate Model (CRCM). For these reasons, we intend to conduct only diagnostic analysis of CRCM model output, and we will seek energetic collaboration with modeling groups. Both **i**) hydrologic models at the earth's surface and **ii**) high-resolution climate models of the atmosphere are different, yet complementary approaches that can be used to for improved understanding of the future distribution of water resources in BC.

1.2. Program Definition

The purpose of this document is program definition: to describe a Research Plan for Hydrologic Impacts that meets the objectives of the Letter of Agreement (Attachment A2) and to assess the impacts of climate change on water resources for hydroelectric power generation in BC and neighbouring watersheds. This plan is consistent with the PCIC Consortium's Strategy and Plan (Swain, 2007b) that defines our vision, focus, objectives and themes of work. It also incorporates viewpoints from the water consultation (Swain, 2007a). Four projects define the program for research on hydrological impacts (Figure 2):

- The Climate Overview
- Diagnostic Hydrologic Modelling
- Regional Climate Modelling Diagnostics, and
- Synthesis and Applications

[7] - Canadian Regional Climate Model, CRCM (Caya and Laprise, 1999; Laprise, 2007)

2. Research Plan

The objective of the proposed research is *to assess the impacts of climate change on water resources for hydroelectric power generation in BC and neighbouring watersheds* (Attachment A2). Increased knowledge of climate change impacts will enhance the ability of BCH to make operational decisions and to plan for future hydropower systems. The ultimate goal of this work is to produce projections of future *surrogate* daily streamflows in select watersheds that are relevant to BCH operational management and planning.

After defining the program in this Research Plan, the next step is to conduct a Climate Overview which sets the foundation for future work. The Climate Overview provides the past and future conditions of hydro-climatology in BC, as determined through an overview of recent research and analysis updates. This work has already been initiated, a workshop conducted, and a final report written (PCIC, 2007b).

Subsequently, our strategy is to adapt models and quantitative tools, or use output from models that are already in existence. This technical capability is highly developed in other centres and national laboratories. Therefore, our intentions are **i**) to transfer and apply existing hydrologic models, and **ii**) utilize existing model output from regional climate models as the basis for climate diagnostics of future water balance conditions in watersheds in British Columbia.

These models are of two types:

- Hydrological models, both macro-scale and high-resolution, that are capable of estimating water balance and,
- Regional climate models that are capable of projecting climate anomalies out to decades in advance.

Finally, a substantial amount of work is required for synthesis, application and interpretation of our results in useful terms and formats. The objective is to define the envelope of possible streamflows within the context of climate change, including seasonal variations, interannual climate variability and extreme weather events. These applied results and the work that substantiates them will contribute to the BCH sponsored Water Use Planning Process.

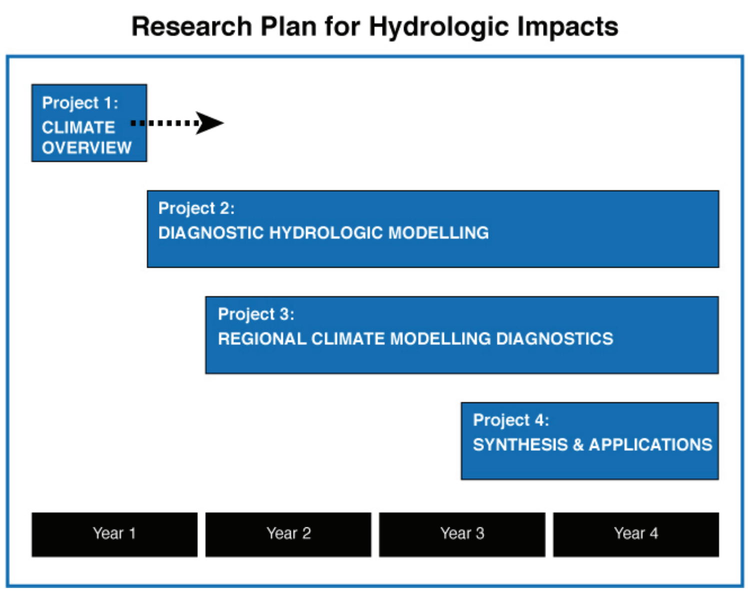


Figure 2 – Schematic schedule of the Research Plan.

3. Climate Overview – Project 1

An overview of the historical hydro-climatology in BC and trends in air temperature, precipitation, streamflow, and snowpack is the foundation for projecting how these variables are changing and are estimated to change in the future, including impacts to water resources. A Draft Report has already been completed entitled "Hydro-climatology and Future Climate Impacts in British Columbia" (PCIC, 2007b). Publication of this report will follow after peer-review by external technical reviewers.

3.1. Objectives

Project objectives of the Climate Overview are to *identify the scope and intensity of the threat of potential impacts to water resources by climate variability and change in the Pacific Northwest, especially in British Columbia,* and to present this information *in terms of traditional climatology of the region and the historical trends* (PCIC, 2006). Key goals of the Climate Overview Project were to present information on past and future hydro-climatology of BC and synthesize this information using vivid and illustrative graphics.

3.2. Scope of Work

The work plan initiated for the Climate Overview Project involves six tasks—proposal development, research, technical development, writing and graphics, review and publication (PCIC, 2006). Each task as listed below is paraphrased from the proposal (PCIC, 2006) and outlines the scope of work. The final two tasks (Review and Finalization) will be carried out subsequently.

Task 1 – Proposal Development: proposal for Climate Overview Project by PCIC staff (PCIC, 2006). Included in this work is the generation of a comprehensive outline that presents the major topics to be covered in the report.

Task 2 – Research: literature review, and other important steps including research design, selection of data sets, generation of example figures and graphics, and preliminary analysis. A key component of this task is the technical workshop, which involves—the development of preliminary results, references and graphics to create a workshop report (PCIC, 2007c); the workshop itself; and a final report (PCIC, 2007d), which is sent to the technical review committee members for their reference.

Task 3 – Technical Development: technical development of the project, incorporating information from the research phase and feedback from the Technical Workshop (see above). Key details can be found in the Draft Report (PCIC, 2007b).

Task 4 – Writing and Graphics: documentation of results of analysis (previous three tasks) and production of final drafts of the graphics. Important components of this work include developing report structure, producing graphics in GIS (ArcGIS 9.3), writing leading paragraphs, and building the storyline (PCIC, 2007a). The outcome of this task is to produce a final draft report for submission to BC Hydro and subsequently to the technical review committee (PCIC, 2007b).

Task 5 – Review: dissemination of draft report for peer-review. The review team will be asked to produce their edits within a one month period. After all comments have been received, the feedback will be incorporated into the draft (see Finalization).

- meet with BC Hydro to present Draft Report (July 23rd, 2007)
- review Executive Summary (by BC Hydro, released Aug 1st, 2007)
- authorize sending Draft Report to the Technical Review Committee (Aug 8th, 2007)
- develop reviewing guidelines and review process
- send Draft Report out for review (Aug 21st, 2007)

Task 6 – Publication: This is the last step in the Project and incorporates all details for a final draft report. Selected sections of the report will be submitted to peer-reviewed journals or publications.

- incorporate feedback and revisions into document, which will include the update of figures and text in response to the reviewers comments
- meet with BC Hydro to present final document (Oct 2007)
- present results at conferences and to community groups
- publish final version of the Climate Overview report online (www.pacificclimate.org)
- publish select sections of the Climate Overview report in peer-reviewed publications such as Streamline, or other applicable journals

3.3. Outcomes

The outcome of the Climate Overview Project is a final report on hydro-climatology and future climate impacts in BC. The Draft Report has already been completed (PCIC, 2007b). The draft document presented the volume of current knowledge and utilized graphical representations (maps, graphs, tables) to show the current hydro-climatic state, historical trends during the 20th century and projections of future climate in the 2050s.

Consequently, the Climate Overview report aims to build capacity in five main subject areas; knowledge of the hydro-climatology of BC, statistical trend analysis, analysis of climate variability, future projections (including downscaling) of climate change, and future climate impacts. Analysis and information is presented to describe the state of knowledge of the historical and future hydro-climatology of BC. The report also aims to update, expand, or increase the resolution of previous pertinent research in the area of trend and composite analysis, and to project hydro-climatic conditions for the 2050s.

After task five and six of this project are completed, the contents of the Climate Overview Final Report will be posted on the PCIC web site. Subsequently, the findings of this report may be considered for reformatting into a concise, popular science, colour document for public distribution.

