Hydrologic Impacts

Research Plan for 2012 - 2016

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About PCIC

The Pacific Climate Impacts Consortium is a regional climate service centre at the University of Victoria that provides practical information on the physical impacts of climate variability and change in the Pacific and Yukon Region of Canada. PCIC operates in collaboration with climate researchers and regional stakeholders on projects driven by user needs. For more information see http://pacificclimate.org/.

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Hydrologic Impacts

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1. Introduction

The hydro-climatology of British Columbia (BC) 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 and western North America by Rodenhuis et al. (2009). Historical changes are in part attributable to climate variability on annual to decadal timescales, such as teleconnection patterns coming from El Niño/Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO). In addition, recent hydro-climatic trends in western North America have also been affected by anthropogenic climate change, predominantly in the form of increased regional warming (Barnett et al. 2008; Bonfils et al. 2008; Pierce et al. 2008). The regional response to climate variability and trends can potentially affect all aspects of the hydrologic cycle, including the hydrologic extremes of flood and drought (Hamlet and Lettenmaier 2007; Sheffield and Wood 2008). Ultimately it is recognized that the hydro-climatic system can no longer be considered stationary, and from a management perspective the past may become progressively less informative of future conditions (Milly et al. 2008).

Consequently, the aim of the Hydrologic Impacts (HI) theme at the Pacific Climate Impacts Consortium (PCIC), and the purpose of the proposed applied research, is to quantify the effects of climate change and variability on water resources within the Pacific and Yukon region (PYR) of western Canada. The main purposes of HI theme products are to:

- Inform and support the sustainable use of the region's water resources in order to help reduce society's vulnerability to climate change and climate variability; and
- Raise awareness of potential hydrologic implications of climate change and climate variability.

All this is to be accomplished at spatial scales relevant to regional and local management and over multiple planning and adaptation time frames. Spatial scales range from several hundreds of thousands of square kilometres (e.g. the Fraser River basin) to several hectares (e.g. drainage culvert design) and timeframes vary from monthly to century. Of particular interest for management and planning is a greater emphasis on knowledge regarding changes in hydrologic variability and changes in extremes, such as flood and drought, and phenomena that affect that variability, such as changes in the frequency and intensity of storms affecting the PYR.

Climate, and subsequently hydrology, varies over a wide range of space and time scales as a result of processes both internal and external to the Earth's climate system (Keenlyside and Ba 2010). *External forcing* includes climate variations caused by factors external to the climate system, such as changes in radiative forcing as a result of human-derived greenhouse gas (GHG) emissions. Internal processes are reflected by *internal climate variability*, which arises from natural interactions within the earth-ocean-atmosphere climate system, such as manifested in the ENSO or Pacific Decadal Oscillation phenomena.

Different time frames can be organized and distinguished by characterizing them by the degree to which the driving climate is dominated by internal climate variability versus external forcing. Therefore, in order to assess the possible hydrologic effects of both climate change and climate variability over a broad range of time scales, the work of the HI theme will be organized along the following three time frames (Figure 1):

- *Short-term* - monthly to annual;
- *Near-term* - annual to multi-decadal; and
- *Long-term* - multi-decadal to century.

Over the short term, hydro-climatic processes are governed predominantly by internal climate variability, whereas over the long-term these processes are strongly affected by external forcing (Figure 1). In the near-term, hydro-climatic processes are affected by both internal variability (particularly for time frames of a decade or less; Keenlyside and Ba 2010) and, over multiple decades, by external forcing.

The activities with which the HI theme intends to address and estimate hydrologic impacts within the short-, near- and long-term timeframes are classified into forecasting, prediction and projection, respectively. A *forecast* is the estimation of values or magnitude of hydro-climatic conditions (or their probabilities) at a specific future time, or during a specific time interval (e.g. reservoir inflow over the coming six months; Lettenmaier and Wood (1993)). A *prediction* is the estimation of future hydro-climatic conditions, but is herein distinguished from forecasting in that it is not referenced to a specific date or time, but instead seeks to predict the statistical characteristics of hydro-climatic conditions over some defined time period (e.g. the frequency of flood events over the next five years). A *projection* is the estimated response of the hydro-climate system to changes in radiative forcing. As projections must be explicitly tied to assumptions of how future greenhouse gas emissions may evolve in response to human activities (in the form of emissions scenarios), they are neither forecasts nor predictions (Bray and von Storch 2009). Projections aim to provide a set or range of plausible, but not necessarily likely, outcomes. Over the short-term, forecasts are an "initial value" problem in that forecast results and skill are sensitive to specified initial states (climatologic and hydrologic) and radiative forcing can be set to reflect present conditions. Long-term projections are "boundary value" problems in that the evolution of hydro-climatology is strongly affected by assumptions regarding the evolution of greenhouse gas concentrations and consequent radiative forcing. Near-term decadal to multi-decadal predictions can be considered a hybrid problem, in that predictions are expected to be sensitive to some aspects of both the initial states and assumptions regarding future greenhouse gas concentrations and other external factors affecting the climate system.