4. Diagnostic Hydrologic Modelling – Project 2

The Climate Overview Project (PCIC, 2007b) has documented streamflow changes across BC, including in some cases a decline in mean annual streamflow in those watersheds that have lost their glacier influence. Seasonal variability of streamflow in response to climate variability (ENSO and PDO signals) was also observed. The timing of historical streamflow response over the past 30 to 50 years in BC has changed depending on flow regime: pluvial, nival, or hybrid.

Several hydrologic models have been applied to specific watersheds in Western Canada, and some identify the hydrological impacts of climate change. The selection of models for the following discussion is not exhaustive.

The UBCWM[8] has been used for operational forecasting by BCH and the BC Ministry of Environment's River Forecast Centre (RFC). This model has also been used in climate change studies in the Okanagan (Merritt et al., 2006) and in the Georgia Basin (Whitfield et al., 2002a). However, the UBCWM is no longer formally maintained and has bulk ("lumped") response units. Therefore, UBCWM may not adequately replicate some of the physical processes that are important for understanding the influence of climate change.

The HBV-EC[9] has been used to model rain and snow dominated basins in BC (Moore, 1993) and around the world. HBV-EC has also shown major advancements in the study of projecting the impact of changes in glacier cover to streamflow (Stahl et al., 2007). The HBV-EC has been used primarily for watersheds less than 4,000 km^2.

The DHSVM[10] has been applied to forest management applications by Canadian researchers (Alila and Beckers, 2001; Thyer et al., 2004; Whitaker et al., 2003). This model has been extensively tested for complex terrain, vegetation types, and climate patterns such as found in the US Pacific Northwest. In this regard, DHSVM has been shown to be effective at simulating the fine-scale hydrologic processes necessary to produce accurate streamflow, snow accumulation, and soil moisture patterns within small watersheds (Bowling and Lettenmaier, 2001; Burges et al., 1998; Kenward et al., 2000; Leung et al., 1996; VanShaar et al., 2002). However, DHSVM also requires input data at high resolution, and its application is limited to select watersheds where sufficient driving data is available.

The WATFLOOD[11] model was utilized for the Mackenzie GEWEX study (MAGS) (Beltaos et al., 2002; Beltaos et al., 2003) and to investigate climate change impacts on the Peace-Athabasca Delta (PAD) in northern Alberta and east of the Rocky Mountains (Pietroniro et al., 2006; Toth et al., 2006). Both of these studies have relevance to hydropower operations in the Mackenzie River basin region. However, WATFLOOD is best adapted to flat terrain and therefore may not be suitable in more mountainous terrain of BC. Additionally, WATFLOOD may not accurately predict streamflow during spring melt because some of the complex physical processes surrounding snow accumulation, redistribution, interception and snowmelt are not well defined in the model (Gray et al., 2001; Pomeroy et al., 1998).

The VIC[12] model is a versatile model that was developed by the CSES at the University of Washington as a land-surface scheme for use with GCMs (Liang, 1994; Liang et al., 1994). VIC is compatible with the gridded data output (i.e. GCM output), and it incorporates enough physical information about the land surface to allow investigation of water balance components such as

8 - UBC Watershed model, UBCWM (Quick, 1995)
9 - Hydrologiska Byråns Vattenbalansavdelning-Environment Canada, HBV-EC (Bergstrom, (1973, 1995); Moore et al., 1993)
10 - Distributed Hydrology Soil Vegetation Model, DHSVM (Wigmosta, et.al., 1994)
11 - Waterloo flood forecasting system, WATFLOOD, (Kouwen, 1988)
12 - Variable Infiltration Capacity, VIC (Liang, et.al., 1994).

snow water equivalent, streamflow, soil moisture, and evaporation. Extensive point data are not required to operate the VIC model to estimate water balance terms on a regional scale. The model output provides useful products for comparison to other historical data sets.

The VIC model has been used successfully to estimate hydrologic impacts for use in water management on the Columbia River Basin, including the Canadian portion (Hamlet and Lettenmaier, 1999b). Coarse resolution runs have been published within a study on predicting global river discharge, including two rivers that are within the PCIC study region, the Mackenzie and the Yukon (Nijssen et al., 2001). VIC has also been used in California to assist decision-makers identify uncertainty bounds present within streamflow projections (Maurer and Duffy 2005). The VIC model is suitable for application over large geographical areas and long time-frames (Matheussen et al., 2000).

An overview of recent research on the Columbia River Basin and in the US Pacific Northwest provides an indication of changes that may also occur in BC. Using the VIC model, Hamlet and Lettenmaier (1999a) projected increased winter runoff due to increased winter precipitation and warmer winter temperatures in the Columbia basin. These changes may cause increased competition for water during the spring, summer, and early fall between uncertain energy production, irrigation, instream flow needs, and recreational requirements. Projections of low summertime streamflow conditions by the VIC model suggest looming conflicts between water users (Miles et al., 2000).

For smaller watersheds, finer-scale models are required, such as the Distributed Hydrology Soil Vegetation Model (DHSVM). Incorporating DHSVM at smaller scales of analysis will allow PCIC to focus on specific issues and to deal with complexities present at this level, such as topography or land use alterations.

Therefore, the Diagnostic Hydrologic Modelling project is planned with the intention of using the VIC model for macro-scale streamflow conditions for a range of locations in BC, while addressing high resolution requirements with the DHSVM. Diagnostic Hydrologic Modelling of the water balance for selected regions and watersheds of British Columbia will identify each component of the hydrologic regime, and subsequent application of climate projections for estimating *future* changes in streamflow is an extension of this work. Output will be used to estimate impacts of climate change on all water components.

The prerequisite for implementing a Diagnostic Hydrologic Modelling project is developing necessary expertise and building strong ties with experienced hydrological modelling groups. The Center for Science in the Earth System (CSES) at the University of Washington is the source of modelling expertise (with the VIC and DHSVM models). From an operational standpoint, the BC Ministry of Environment's River Forecast Centre (RFC) will assist PCIC to develop deliverables specifically for comparison and integration with operational forecasting models. Environment Canada's Water and Climate Impacts Research Centre (W-CIRC) is a Consortium member, and they intend to conduct intercomparison studies of different hydrologic models. W-CIRC is also a valuable resource for experimental measurements from research sites. Other research groups and their interests are also acknowledged, including the Environment-Canada Hydrologic Applications (EC-HA) group and scientists at UBC (Geography and Forestry departments).

A Diagnostic Hydrologic Modelling project requires substantial effort. The computational structure of the VIC requires comprehensive understanding. Therefore the training phase of this proposal will be an important step in model development. Initializing (setting up) the model requires selection of available data and reformatting to conform to model requirements.

In support of this project, climate diagnostics from the Canadian Regional Climate Model of the atmosphere (Project 3; section 5) will be developed simultaneously at PCIC. The outputs from these two projects can be compared and contrasted for their relative usefulness in select watersheds in BC.

4.1. Objectives

The objective of this Project is **i)** to compute the water balance for selected regions and watersheds of British Columbia by performing diagnostic analyses of model output from either a macro-scale hydrological model, and/or high-resolution hydrologic model. The choice of model depends on data availability and size of the watershed/region. On this basis, future projections of climate change impacts to water resources can be undertaken to provide estimates of future streamflow conditions in select watersheds in BC. An important prerequisite towards achieving this objective is the transfer of modelling technology from the CSES at the University of Washington to PCIC at the University of Victoria.

This project will be accomplished by substantial collaboration with other laboratories: the W-CIRC at the University of Victoria, and the RFC in the BC Ministry of Environment. This leads to additional objectives: **ii**) to perform inter-comparison of select hydrological models, including the assessment of additional experimental observations; and **iii**) to improve the hydro-meteorological data base for BC. The RFC will provide valuable guidance on data and operational considerations for assessing the results of hydrologic models. Collaboration with these organizations is not yet fully established.

In addition, this work requires training on model technology, collection of hydro-meteorological data sets, and a substantial increase in PCIC staff. In this regard, the experience of the CSES hydrologists at the University of Washington is a critical resource. They have successfully demonstrated the value of the VIC hydrological model, and are applying the DHSVM model to other watersheds. In order to achieve success, our strategy is to contribute to the CSES project, gain experience, and their cooperation, transfer this technology to BC and to the PCIC Consortium.

4.2. Scope of Work

This project is a multi-stage effort that incorporates several major tasks: preparation and training, model and dataset development, calibration and validation, and reporting. The VIC model is planned for this work, but other models are not excluded. Included in this scope is model intercomparison by the W-CIRC.

The Columbia Basin (Prototype 1) site will be used to learn about the model (including set-up, operation, calibration and validation, and how to format and input data). Subsequently, an alternate region in BC (Prototype 2) will be selected for modelling and analysis. Although the tasks as outlined below are presented in a linear fashion, some tasks will be carried out in tandem, synchronously.