2. Research Plan

2.1 Purpose

The purpose of this Research Plan is to provide strategic program definition to address the aim the Hydrologic Impacts (HI) theme at PCIC. The Research Plan guide activities over the coming five years by defining the major objectives of the HI theme and indicating applied research required to achieve the stated objectives. Nevertheless, the Research Plan will remain flexible and responsive to the changing priorities and requirements of consortium members and stakeholders and as such, is envisaged to be a living and evolving document.

The Research Plan predominantly guides the work of the Hydrologic Impacts (HI) theme at PCIC and the research objectives are the primary responsibility of the Lead, Hydrologic Impacts. Regardless, the objectives and requirements spelled out in the following plan are not the exclusive domain of HI and will draw upon resources, skills and expertise found in the other PCIC themes, namely Regional Climate Impacts (RCI), Climate Monitoring and Analysis (CAM) and Computational Support Group (CSG) (PCIC 2009). In particular, several of the research activities in support of the HI theme will fall under the management of the RCI theme.

2.2 Research Objectives

The four objectives of the HI theme over the next 5 years are intended to address the hydrologic effects of climate variability and change at the three timescales defined in section 1 (Figure 1), plus possible extension of those results to assess impacts on water resources. The objectives are described in Table 1. It is the intent that all four objectives will address the expanded spatial domain described in Section 2.3.

Table 1. Hydrologic Impacts theme Research Objectives

Objective	Description	Priority
1	**Short-term Forecasting**: Skill assessment and demonstration of monthly, seasonal and annual hydrologic forecasts including establishing a test-bed hydro-climatological forecast system	1
2	**Long-term Projection**: Comprehensive projections of hydrologic impacts to year 2100 due to anthropogenic climate change using updated climate change projections and improved hydrologic modelling tools, including the study of projected changes in hydro-climate variability including extremes and the causes of changes in extreme behaviour	1
3	**Extended Applications**: Exploration and assessment of subsequent impacts of hydrologic changes on water resources and water-dependent activities (i.e. hydro-power generation, reservoir management, water supply, in-stream flow needs, etc.)	2
4	**Near-term Prediction**: Diagnosis, validation, and skill assessment of decadal and multi-decadal hydrologic predictions including hydro-climatic predictions to year 2035	3

Operational hydrologic forecasting practise is generally based on tools and data that have remained unchanged for several decades. In most cases seasonal and sub-seasonal streamflow forecasting in western North America is regression-based, although the use of ensemble streamflow prediction (ESP), is gaining prominence (Wood and Lettenmaier 2006). Regardless, these approaches are sub-optimal in an environment in which hydroclimatological relationships have been shown to be non-stationary on various timeframes. Further, operational hydrological forecasting has yet to take full advantage of the marked improvements in weather and climate prediction that have occurred over the past decades (Wood et al. 2002; Wood and Lettenmaier 2006). Consequently, the goal of Objective 1 is to explore and assess the skill of hydrologic forecasts up to one year in advance for watersheds in western Canada based on deterministic forecasts from modern climate models. Provided these forecasts have demonstrated skill, it is also the goal of this objective to deliver a test-bed hydrologic forecast system for demonstration and potential technology transfer to operational forecasting agencies. The intent of this objective is to complement and inform current in-house forecasting capabilities of PCIC stakeholders, such as BC Hydro, the BC Ministry of Environment, and Environment Canada.

The purpose of Objective 2 is to expand upon the previous hydro-climate projection work of the HI theme, as laid out in Rodenhuis et al (2007) and reported by Schnorbus et al (2011). This will be delivered on by utilizing the latest generation of climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2008), which are based on the new Representative Concentration Pathways (RCP) emissions scenarios (Moss et al. 2010; van Vuuren et al. 2011). The goal of this objective is to deliver updated projections of hydrologic impacts due to anthropogenically induced climate change over the period 2030 to 2100. These projections will cover the full range of potential future climates encompassed by the various RCP scenarios. Projections will be based on improved hydrologic modelling, with more explicit emphasis on accurately modelling potential cryospheric changes within the PYR. Projections will more fully explore potential changes in hydrologic variability, including changes to extreme phenomena (floods and droughts), and the underlying physical mechanisms affecting such changes (e.g. changes in the frequency of synoptic events controlling local or regional flooding).

The purpose of Objective 3 is to extend the results from Objectives 1 and 2 (but primarily Objective 2), which focus exclusively on hydrologic changes, to more specifically address impacts on water as a human and ecological resource. Specifically, the intent is to quantify possible impacts to such water-related resources and water-dependent activities as, for example, hydroelectric generation, municipal water supply, flood management, in-stream flow needs and fish habitat, irrigated agriculture, recreation and navigation. The purpose of this objective is also to place the hydrologic effects of climate change and variability within the context of other externally-driven changes to hydrologic systems within the PYR, including flow regulation and land-use change. The scope of applied research pursued under this objective will be developed over time in response to partner and stakeholder needs and the availability of external expertise and resources.

The purpose of Objective 4 is to assess how skilful are predictions of the time-evolving state of hydrology of western Canada over the next three decades (2015 to 2035). This objective will take advantage of the new decadal climate predictions that will be made available as part of CMIP5. Nevertheless, as decadal climate prediction, which drives decadal hydrologic prediction, is still highly experimental (Meehl et al. 2009; Keenlyside and Ba 2010), this objective occupies the lowest priority. The final scope of this objective, and the decision on whether or not to pursue it, will rely strongly on the findings of the IPCC assessment of the decadal prediction component of CMIP5.

2.3 Spatial Domain

The spatial domain for Objectives 1 through 4 is intended to include all drainage areas encompassed by the Pacific and Yukon region. This is defined as the contiguous landmass contained within the provincial and territorial boundaries of BC and the Yukon (YK), respectively, plus all upstream drainage areas, plus any additional ‘downstream’ drainage areas considered relevant by consortium members and stakeholders.

A proposed spatial domain, which is shown in Figure 2, is organized into the following major drainage regions:

1. *Upper Columbia*, a trans-boundary (Canada-United States) watershed which contains the drainage area upstream of the confluence of the Columbia and Okanagan Rivers and includes the Kootenay (Kootenai in the United States), Pend Oreille, Spokane, Similkameen, Okanagan, Granby and Kettle Rivers. Note that the Skagit River is also included in this group;
2. *Fraser*, which includes the entire Fraser River watershed upstream of tidewater;
3. *Vancouver Island*; which includes the entire area of Vancouver Island;
4. *South Coast*, which includes all areas draining to tidewater from Indian Arm in the south to the north end of Queen Charlotte Strait in the north, including the Squamish, Toba, Homathko, Klinaklini and Kingcome Rivers;
5. *Central Coast*, which includes all areas draining to tidewater extending from entrance of Queen Charlotte Strait in the south to Laredo Sound in the north and includes the Atnarko/Bella Coola, Dean and Kimsquit Rivers;
6. *North Coast*, which includes all areas draining to tidewater from roughly Laredo Sound north to head of Portland Canal plus the islands of Haida Gwaii, and includes the Skeena and Nass Rivers;
7. *North Coast Mountains*, which includes all areas draining the western (Pacific) divide of north-western BC and south-western YK north of Portland Canal, including the trans-boundary (BC/YK and AK) watersheds of the Iskut-Stikine, Taku and Alsek Rivers;
8. *Upper Peace*, a trans-boundary (BC and AB) watershed that includes the drainage area roughly upstream of the confluence of the Peace and Smoky Rivers, near the town of Peace River, Alberta.
9. *Upper Hay*, a trans-boundary (BC and AB) watershed upstream of the confluence of the Chinchaga and Hay Rivers.
10. *Liard*, a trans-boundary (BC, YT and NT) watershed that includes the entire drainage area of the Liard River (i.e. upstream of the confluence with the Mackenzie River).
11. *Upper Yukon*, a trans-boundary watershed (BC, YT and AK) that includes the headwaters of the Yukon River as well as the headwaters of the Porcupine River (a major tributary of the Yukon River).
12. *Peel,* the entire Peel River watershed, upstream of its confluence with the Mackenzie River.