Task 1 – Project definition, agreements, and coordination: More detailed plans for the scope of work and institutional agreements must be developed for collaboration to occur.

Task 2 – Preparation and Training: Prepare to set-up the model and train staff in computational running of the model. This task includes an introductory workshop to modelling that has already taken place (Attachment A3).

- augment PCIC staff
- undertake a concise review on hydrologic modelling in BC and within the Columbia Basin (including contiguous regions in the U.S.)
- select prototype sites for application (in consultation with BC Hydro, RFC, and W-CIRC)
- train PCIC staff on the models (fall 2007) at the University of Washington (UW)

Task 3 – Model and Dataset Set-up of Columbia Basin Prototype 1: The VIC model and all the data to run the Columbia Basin were provided to PCIC hydrologists at the 2006 VIC training session. The prototype model is a 1/8th degree resolution representation of the Columbia Basin.

- run the model at UVic (Prototype 1) as provided by the UW (primary; version 4.1)
- gather and reformat new datasets (e.g. soils, etc.), and new historical driving data sets (Hamlet and Lettenmaier, 2005), and iteratively input into the original UW model
- test the model with new data in comparison to the *primary* UW model

Task 4 – Calibration, Bias Correction, and Validation of Columbia Basin, Prototype 1

- define river routing, explore new methods for river routing schemes
- calibrate and validate the outputs with observational data
- employ non-parametric, statistical bias correction techniques to remove systematic bias from the streamflow simulations (Snover et al., 2003)
- run model, test output routines and compare results with the *primary* UW model

Task 5 – Model and Dataset Set-up of Columbia Basin Prototype 2: After training and model development is successfully achieved using the Prototype 1 VIC model, a new site in BC will be selected for modelling.

- gather input data sets or adapt as necessary (from Prototype 1)
- create historical driving data sets or adapt (from Prototype 1)
- naturalize the streamflow systems, if possible
- run and test model performance on Prototype 2, compare

Task 6 – Calibration and Validation for Prototype 2

- calibrate and validate model for a selected study region
- apply statistical bias correction techniques as described for Prototype 1
- investigate avenues for potentially improving glacier parameterization

Task 7 – Evaluation and Reporting: Evaluation is the payoff for running the model, and the results will be distributed to the scientific community. Reporting will be continuous throughout each task as described above. Several major reports will be produced, as detailed below.

- downscaling future climate conditions and estimate climate impacts
- comparison of BC-specific VIC hydrologic model to the US-based model application (Columbia Basin)
- interim (6-monthly) and yearly reporting to BCH
- VIC and DHSVM training manual for PCIC staff at University of Victoria (UVic)
- technical report of hydrologic and climate database

4.3. Outcomes

Future projections of water supply for select watersheds in BC will be developed at a monthly time-scale, including estimates at the resolution of reservoir inflow. Sample hydrographs at a daily time scale will be computed for future climate conditions. This output will be used to assess future climate change impacts in comparison to the historical baseline.

The outcomes for this Project will to be utilized for input to BCH planning and management processes, for comparative tools for the next Project (RCM), and for demonstrating the utility of hydrologic diagnostics in specified applications. The PCIC participants will build technical capacity, and PCIC staff will gain the expertise necessary to run BC-specific water balance models and project future streamflow conditions.

An important consequence of this work is the development of a hydrologic database of water balance variables, climate parameters and streamflow scenarios (both natural and "regulated") for selected locations through BC. This database will include climate and streamflow data for the historical period and projections into the 21^{st} century. The database will serve BCH requirements for improved input into their existing operational models and can be utilized by all Consortium members.

Interim (6-monthly) and yearly reporting will form the backbone for communicating research progress. Each task as listed above in scope of work will either have a stand-alone report or be incorporated into the reporting schema. Finally, journal articles or other peer-reviewed publications will communicate our research results to the scientific community.

5. Regional Climate Modelling Diagnostics - Project 3

Global Climate Models (GCMs) use a coarse grid to project major changes in climate on a global scale. In order to estimate *regional* impacts on hydro-climatology, some form of “downscaling” to higher resolution is required. This is especially true in Pacific North America and British Columbia where topography and contrasts of marine and continental climates creates high spatial diversity, as described and updated in the report of the Climate Overview Project (PCIC, 2007b). In that report, empirical downscaling was successfully used to describe topographic influences, and sample results from the Canadian Regional Climate Model (CRCM) were used to resolve some hydrologic components; e.g., water storage (winter snowpack).

The Canadian Regional Climate Model (CRCM) was developed by members of the RCM network, Consortium Ouranos and the CCCma, as described recently by Laprise (2007). The model is non-hydrostatic, with a resolution that makes it suitable for regional studies: 45-km grid in the horizontal and 27 levels in the vertical. The model also maintains a water balance at the surface, including hydrologic components of soil moisture, runoff, and accumulated snowpack. The physical parameterizations were adapted from the CGCM (Flato and Boer, 2001; McFarlane et al., 1992) and are summarized by Caya and Laprise (1999). Climatology of the model was presented in Plummer et al. (2006). Current projects that investigate RCM output are described in a report of the Canadian RCM Network (CRCM-Network, 2007). The model has evolved in 4 major upgrades and the current version is CRCM4 that uses the Canadian Land Surface Scheme (CLASS), currently being used in the North American Regional Climate Change Assessment Program (NARCCAP).

In addition to improved resolution, regional models have improved dynamic features when compared to Global Climate Models (GCMs). RCMs can simulate high-frequency, short wave-length weather variability, and have demonstrated a capability to produce the relevant features of the seasonal atmospheric water cycle (Bielli and Laprise, 2006; Bielli and Laprise, 2007). The important influence of topography is detected on the Pacific Coast of North America (during the winter season): moisture flux convergence (by transient eddy fluxes) arises from the smallest scales of motion and contributes to the large-scale precipitation mechanism. These physical mechanisms are essential for estimating the hydrologic components in a small domain of thermal and topographic contrasts.

RCMs have been applied to several large watersheds. Although the objective was error-detection or model inter-comparison, the results are also useful to demonstrate the feasibility of using an RCM to diagnose hydrologic impacts, to understand the linkages and feedbacks between climate and hydrologic systems, and to evaluate the impact of climate change on water resources. Several examples are presented below.

A comparison of the RCM (CRCM2) and GCM results was made in Pacific North America and included a water balance (Laprise et al., 2003). Plummer et al. (2006) used regions of North America; e.g., “West Coast” (containing the Pacific States of the US, BC, and portions of the Yukon and Alaska) to study model bias and variability. Consistent results were obtained from both models. A large bias in summertime model precipitation was identified, and this issue was subsequently addressed by Jiao and Caya (2006) in Version 3 of the CRCM. Further reduction in the bias is expected in the next version (4) of the CRCM.

The CRCM has also been used over several large watersheds (Brochu and Laprise, 2007) to study surface water and energy budgets in NW North America, and demonstrates what can be achieved with the CRCM in larger watersheds. The average monthly evaporation, precipitation, and runoff for the study period (1987-1994; 8 years) was estimated for each month of the year. The CRCM results contain a large bias in all components for most months of the year and the snow depth from the CRCM3 is greatly overestimated. This bias has been noted and will be corrected in subsequent versions of the CRCM. In summary, a surface hydrologic model has been used to upgrade the CRCM model—to reduce climate bias and to improve the surface water balance.

Another example is a study of five watersheds in Canada and the Mississippi Basin in the US by Sushama et al. (2006). The CRCM was used to test the model with historical data, and subsequently, to project future climate scenarios (forced by a GCM) and study the hydrologic impacts on major watersheds of North America. Different versions of the RCM produced similar and credible results for precipitation, snowpack (SWE), and runoff in each of the river basins. Results from climate scenarios show a sharp decrease in SWE in most northerly basins, while precipitation changes are somewhat increased, and this implies an increased runoff, especially in winter.

A practical result is the estimation of return periods for extreme flows (Sushama et al., (2006). They demonstrated the value of CRCM capability in a study of frequency, timing and return-levels of both low and high streamflows. However, the results were dependent on the watershed under consideration.

In conclusion, model inter-comparison and error diagnostics have encouraged steady improvements in the model, so that hydrologic balance in watershed basins can be studied with increasing confidence. Although model biases remain, the value of RCM output lies in the calculation of anomalies and ensemble results—not absolute and individual projections. The recent papers demonstrate both the sensitivity of the CRCM as well as its capability to estimate the water balance for selected regions and individual watersheds: the Columbia, Fraser, Mackenzie, Yukon, Nelson, Churchill, and Mississippi River basins. The projected decrease in SWE and increase in runoff throughout the most of the northern watersheds determined from RCM modelling diagnostics corroborates results from the Climate Overview report (PCIC, 2007b). At the northern boundary of the Province, SWE is increasing, but corroboration is continued.