Only the 'core' spatial domain is identified in Figure 2. Optional expansion of the spatial domain could include the entire Columbia, Yukon and Peace drainages. Prioritization of the spatial domain may be required for work planning purposes – this would be guided by stakeholder requirements. Note that the extent of the spatial domain may be governed by additional constraints such as the domain of high-resolution dynamically-downscaled RCM output(s) and/or the spatial domain of climate forecast products. Note also that the downstream extent of any drainage areas will be practically dictated by the location of hydrometric sites, which will be required for calibration of the hydrologic model(s).

3. Approach

3.1 Roles and Resources

PCIC plans to take a leading role in pursuing research activities in support of Objectives 1, 2 and 4, subject to the guidance and the evolving requirements of PCIC's stakeholders and consortium members. It is intended that, as sufficient expertise resides within PCIC, the work required to accomplish Objectives 1, 2 and 4 will be predominantly scoped, resourced and managed in-house by PCIC core staff. Nevertheless, collaborative opportunities will be exploited where possible or in specific cases where external expertise is required.

Under Objective 3, PCIC will be available to support research activities designed to address the subsequent water resource impacts of hydrologic change and variability diagnosed under Objectives 1, 2 and 4. However, as the expertise required to address specific water resource impacts does not currently reside at PCIC, any research activities will rely on collaboration with stakeholders and other organizations. As PCIC plans to assume a supporting role (not a lead role) in subsequent research activities, research will be predominantly scoped, defined and managed by stakeholders and potential external collaborators.

3.2 Objectives 1, 2 and 4 - Forecasting, Projection and Prediction

The PCIC HI theme will adopt a comprehensive approach characterized by the use of leading-edge methodology and tools. For Objectives 1, 2 and 4, the approach shown schematically in Figure 1 will generally be followed. The intent is that hydro-climate assessments at all time frames (whether projections, predictions, or forecasts) will utilize, to the extent possible, the same methodological approach and tools. The proposed method will generally involve three steps (Figure 1):

1. Obtain global or regional climate data (forecast, prediction or projection)
2. Apply some form of downscaling (statistical or dynamical or combination) and/or bias-correction, and
3. Force a hydrologic model with the downscaled climate forecasts, predictions or projections.

The distinction between an "initial value" (forecast) versus a "boundary value" (projection) problem is largely addressed by selecting the appropriate source global climate data (step 1), which is produced by external agencies, and is largely transparent to PCIC's core activities. Dynamical downscaling (step 2) is a computationally expensive effort that is also conducted by external agencies; PCIC's primary role is diagnostic. PCIC's primary effort will focus on the selection of appropriate global climate data (step 1), processing and diagnosis of dynamically downscaled hydro-climate data and/or production of high resolution statistical downscaled climate projections (step 2) and hydrologic modelling (step 3). Unique to past hydrologic modelling work, which was designed strictly for hydrologic projections, will be the important requirement to explicitly initialize the hydrologic model for generating hydro-climatic forecasts and predictions.

Methodological details include:

1. Use of ensemble simulations to quantify the following major sources of uncertainty:
    a. Emissions uncertainty (hydro-climate predictions and projections);
    b. Variation in climate sensitivity to a given radiative forcing between individual GCMs (hydro-climate predictions and projections); and
    c. Effect of uncertainty in initial conditions and internal climate variability (hydro-climate forecasts, predictions and projections).
2. Selecting and processing global and/or regional climate data from external agencies:
    a. Hydrologic forecasts will employ hindcast and forecast output from the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Historical Forecast Project

(CHFP; Merryfield et al. 2010). This coupled forecast system is currently being implemented for operational use at the Canadian Meteorological Centre*;*

b. Hydrologic predictions will employ results of CMIP5 near-term climate prediction experiments (Doblas-Reyes et al. 2011); and

c. Hydrologic projections of will be based on results of CMIP5 long-term experiments (Stouffer et al. 2011).