5.1. Objectives

The principle objective is to exploit the CRCM technology and diagnostic tools to validate current water balance in watersheds and regions of British Columbia.

Based on these results, subsequent objectives are to use the CRCM to simulate *future* climate conditions (e.g., 2050s) when forced at the boundary by a Global Climate Model with a specified emissions scenario. Estimates of high-resolution projections of future climate conditions (temperature and precipitation) will also be used to drive an independent hydrologic model (Project 2).

Finally, some estimates of daily streamflow—averaged, composite, or envelope solutions ("*surrogate* streamflows") are needed as a surrogate of future hydrologic impacts under conditions of climate change.

Although preliminary work has already begun, only the initial steps of this project can be accomplished with the present PCIC staff. The scope of work has been designed around additional technical capacity in climate diagnostics and also based upon extensive collaboration with modelling centers at Consortium Ouranos, the Canadian Regional Climate Modeling Network (CRCMN), and at the national laboratory of the Canadian Climate Centre for modelling and analysis (CCCma) at the University of Victoria.

5.2. Scope of Work

The concept for this work requires a systematic development of tasks. Even though a temporal sequence to these tasks is evident, there is great overlap and interaction, and several tasks may be initiated in tandem, synchronously. For this work we have selected the Canadian RCM. However, Ouranos is a resource of other regional climate models from international research centres. Ouranos is also a participant in NARCCAP.

Task 1 - Preparations: More detailed plans will be developed, including scope of work and institutional agreements for collaboration.

- Staff development and collaboration
  - Sponsor a Visiting Scientist from Consortium Ouranos and initiate the RCM Diagnostics Project
  - Augment PCIC staff with a Model Diagnostics Scientist
  - Develop adequate infrastructure and communications (or agreements to use existing facilities of the PCIC Consortium) for storing data and performing climate diagnostics
  - Affirm computational support at UVic (agreement with School of Earth and Ocean Sciences (SEOS) and the Canadian Climate Centre for modeling and analysis (CCCma))
  - Engage CCCma in plans and outcomes; consulting

Task 2 - Preparatory work: Build on preliminary concepts and engage the members of PCIC in using existing tools, models and datasets for directed research on hydrologic impacts.

- Preparation and Test
  - Utilize test data sets; data management preparations
  - Coordination with Ouranos and the CRCMN
- Data and experimental design
  - Evaluation of results from the 30-year data set (Sushama et al., 2006)
  - Consider experimental design for CRCM, Version 4

Task 3 – Testing and Analysis: Utilize existing model output, and initiate new studies on selected watersheds.

- Select watersheds for testing
- Analysis of historical conditions: analysis of BC water balance (precipitation, evapotranspiration, runoff, and storage) for months/seasons
- Comparison with results for other regions, and to other studies
- Comparison with results from other hydrologic models and RCM models
- Presentation of results and solicit feedback

Task 4 – Hydrologic impacts: calculations from model output for projected decadal epochs. This is the ultimate goal of the project, but is using the model at the limits of its capability. This goal will require additional consideration, invention, and original thinking.

- Analysis of water balance by decadal epochs
- Analysis of water balance by months/seasons
- Analysis of extreme events and return periods
- Construction of surrogate hydrographs of watershed runoff on a daily timescale
- Examples of daily projected streamflow
- Envelope of daily projected streamflow
- Composite streamflow relative to indexed events (e.g., onset of freshet; max flow, lake ice break-up)

Task 5 – Evaluation and Reporting: Continuing throughout the period for all tasks.

- Presentation of results and feedback
- Reports and publications
- Integration and synthesis of results

5.3. Outcomes

CRCM diagnostics and the application to large watersheds will build a foundation of resident expertise within the PCIC Consortium to diagnose and understand the current water balance in British Columbia and surrounding areas of Pacific North America. The value and the limitations of the CRCM and its capability to estimate the water balance will be quantitatively understood. This is a foundation resource for the continuing work of PCIC in climate applications.

This project will supply estimates of future climate conditions for the hydrological model (Section 4). Results from both the RCM Diagnostics and the Diagnostic Hydrological Modelling projects will demonstrate hydrologic impacts of future climate scenarios—their potential utility and limitations. Estimates of future runoff for selected watersheds will be estimated and described using some form of *surrogate* daily hydrographs.

This work of the PCIC Consortium will bring the research results and tools from the CRCM Network to bear on issues of water resources of British Columbia. Ongoing work in other regions of Pacific North America will be acknowledged and will contribute to a context for understanding the changing conditions in BC.

6. Synthesis and Applications – Project 4

The objectives for three projects have been specified for a systematic development of work leading to future estimates of hydrological impacts of climate change. The scope of work that needs to be done for each project has been described independently. However, there is a strong linkage between the foundation (Climate Overview) and the subsequent work of Diagnostic Hydrologic Modelling, and Regional Climate Model Diagnostics (Figure 3). The Fourth Project is designed to reinforce convergence of results coming from the two different methodologies. This is an active area of research and development, i.e., (Lucas-Picher et al., 2003) and others.

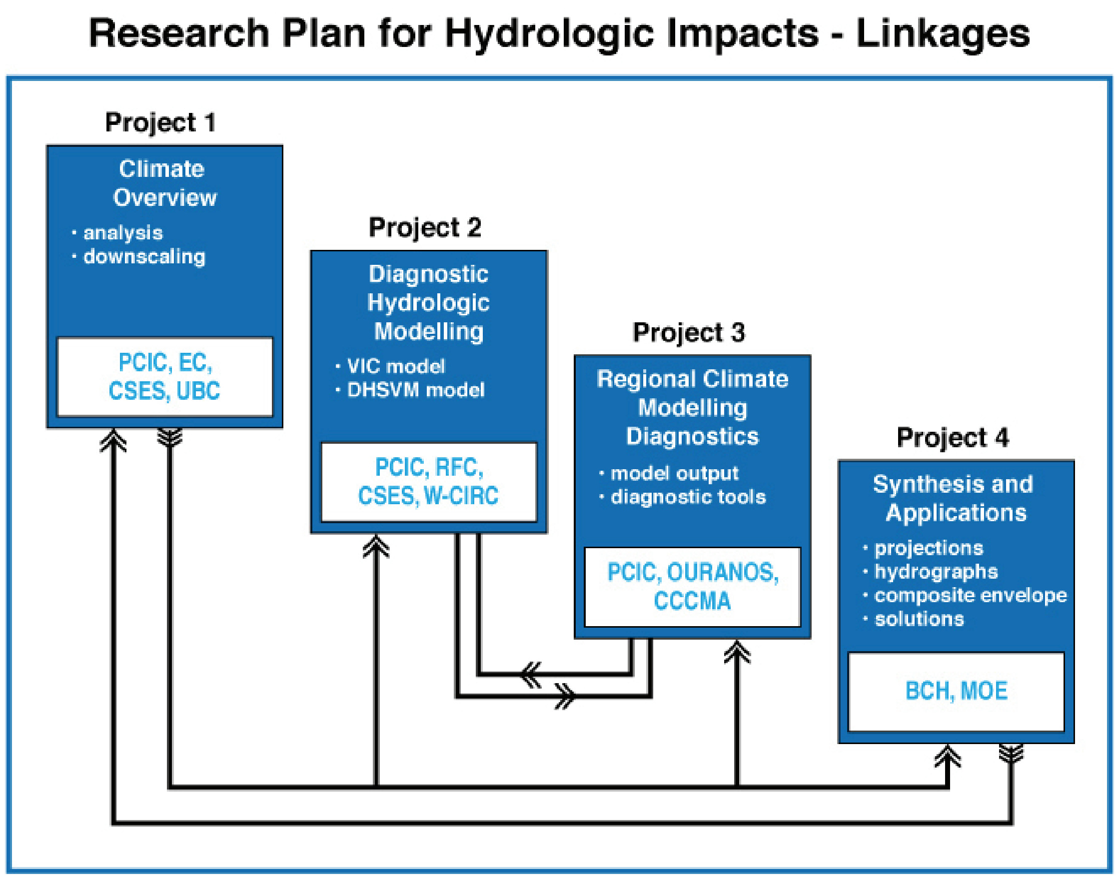


Figure 3 – Linkages between projects and intended participation.

The Climate Overview Project has reached the first milestone: an assessment of the current hydro-climatology, trends and projections of future climate impacts. With this foundation, additional work will add to this perspective by contradicting, confirming, extending and synthesizing results into new knowledge of present trends and future projections of hydrological impacts.