3. Downscaling to produce a set of consistent domain-wide climate projections, predictions and forecast ensembles. The downscaling must be tailored and/or appropriate to addressing the effects of climate change and variability on hydro-climatic phenomena at a sub-monthly timescale (to daily, if possible), particularly extreme events.
4. High resolution (currently 1/16-degree), spatially-distributed, physically-based (where possible) and locally calibrated hydrologic modelling applied consistently throughout the study domain with explicit representation of relevant hydrologic and cryospheric processes. The specified model resolution is currently tied to PCIC's investment in the Variable Infiltration Capacity (VIC) model (Liang et al. 1994). It is likely that many of the assumptions inherent in the VIC approach, which make it computationally efficient for modelling large regions (such as parameterizations of small-scale sub-grid phenomena), would become invalid below a threshold resolution of approximately 1/16-degree. The possibility of using a higher resolution with one or more alternative hydrologic model(s) (e.g. WaSIM-ETH) for select case study watersheds will also be explored.
5. Future work will also remain open to opportunities, via collaborative efforts at external organizations, to employ a multi-method approach for producing hydro-climate projections. Additional methods may include investigation and adoption of various combinations of alternative downscaling and hydrologic modelling tools (Figure 1).

3.3 Objective 3 – Extended Applications

The approach required to address Objective 3 is yet to be determined in detail, but will likely involve various types of impact modelling (e.g. reservoir modelling, analysis of in-stream flow indices, habitat suitability modelling, etc.) as well as water quality modelling. Additional activities may include extending the hydrologic modelling work conducted under Objectives 1, 2, and 4 to include scenarios dealing with land use change, current or planned flow regulation and diversion projects, and water abstraction for irrigation. Simple (i.e. static) land use change scenarios can be dealt with in a straightforward manner with current hydrologic modelling tools (i.e. parameters of the hydrology model are altered to reflect changes in land cover). More complicated land-use change scenarios (e.g. those involving dynamic forest cover) demand a more involved process that would require access to additional modelling capability. Incorporation of the effects of flow regulation, diversion and irrigation would also require access to alternative models or upgrades to PCIC's current hydrology modelling (by integrating or coupling to existing models). The scope of applied research activities pursued under this objective will rely upon guidance from stakeholders and the availability of expertise from external agencies and researchers.

4. Applied Research

In order to achieve the stated objectives following the approach outlined in Section 3, a number of applied research requirements have been identified. These fall under the general categories of hydrologic modelling, downscaling, baseline historical data, climate model output selection and processing, forecasting and prediction, and high-resolution hydrologic modelling. In the following, individual sub-sections are used to describe each requirement. In some cases, specific commitments (or tasks) are identified for each requirement. Each commitment provides an approximate timeline for completion.

Many of the commitments identified have close linkages with and/or require the support of personnel attached to other PCIC themes other than HI, as well as collaboration with external experts and agencies – these are also anticipated and identified for each commitment. The other themes at PCIC include Computational Support Group (CSG; computing, coding, scripting and data management and dissemination), Climate Analysis and Monitoring (CAM; data and data management) and Regional Climate Impacts (RCI; downscaling and regional impacts assessments). Potential external collaborators include the Canadian Centre for Climate Modelling and Analysis (CCCma), the Department of Fisheries and Oceans (DFO), the Water and Climate Impacts Research Centre (W-CIRC), and individual researchers at the University of Victoria (UVic), the University of British Columbia (UBC), the University of Northern British Columbia (UNBC), the University of Washington (UW) and Oregon State University (OSU).

Computing will rely predominantly on hardware resources available both within PCIC and through the University of Victoria. Data analysis and processing will utilize PCIC computing resources, whereas resource intensive model simulations will utilize resources available through the UVic Research Computing Facility. The option also exists to utilise computing resources available through the Western Canada Research Grid (WestGrid; http://www.westgrid.ca/), although access is on a competitive basis and, therefore, not guaranteed. Data management and storage will utilize PCIC data and computing resources.

4.1 Requirement 1 - Hydrologic Modelling

This requirement addresses improvements to PCIC's hydrologic modelling capability and technology, predominantly as it pertains to satisfying Objectives 1, 2 and 4. This will be affected by upgrades to the VIC model, or if merited, adopting an alternative model. General topics include additional parameterizations and/or processes required to model conditions relevant to the Arctic, sub-Arctic and mountain environments. In many areas of the PYR, hydrology is affected by glacier runoff. Consequently, representation of glacier runoff is imperative for accurate estimation of hydrologic response to short-, near- and long-term climate variability and change. In addition, over the near- and long-term, correctly representing glacier dynamics (i.e. changes in glacier volume and morphology in response to mass balance change) also becomes critical. Additional activities revolve around model set-up, parameterization and calibration to the expanded spatial domain.