After coordination and agreement on the Diagnostic Hydrological Modelling Project, early milestones will be the formatting the historical driving dataset, and successfully operating the selected model(s). The RCM Diagnostics Project will achieve early milestones by successfully conducting a suite of model diagnostics to define the surface water balance. Subsequently, these milestones, models and diagnostic tools will be applied to watersheds and selected regions to estimate the impact of future climate projections on water resources in British Columbia.

Several other projects in the PCIC Consortium should be acknowledged and may contribute to the synthesis of this Research Plan:

- GCM Climate Projections and Downscaling – This project is the source of GCM model output and emission scenarios that are used to force the CRCM regional model. Low-resolution GCM projections and high-resolution downscaling of temperature and precipitation will be used for comparison with the CRCM results.
- Storm Surge, Sea Level Rise, and Extreme Weather Events – The study of extreme events that are embedded in the CRCM model output will be guided by analyses of historical events that had important influences on the bays, deltas, and estuaries within the Georgia Strait. In particular, information is needed on the threshold levels that generate serious practical consequences.
- Other projects that are still under development within the PCIC Consortium (Attachment A1) are:
    - Economic Impacts
    - Historical Data, Analysis and Climate Assessment
    - Seasonal Climate Prediction

These projects are not yet sufficiently developed to contribute to Hydrologic Impacts Plan, but are noted here as reference and a resource.

6.1. Objectives

The objective of Synthesis and Applications Project is to stimulate the use of the Diagnostic Hydrologic Modelling and the RCM Modelling Diagnostics to examine the water balance in selected regions and watersheds of British Columbia and project estimates to the 2050s. The model and diagnostics will be used to extend the results now evident from the Climate Overview— the current trends and future projections of hydrological impacts of climate variability and change.

6.2. Scope of Work

The scope of work is clear from the published record of CSES, University of Washington, and the RCM Network, especially the University of Québec (UQAM) and Consortium Ouranos. The task is to apply these models and diagnostics to selected regions and watersheds in BC, and some of this has already been described within Projects 2 and 3. Beyond that, synthesis and applications can be described only in general terms, and the details will be developed with more experience.

Task 1 – Collaboration

Engagement of the leadership and expertise of the modelling research centers to ensure a good technical foundation is available for this project. In the case of hydrologic modeling, the primary collaborators (4) have been already identified. For RCM diagnostics, the primary linkage is with Consortium Ouranos, and a stronger engagement with the Canadian Climate Centre for modelling and analysis (CCCma) is also important.

Task 2 – Resident Expertise

Substantial enhancement of the PCIC staff is required to meet the objectives of this Research Plan and to keep the focus on directed research. A talented staff will be able to work well with more experienced members of the Consortium and with affiliated laboratories.

Task 3 – Data Management

Special consideration for data access is required to work with the data volume requirements from the RCM output, and the driving data sets for the hydrological model. In addition, diagnostic results and graphics require more than simply digital capacity and disk space; it requires data management.

Task 4 – User Focus

Provincial and commercial users in planning and decision-making need results that are qualified by statements of uncertainty. Outreach to users is needed as the diagnostic results, updated trends, and projected conditions in the future become substantiated.

Task 5 – Grand Synthesis

A synthesis will bring water balance from hydrologic models and the results of CRCM diagnostics into coherence for BC in the context of results from other parts of Pacific North America. This work will complete the intention of Project 1 by updating and extending the Climate Overview (PCIC, 2007b) of British Columbia. This synthesis will prepare a comprehensive view of future hydrologic impacts that acknowledges all contemporary research results and applications.

6.3. Outcomes

The application of research technology and the synthesis of results will present the analysis and future projections of the hydrologic components in a context of referenced work and specific watersheds. Future hydrologic information will be qualified with the knowledge of comparable studies and results from different methods and models.

The capacity of the PCIC Consortium will be improved through first-hand technical knowledge and experience. Member laboratories of the Consortium will be strengthened and their expertise will be accessible through PCIC. New, resident expertise of the PCIC Consortium will address new questions, developing issues, and operations research as it becomes a better, long-term, resident technical resource for Provincial users – BCH and government.

Traditional methods of exchanging technical information will be used: published reports, peer-reviewed papers in the scientific literature, technical seminars, and presentations at technical meetings. In addition, outreach workshops to segments of users will be initiated.

7. Conclusions

A research plan has been described that meets the objectives of BC Hydro for improving knowledge of the current and future hydrologic impacts of climate variability and change, including some aspect of extreme weather events. This program definition has been developed on the basis of the Letter of Agreement (Attachment A2), consistent with the mission of the PCIC Consortium (Attachment A1), with an awareness of the results of a water consultation project (Swain, 2007b), and the operational requirements of BC Hydro.

A first step has been taken with the Climate Overview Project and the Draft Report, *Hydro-climatology and Future Climate Impacts of British Columbia* (PCIC, 2007b). Furthermore, the PCIC staff has already invested in training on hydrologic modelling, have identified four laboratories as collaborators, and have gained some experience with CRCM datasets. At this point, we are ready to continue with implementation of this Research Plan for Hydrologic Impacts.

It is recognized that this Research Plan is an ambitious and substantial undertaking. PCIC does not currently have the experienced staff to implement this program. Although the members and affiliates of the Consortium have the intellectual resources, they are dedicated to research or to other projects. This plan is feasible only because, **i)** models and tools are adapted and applied from existing research applications, and **ii)** collaboration is possible with the members and affiliates of PCIC Consortium. The linkages between projects and the primary collaborators were identified in Figure 3. To accomplish this Research Plan, PCIC depends both on new resources and augmentation of existing staff.

This work will substantially improve resident expertise in PCIC and increase the capacity to address current and future hydrologic impacts. This strengthens PCIC as a resource to BC Hydro and to the Province. For that reason the BC Ministry of the Environment has also encouraged the objectives of this Plan.

In summary, the elements of this research plan are:

Climate Overview

Many studies of changes in temperature, precipitation, snowpack, and streamflow exist for BC but few are comprehensive or up-to-date. The Overview has consolidated existing research results, identified gaps, extended the spatial coverage, and utilized methodologies which could be adapted for bringing trends and future climate projections up-to-date. The results, presented using vivid graphics and illustrative tables, established a foundation for future work in the realm of hydro-climatology in BC, and prepared the context for hydrologic modeling of future climate impacts.

Diagnostic Hydrologic Modelling

The value of hydrologic modelling has already been demonstrated for the Columbia River watershed using the VIC hydrologic model. This model allows a common framework to evaluate all hydrologic components: precipitation, temperature, storage (snowpack, glacier, and soil moisture), ground water, interception, evapotranspiration and streamflow. First, a model would be adapted to BC watersheds. Subsequently, diagnostic studies would assess the hydrologic impact of climate variability and change, as well as the consequences of feedback mechanisms.

Regional Climate Model (RCM) Diagnostics

The diverse topography and climatology of British Columbia require an RCM at sufficient resolution to match important watersheds with the dimensions of the hydrological model. This work requires the substantial physical and intellectual resources of national laboratories.

Fortunately, collaboration with Consortium Ouranos, Montréal, and a national laboratory (CCCma) at the University of Victoria, bring expertise and tools to interpret these model results. The output from this model is a resource for diagnostic studies of the climate and hydrological components.

Synthesis and Application

The results derived from the adaptation and extension of existing research models and diagnostic tools will be used to compare results from Diagnostic Hydrologic Modelling and the RCM Diagnostics Projects. The synthesis will be based on an examination of conditions of existing and future water balance in selected BC watersheds.

References

Alila, Y. and Beckers, J., 2001. Using numerical modelling to address hydrologic forest management issues in British Columbia. Hydrological Processes, 15: 3371-3387.

Beltaos, S., Prowse, T. and Pietroniro, A., 2002. Climate impacts on ice-jam floods in northern rivers with specific focus on the hydroelectric industry in Western Canada. In: D. Cenzo (Editor), 7th Mackenzie Annual Scientific Meeting of the Mackenzie GEWEX Study (MAGS), Hamilton, Ontario, pp. 108-114.

Beltaos, S., Prowse, T. and Pietroniro, A., 2003. Climate impacts on ice-jam floods in northern rivers with specific focus on the hydroelectric industry in Western Canada. In: D. Cenzo (Editor), 8th Mackenzie Annual Scientific Meeting of the Mackenzie GEWEX Study (MAGS), Jasper, Alberta, pp. 141-150.

Bielli, S. and Laprise, R., 2006. A methodology for the regional-scale-decomposed atmospheric water budget: Applications to a simulation of the Canadian Regional Climate model nested by NCEP-NCAR reanalyses over North America. Monthly Weather Review, 134: 854-873.

Bielli, S. and Laprise, R., 2007. Time mean and variability of the scale-decomposed atmospheric water budget in a 25-year simulation of the Canadian Regional Climate Model over North America. Climate Dynamics, Online First™

Bowling, L.C. and Lettenmaier, D.P., 2001. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas, 2. AGU Water Science and Application, 145-164 pp.

Brochu, R. and Laprise, R., 2007. Surface water and energy budgets of the Mississippi and Columbia River basins as simulated by two generations of Canadian Regional Climate Model. Atmosphere-Ocean, 45(1): 19-35.

Burges, S.J., Wigmosta, M.S. and Meena, J.M., 1998. Hydrological Effects of Land-Use Change in a Zero-Order Catchment. ASCE Journal of Hydrologic Engineering, 3: 86-97.

Caya, D. and Laprise, R., 1999. A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. Monthly Weather Review, 127: 341-362.

CRCM-Network, 2007. The Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) Final Report.

Flato, G.M. and Boer, G.J., 2001. Warming asymmetry in climate change simulations. Geophysical Research Letters, 28: 195-198.

Gray, D.M., Toth, B., Zhao, L., Pomeroy, J.W. and Granger, R.J., 2001. A deterministic approach of modeling and scaling frozen soil infiltration during snow ablation. Hydrological Processes, 15: 3095-3111.

Hamlet, A.F. and Lettenmaier, D.P., 1999a. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resource Association, 35(6): 1597-1623.

Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.

Hamlet, A.F. and Lettenmaier, D.P., 2005. Production of temporally consistent gridded precipitation and temperature fields for the continental United States. Journal of Hydrometeorology, American Meteorological Society, 6: 330-336.

Jiao, Y. and Caya, D., 2006. An investigation of summer precipitation simulated by the Canadian Regional Climate Model. Monthly Weather Review, 134: 919-932.

Kenward, T., Lettenmaier, D.P., Wood, E.F. and Fielding, E., 2000. Effects of Digital Elevation Model Accuracy on Hydrologic Predictions. Remote Sensing Environment 74: 432-444.

Laprise, R., 2007. Regional climate modeling. Journal of Computational Physics, in press.

Laprise, R., Caya, D., Frigon, A. and Paquin, D., 2003. Current and perturbed climate as simulated by the second-generation Canadian regional Climate Model (CRCM-II) over northwestern North America. Climate Dynamics, 21(5-6): 405-421.

Leung, L.R., Wigmosta, M.S., Ghan, S.J., Epstein, D.J. and Vail, L.W., 1996. Application of a Subgrid Orographic Precipitation/Surface Hydrology Scheme to a Mountain Watershed. Journal of Geophysical Research, 101(D8): 12,803-12,817.

Liang, X., 1994. A two-layer variable infiltration capacity land surface representation for General Circulation Models, University of Washington, Seattle, Washington, US.

Liang, X., Lettenmaier, D.P., Wood, E.F. and Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research, 99(D7): 14,415-14,428.

Lucas-Picher, P., Arora, V.K., Caya, D. and Laprise, R., 2003. Implementation of a large-scale variable velocity river flow routing algorithm in the Canadian Regional Climate Model (CRCM). Atmosphere-Ocean, 41(2): 139-153.

Matheussen, B., Kirschbaum, R.L., Goodman, I.A., O'Donnell, G.M. and Lettenmaier, D.P., 2000. Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). Hydrological Processes, 14: 867-885.

McFarlane, N.A., Boer, G.J., Blanchet, J.P. and Lazare, M., 1992. The Canadian climate centre second generation circulation model and its equilibrium climate. Journal of Climate, 5: 1013-1044.

Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.

Miles, E., Snover, A., Hamlet, A.F., Callahan, B. and Fluharty, D., 2000. Pacific northwest regional assessment: the impacts of climate variability and climate change on the water resources of the Columbia River Basin. Journal of the American Water Resource Association, 36(2): 399-420.

Moore, R.D., 1993 Application of a conceptual streamflow model in a glacierized drainage basin. Journal of Hydrology, 150: 151-168.

Maurer, E. P., and Duffy, P.B. 2005. Uncertainty in projections of streamflow changes due to climate change in California. Geophysical Research Letters. 32: L03704, doi:10.1029/2004GL021462.

Nijssen, B.N., O'Donnell, G.M., Lettenmaier, D.P. and Wood, E.F., 2001. Predicting the Discharge of Global Rivers Journal of Climate, 14(15): 3307-3323.

PCIC, 2006. Climate Overview Proposal, Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC.

PCIC, 2007a. Climate Overview Interim Report: Figures for Climate Overview Report, Pacific Climate Impacts Consortium, Victoria, BC.

PCIC, 2007b. Climate Overview Project: Hydro-climatology and Future Climate Impacts in British Columbia Draft Report, Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC.

PCIC, 2007c. Climate Overview: Technical Workshop, Environment Canada, Vancouver, BC Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC.

PCIC, 2007d. Summary Report of the Technical Workshop, Climate Overview, Pacific Climate Impacts Consortium, University of Victoria Victoria, BC.

Pietroniro, A. et al., 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: III - integrated model assessment. Hydrological Processes, 20(19): 4231-4245.

Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112-3132.

Pomeroy, J.W. et al., 1998. An evaluation of snow accumulation and ablation processes for land surface modelling. Hydrological Processes, 12: 2339-2367.

Snover, A.K., Hamlet, A.F. and Lettenmaier, D.P., 2003. Climate change scenarios for water planning studies. Bulletin of the American Meteorological Society, 84(11): 1513-1518.
Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., 2007. Coupling modelling of glacier and streamflow response to future climate scenarios. Water Resources Research, submitted.
Sushama, L., Laprise, R., Caya, C., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26(15): 2141-2159.
Swain, H., 2007a. Climate change and water users in British Columbia, Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC.
Swain, H., 2007b. Strategy and Plan (2007-2011): Themes and Products, Victoria, BC.
Thyer, M., Beckers, J., Spittehouse, D., Alila, Y. and Winkler, R., 2004. Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand and basin- scale data. Water Resources Research, 40(W01103): 1-20.
Toth, B., Pietroniro, A., Conly, F.M. and Kouwen, N., 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: I - hydrological model application. Hydrological Processes, 20(19): 4197-4214.
VanShaar, J.R., Haddeland, I. and Lettenmaier, D.P., 2002. Effects of land cover changes on the hydrologic response of interior Columbia River Basin forested catchments. Hydrological Processes, 16: 2499-2520.
Whitaker, A., Alila, Y., Beckers, J. and Toews, D., 2003. Application of the Distributed Hydrology Soil Vegetation Model to Redfish Creek, British Columbia: model evaluation using internal catchment data. Hydrological Processes, 17: 199-224.
Whitfield, P., Reynolds, C. and Cannon, A., 2002a. Modelling streamflow in present and future climates: examples from the Georgia Basin, British Columbia. Canadian Water Resources Journal, 27(4): 427-456.
Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling Streamflows in Present and Future Climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.

Additional References of Contemporary Research

Hydrologic Modelling

Beltaos, S., T. Prowse, B. Bonsal, R. MacKay, L. Romolo, A. Pietroniro, and B. Toth, 2006. Climate e effects on ice-jam flooding of the Peace-Athabasca Delta. Hydrological Processes, 20: 4031-4050.
Loukas, A., L. Vasiliades, and N.R. Dalezios, 2000. Flood producing mechanisms identification in southern British Columbia, Canada. Journal of Hydrology, 227: 218-235.
Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier. 2004. Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin. 62: 233-256.
Pietroniro, A., F.M. Conly, B. Toth, R. Leconte, N. Kouwen, D.L. Peters, T.D. Prowse, 2005. Modelling climate change impacts on water availability in the Peace Athabasca catchment and delta. NWRI contribution #04-029. Conly FM (ed.). Northern Rivers Ecosystem Initiative Report, Environment Canada: Saskatoon, SK; 43.
Pike, Robin. 2003. Streamline Watershed Management Bulletin Vol. 7/No. 3 Fall 2003 Approaching Watershed Modelling.

Schnorbus, M. and Y. Alila, 2004. Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modelling. Water Resources Research, 40(W05205): 1-16.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier, 2004. Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. Climatic Change, 62: 189-216.

Regional Climate Models and Analysis

Arora, V. and G.J. Boer, 2006. The temporal variability of soil moisture and surface hydrological quantities in a climate model. Journal of Climate, 19: 5875-5888.

Bielli, Soline and Rene Laprise, 2007. Time mean and variability of the scale-decomposed atmospheric water budget in a 25-year simulation of the CRCM over North America. Climate Dynamics, Springer-Verlag, online.

Brochu, Raphael and Rene Laprise, 2007. Surface water and energy budgets over the Mississippi and Columbia River Basins as simulated by two generations of the CRCM. Atmosphere-Ocean, 45: 19-35.

De Elía, Ramón, D. Caya, H. Côté, A. Frigon, Sl. Biner, M. Giguère, D. Paquin, R. Harvey, D. Plummer, 2007. Evaluation of uncertainties in the CRCM-simulated North American climate. Climate Dynamics, Springer-Verlag, online.

De Elía, Ramon, D. Plummer, D. Caya, and A. Frigon, 2006. Sources of uncertainty in the RCM projections: A primer. Canadian DAM Association, ms., 8 pp.

Frigon, A., M. Slivitzky, D. Caya, and R. Roy, 2007. Construction of hydro-climatic projections and first-order estimation of their associated uncertainties from regional climate model simulations: Application to water management of hydropower reservoirs in Quebec. In press.

R. Laprise, 2006. Regional climate modelling, Journal of Computational Physics. doi:10.1016/j.jcp.2006.10.024.

Laprise, R., D. Caya, A. Frigon and D. Paquin, 2003. Current and perturbed climate as simulated by the second-generation CRCM-II over northwester North America. Climate Dynamics, 21: 405-421.

Music, B. and D. Caya, 2007. Evaluation of the Hydrological Cycle over the Mississippi River Basin as Simulated by the Canadian Regional Climate Model (CRCM). Submitted to the Journal of Hydrometeorology.

Sushama, L., R. Laprise, and M. Allard, 2007. Modeled current and future soil thermal regime for northeast Canada. Journal of Geophysical Research, 111(D18111): 1-13.

Attachments

A1 – Pacific Climate Impacts Consortium

A2 – Letter of Agreement

A3 – VIC Training Report

A1 – Pacific Climate Impacts Consortium (PCIC)

Pacific Climate Impacts Consortium

Adaptation to Climate Variability and Change in Pacific North America

At an organizational workshop (2005) representatives from academic and government research labs, industry and stakeholders in BC and the US urged the formation of a consortium to focus resources on assessment of climate impacts in Pacific North America. The evidence of climate variability and change are now evident. The mean annual temperature is increasing, the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation influences are documented, and unusually extreme weather events are a frequent reminder that we must live with Nature in the world that we have created. In order to adapt to an uncertain future, industry and governments that make long-term investments recognize the importance of threat assessment and the necessity of long term planning. The *Pacific Climate Impacts Consortium* (PCIC) was created to bridge the gap between climate research and practical applications; between information sources on climatic hazards, commercial decision-making, and government planning; and among the technical disciplines that assess climate impacts.

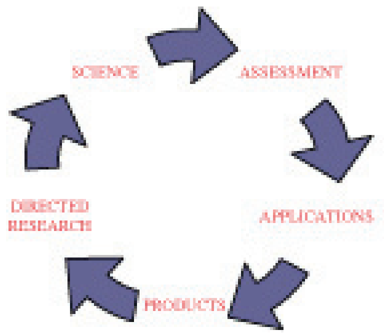
The focus region in Pacific North America includes the water resources originating in British Columbia. Source: Hydro1K

Vision [13]

- ... to stimulate collaboration between government, academe and industry to reduce vulnerability to extreme weather events, climate variability and the threat of global change. The consortium for climate impacts will bridge the gaps between climate research and climate applications, and will make practical information available to government, industry, and the public

Objectives

- to foster collaborative and interdisciplinary approaches to research on meteorology, atmospheric science, climate variability, climate change, social sciences and economics
- to channel and strengthen the capacity to address regional climate change and variability, including extreme weather events.
- to focus research on public and private sector needs in order to provide the scientific basis to develop policy options



Bridge the gap between…

- science and applications
- geophysical sciences: meteorology, hydrology, geography
- physical sciences, economics, social relevance
- researchers and users
- climate centers in Pacific North America

Scope and Context

- British Columbia and Pacific North America
- climate variability, climate change, and extreme weather events
- resident expertise in the physical sciences

Themes[14]

- global climate variability and change: Regional application of global climate scenarios; water resources: Hydrological modeling and impacts
- ocean influences: storm surge, sea level rise, and extreme weather events
- economic impacts of climate variability and change (TBD)

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[13] Meeting Summary & Proposed Strategy, 2005, 5 pp

[14] Strategy and Plan (2007-2011), Pacific Climate Impacts Consortium, 2007, 10 pp.

- historical data, analysis and climate assessment (TBD)
- seasonal climate prediction (TBD)

Operating Plan

- Determine the needs of stakeholders and end users of climate information. Seek out research experts and partners to develop joint proposals. Engage resident post-doctoral staff, graduate students, and research partners in collaborative, directed research that addresses the needs of stakeholders. Attract sustained support for directed research on climate impacts requiring adaptation.

Current Projects

- Future Climate Scenarios and Downscaling
    - Spruce Bark Beetle and Bud Worm (FSP)
    - Dynamic Downscaling
- Hydrological Impacts (BCH, MoE)
    - Climate Overview
    - Diagnostic Hydrological Models - Development
    - Regional Climate Modelling Diagnostics
    - Synthesis and Applications
- Storm Surge, Sea Level Rise and Extreme Weather
    - Storm Surge (MoE)
    - Transportation (TBD)
- Outreach: Presentations, Consultation, Assessment Reports, and Website
    - Water Consultation (MoE and BCH)
    - Website development

Paradigms for Collaboration

- With researchers……..
    - Seeding PCIC staff
    - Extension of the lab to directed research
    - Joint proposals for directed research
    - Technology transfer to PCIC
- With stakeholders and end users ……
    - Consultations
    - Presentations
    - Seminars and Information workshops
    - Directed research (contracts)
    - Climate assessments

Consortium

- BC Hydro, Burnaby, BC
- BC Ministry of the Environment, Victoria, BC
- Water-Climate Impacts Research Centre (W-CIRC), Environment Canada, University of Victoria, BC.
- Climate Modelling Research Group, School of Environmental and Ocean Sciences, University of Victoria, BC
- Consortium Ouranos, Montréal, Québec

- Hydrology Applications Group, Western Regional Office, Environment Canada, Vancouver, BC

Affiliations

- TBD
- TBD
- TBD

Leadership

- David R. Rodenhuis, PhD Atmospheric Sciences
  Acting Director, Pacific Climate Impacts Consortium
- Ben Kangasniemi, BC Ministry of Environment
  Chair, Management Committee
- Harry Swain, Ph.D. Geography
  Senior Advisor
- Annette Phillips
  Office Administrator

Consortium Staff

- David Rodenhuis, Ph.D., Atmospheric Science
  Senior Scientist
- Trevor Murdock, M.Sc., Earth and Ocean Sciences
  Associate Director
- Katrina Bennett, M.Sc., Hydrology
  Hydrologist
- Arelia Werner, Candidate, M.Sc., Geography
  Hydrologist
- David Bronaugh, B.Sc., Computer Science
  Programmer Analyst
- Dilumie Abeysirigunawardena, Candidate, Ph.D., Geography
  BC Coop position

(PCIC, 20 August 2007)

A2 – Letter of Agreement

Chris O'Reily
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Letter of Agreement

Pacific Climate Impacts Consortium (PCIC) and BC Hydro

Date: January 2, 2007

BC Hydro is pleased to be a member organization and support the Pacific Climate Impacts Consortium (PCIC) in a four year program to assess the impacts of climate change on water resources for hydroelectric power generation in BC and neighbouring watersheds. This letter outlines the terms of the agreement between PCIC and BC Hydro.

<u>Deliverables</u>

Funding

- **BC Hydro will provide PCIC with approximately $200,000 for four consecutive years to a maximum of $800,000.**

PCIC will:

Work Program

- Work with BC Hydro to develop a four year research program directed at enhancing the ability of BC Hydro to model and optimize the operation and future planning of its hydropower system. The work and payment schedules will be defined as a series of contracts. The program could include, but not be limited to, the following research subjects.
    - Conduct a comprehensive survey of our current knowledge of climate variability and change, including historical trends and estimates of future climate scenarios.
    - Produce a climate change scenario(s) for water supply at three watersheds that represent different climatic regions where BC Hydro has power projects. The resolution may be monthly reservoir inflow.
    - Produce a climate change scenario(s) for water supply at three or more watersheds at the daily reservoir inflow resolution. The daily time scale would allow assessments of economic, social and environmental impacts using the methodologies established during BC Hydro's Water Use Planning processes.

Participation

- Provide the opportunity for a BC Hydro representative to sit on the PCIC Board of Directors.
- Provide the opportunity for a BC Hydro representative to sit on the PCIC Management Committee.

BC Hydro will:

- Provide the funds as outlined in the series of contracts defined by the work program within the above funding limit.
- Endeavour to provide student work terms for graduate and under graduate students to foster the development of expert capacity in climate change science. Funding would be over and above the PCIC direct funding by BC Hydro.
- Provide a BC Hydro liaison to help develop and manage the work plan and its scientific basis.

Term

- This agreement will be effective April 1, 2006 to April 1, 2010.

Termination Policy

- This agreement may be terminated with thirty (30) days written notice by either party.

Confidentiality

- Both parties agree not to disclose confidential information pertaining to BC Hydro or PCIC that may be acquired over the course of this agreement, subject to any lawful requirement to disclose the same.

By signing below we acknowledge that this letter outlines our mutual understanding of our rights and responsibilities with respect to supporting the climate change research program.

Chris O'Reily

Harry Swain Executive Director PCIC

Renata Kurschner
Director, Generation Resource Management
Signing on behalf of Chris O'Riley

A3 – VIC Training Report

Applicability of VIC Model in BC: Model Overview and Workshop Notes

Arelia T. Werner and Katrina E. Bennett
Pacific Climate Impacts Consortium
University of Victoria
December 6, 2006

[This information on the VIC (Variable Infiltration Capacity) model is based on a VIC Workshop, hosted by Center for Science in the Earth System (CSES) at the University of Washington, November 2006. The Workshop was conducted by Dr. Alan Hamlet.]

Strengths of the VIC Hydrologic Model

- The VIC model handles snow well, which is important because of its significant influence on stream-flow. Snow is handled explicitly using DHSVM within VIC.
- VIC represents soil moisture well, which has been found to be important in accurately coupling the land surface to the atmosphere to drive winds properly.
- Calibration of the model requires only a few parameters to be adjusted and there are automated routines to handle components of the calibration.
- VIC can be used to answer questions that cannot be answered with observed data alone due to the lack of spatial coverage. Some examples in BC may include impacts of changing land cover (biodiversity) on streamflow as a result of climate variability.
- The model makes up for what is not known at the fine scale by averaging over the broad scale. This statement is supported by the success of VIC in producing meaningful results.
- Ideal for use with something like Mountain Pine Beetle because Leaf Area Index can be altered with relative ease in model.
- Can run VIC in either water balance or energy budget mode.
- Computational power can be saved if only water balance is of interest, but the energy budget can be engaged to drive the model in a coupled manner to get more physically representative results if required.

Limitations of the VIC Hydrologic Model

- VIC cannot be run on basins smaller than 1440 km^2 (ten 12 x 12 km grid cells).
- Many of the watersheds that are of interest to BC Hydro and the Ministry of the Environment are less than 1440 km^2. Hence, the need for DHSVM.
- It is wise to pick grid cells that have equal distributions of north and south aspect because aspect is not directly addressed in the model. This is thought to be achievable by counting watershed ridge lines within the DEM. This is important for accurate capture of processes such as blowing snow.
- Glaciers are not currently incorporated explicitly in VIC. Manual manipulation of the model is required to ensure that glaciers advance and recede appropriately, or the model will grow ice continually through time. As glaciers account for 3% of land mass in BC or 30,000 km^2, and 50% of summer flows at locations such as the Columbia Basin (Menounos, 2006) this is important point to consider.

- Many months are required to set-up the data files and to correct the flow direction files.
- The relationship between the soil depths and rooting depths may interfere with accurate evaporation estimates. Roots may have to be decoupled from the 3rd layer to achieve accurate values.

VIC Compared to other Hydrological Models

- VIC uses a gridded coverage to represent a broad scale area.
- Links more directly to RCM and GCM data.
- Coupled land and atmosphere.
- Not as limited by the lack of observational data as semi-distributed and lump sum models would be.
- The predominant models applied in BC are the UBC Watershed model (UBCWM), HBV-EC model, and Distributed Hydrology Soil Vegetation Model (DHSVM).
- The UBCWM (Quick, 1995) lumps the response of a given watershed by elevation bands to give the total runoff contribution from both snowmelt runoff and rainfall runoff. This model has been applied for the purposes of operational forecasts. There are concerns that this model does not adequately replicate some of the necessary physical processes, especially those that are important for understanding the influence of climate change, and there is no longer someone responsible for maintaining the model, which has lead users to look for other models.
- The DHSVM model is fully spatially explicit based on digital elevation model (DEM) resolution and a physically based conceptual mode. Unfortunately, although the model has the capability to model explicitly at the DEM grid resolution the input data is rarely available at the same scale, requiring many of the values to be approximated. It is also an ever evolving model, which is not very user friendly, and technical support is not provided to users.
- Much work towards developing the semi-distributed, deterministic model *Hydrologiska Byråns Vattenbalansavdelning* (HBV) model, which was first developed in 1972 (Bergstrom, 1995; Bergstrom and Forsman, 1973), has been adjusted to allow for discretization of the landscape based on climate, elevation, land use, slope, and aspect making it a leader in applications that involve snow and glacier processes. This version is now referred to as HBV-EC.

Applying VIC in BC

Opportunities

- CIG has provided the 1/8th degree latitude longitude grid cell coverage for the Columbia River Basin to PCIC. This will allow PCIC to test its skills in compiling necessary data from Canadian sources, creating the input files, and testing results against those found by the CIG group.
- CIG has created a 1^{o} version of VIC that covers all of BC. Although this resolution is not the finest available it would help to test the creation of input files and to start doing the preliminary work within the VIC model environment to build gridded datasets relevant to climate change studies.
- CIG has also investigated trends in the McKenzie Basin with a 2^{o} version (Nijssen et al., 2001a; Nijssen et al., 2001b)

- KENUE (previously known as ENSIM Hydrologic) of the Canadian Hydraulics Centre has a flow direction component for WATFLOOD (Kouwen, 1988; Kouwen, 2005) that may be applicable in VIC.
- It may be possible to adapt the script from HBV-EC for glaciers for input into the VIC model to increase its ability to address glaciers (David Hutchinson of Meteorological Services of Canada, Environment Canada, Vancouver, BC, pers. comm.). This relies somewhat on aspect in the HBV-EC model and would require further investigation.

Challenges

- The observational datasets in BC are sparser than those in the US.
- The largest errors in the model output are a result of errors in the precipitation and temperature data (Alan Hamlet, University of Washington, CSES, pers. comm.). The CIG group has created rigorous techniques for transforming the US input data to better feed the VIC model (Hamlet and Lettenmaier, 2005; Maurer et al., 2002; Nijssen et al., 2001b).(Regonda et al., 2005) These techniques need to be evaluated for use in BC to ensure that they are adequate to adjust available data sets.
- To run VIC in real- time for now-casting and fore-casting, access to up- to-date snow cover like MODIS and SWE is required.
- The stream-flow bias correction procedures developed by CIG destroy the mass balance to obtain a representative measure of discharge. It will not be possible to investigate the water balance components with the model if these procedures are applied.

References

Bergstrom, S., 1995. The HBV model Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO, USA, 443-476 pp.

Bergstrom, S. and Forsman, A., 1973. Development of a conceptual deterministic rainfall–runoff model. Nordic Hydrology, 4: 147–170.

Hamlet, A.F. and Lettenmaier, D.P., 2005. Production of temporally consistent gridded precipitation and temperature fields for the continental United States. Journal of Hydrometeorology, American Meteorological Society, 6: 330-336.

Kouwen, N., 1988. WATFLOOD: A micro-computer based flood forecasting system based on real-time weather radar. Canadian Water Resources Journal, 13(1): 62-77.

Kouwen, N., 2005. WATFLOOD User's Manual, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P. and Nijssen, B.N., 2002. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States Journal of Climate, 15(22): 3237-3251.

Menounos, B., 2006. Proposal: Western Canadian Cryospheric Network.

Nijssen, B., O'Donnell, G.M., Hamlet, A.F. and Lettenmaier, D.P., 2001a. Hydrologic Sensitivity of Global Rivers to Climate Change. Climatic Change, 50(1-2): 143-175.

Nijssen, B.N., O'Donnell, G.M., Lettenmaier, D.P. and Wood, E.F., 2001b. Predicting the Discharge of Global Rivers Journal of Climate, 14(15): 3307-3323.

Quick, M.C., 1995. UBC Watershed Model Manual—Version 4.0., Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.

Regonda, S.K., Rajagopalan, B., Clark, M. and Pitlick, J., 2005. Seasonal cycle shifts in hydroclimatology over the western United States. Journal of Climate, 18: 372-384.