Although explicit modelling of lakes and wetlands, groundwater, frozen soils and permafrost, and river ice have also been identified as necessary components of PCIC's hydrologic modelling capability, limited time and in-house resources places them at a lower priority at this time. No specific commitments have been assigned. Nevertheless, opportunities to address these specific issues over the next five years may be possible via collaborative arrangements.

Stream temperature is a corner-stone water quality variable and understanding potential changes due to climate change and variability would factor prominently in any potential activities pursued under Objective 3. Integration or coupling of a stream temperature model will allow for the estimation of potential climate-induced temperature changes, which would be relevant at all timescales. Other than stream temperature, no other modelling capability improvements are currently planned with respect to satisfying Objective 3. Any additional commitments would need to rely heavily on external expertise and resources.

This requirement identifies what will essentially be the core responsibilities of the HI theme at PCIC over the coming five years. Nevertheless, significant contributions will be required from the CSG and CAM groups at PCIC, well as expertise and/or products from external agencies. Specific commitments are as follows.

4.1.1 **Update to VIC 4.1.1** – Adopt latest version of VIC, v4.1.1 (see http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Development/CurrentVersion.shtml), including code audit. This commitment will also model updates to introduce standardization of the VIC model input and output data formats ▪ *Timeline*: March 2012 ▪ *Lead*: HI ▪ *Support*: CSG

4.1.2 **Modelling of glacier melt and mass balance** – introduce ability to accurately model glacier runoff (given a static glacier mask), without the additional complexity of glacier dynamics. Note that this will involve some restructuring and recoding of the VIC model in order to introduce this capability. If a VIC re-write is assessed to be too risky, this may require adoption of an alternative hydrology model ▪ *Timeline*: December 2012 ▪ *Lead*: HI ▪ *Support*: CSG + CAM ▪ *Collaboration:* UBC/UNBC/UW

4.1.3 **Modelling of glacier volume and dynamics** – include the ability to also model glacier volume changes and dynamics. It is currently envisaged that this will likely involve the coupling of separate hydrology and glacier dynamics models ▪ *Timeline*: 2012/13 ▪ *Lead*: HI ▪ *Support*: CSG + CAM ▪ *Collaboration:* UBC/UNBC/UW

4.1.4 **Hydrology model parameterization, calibration and validation** – set-up, parameterize and calibrate VIC (or other) hydrology model to expanded spatial domain (Figure 2). Calibration of the hydrology model(s) will likely involve a staged approached: calibration will begin with the Upper Peace, Fraser and Upper Columbia watersheds, followed by the remaining drainages in (or flowing into) BC, to be then followed by and remaining YK drainages ▪ *Timeline*: 2012/13 ▪ *Lead*: HI ▪ *Support*: CAM + CSG

4.1.5 **Spatially-distributed, energy-balance stream temperature model** – coupling or integration of an energy-balance model with the hydrology model in order to model stream temperature in a spatially-distributed manner ▪ *Timeline*: 2013/14 ▪ *Lead*: HI ▪ *Support*: CSG ▪ *Collaboration:* DFO/UBC/UW

4.2 Requirement 2 - Downscaling

Short-term forecasts, near-term predictions and long-term projections will all be driven by outputs from coarse resolution global climate models. Consequently, downscaling to higher resolution is a cornerstone activity for three of the four objectives given in this research plan. The hydrologic projections recently completed by PCIC (Schnorbus et al. 2011) relied predominantly on a statistical downscaling procedure that, although generating high-resolution spatially downscaled climate projections at daily temporal resolution, only explicitly captured the monthly transient climatic response to various radiative forcing scenarios (Werner 2011). Consequently the downscaling employed did not explicitly address potential changes in daily climate statistics (e.g. changes in the frequency of wet and dry days, wet spell length, etc) and implications of climate change and variability to extreme events at the regional and local scale. Although critical to the success of the HI theme, this requirement is a core activity of the RCI Theme. As such, HI will operate in support of and under the lead of the RCI theme. The following commitment has been identified:

4.2.1 **Downscaling** – investigate, evaluate and implement statistical, dynamical (or some combination thereof) downscaling procedures that accurately estimate the daily (including extremes) predicted and projected climate response, including changes in the variability of daily phenomena ▪ *Timeline*: 2012/13 ▪ *Lead*: RCI ▪ *Support*: CSG + HI ▪ *Collaboration:* CCCma/Ouranos/UVic

4.3 Requirement 3 – Baseline Historical Climate Data

Several of the commitments identified as part of both Requirements 1 and 2 (Hydrologic modelling and downscaling) critically rely on the use of gridded historical, baseline climate data, which is derived from the interpolation of observed station data. This includes calibration of hydrology models and statistical downscaling techniques as well as validation and diagnosis of dynamical downscaling products. Consequently, there is a need to update and maintain a high-quality data set of spatially distributed (i.e. gridded) historical climate data that encompasses the spatial domain given in Figure 2. This data must be available at a daily temporal resolution and a minimum spatial resolution of 1/16-degree (consistent with the current resolution of the VIC hydrology model). Although any work conducted in support of this requirement will overlap considerably with the activities of the CAM theme, the need for daily baseline data is currently a more pressing requirement for, and as such falls under the lead of, HI. Nevertheless, the commitments that follow will rely heavily on data and products from the CAM group. Specific commitments are as follows:

4.3.1 **Interpolation algorithm** – Review, validate, diagnose and, if necessary, update interpolation algorithms, incorporating data from as many observational networks as possible, including the new PRISM products produced under the CAM theme. This task will also include auditing and error-checking of current codes and scripts ▪ *Timeline*: March 2012 ▪ *Lead*: HI ▪ *Support*: CSG + CAM

4.3.2 **Build baseline data set** – Build baseline data set for expanded spatial domain for the minimum required variables of daily minimum and maximum temperature, precipitation and wind speed. This commitment will tie in closely to data and derivative products, such as PRSIM, managed under the CAM theme ▪ *Timeline*: December 2012 ▪ *Lead*: HI ▪ *Support*: CAM

4.4 Requirement 4 – Climate Model Output

The IPCC Fifth Assessment Report (AR5) will be based on analysis of climate projections and predictions provided by the World Climate Research Programme's CMIP5 experiments. The CMIP5 results derive from the latest generation of Global Climate Models and Global Earth System Models, where climate projections are driven by the new RCP scenarios. Consequently, some effort will be required in deciding on an appropriate ensemble of GCMs and emissions scenarios for the purposes of producing hydrologic projections and predictions. Research will also focus on applying appropriate techniques for quantification of projection and predictions uncertainty stemming from emissions, GCM climate sensitivity and internal variability. At this time only very general commitments have been assigned to this requirement as any details will rely strongly on the findings of the IPCC assessment of the CMIP5 results. This requirement falls under the lead of the RCI Theme, with HI acting in a supporting capacity. The following commitments have been identified:

4.4.1 **Ensemble Selection** – Assessment and construction of optimal ensembles of global climate models and emissions scenarios for hydrologic projections and predictions ▪ *Timeline*: 2013/14 ▪ *Lead*: RCI ▪ *Support*: HI

4.4.2 **Uncertainty** – Quantify and compare climate prediction and projection uncertainty due to GCM climate sensitivity, internal variability and choice of emissions trajectory ▪ *Timeline*: 2013/14 ▪ *Lead*: RCI ▪ *Support*: HI

4.5 Requirement 5 – Forecasting and Prediction

A new requirement will be the need to conduct applied research focused on skill assessments of hydrologic forecasts and predictions in support of Objectives 1 and 4. Also, as distinguished from hydrologic projections, the skill of hydrologic forecasts and predictions can be greatly improved with accurate knowledge of initial conditions and appropriate model initialization. For watersheds in western North America, forecast skill will be dependent on accurate initialization of the state of snow and, to a lesser degree, soil storage (Koster et al. 2010). Addressing this requirement will draw upon data products and resources from the CAM theme and may utilize expertise in model initialization and hydro-climatic forecast and prediction skill evaluation from external agencies. Specific commitments include:

4.5.1 **Hydrologic model initialization** - Investigate various methodologies for model initialization. A priority will be investigating techniques for using point and remotely-sensed snow data for model initialization. Secondary consideration will be given to techniques for utilising soil moisture data ▪ *Timeline*: 2012/13 ▪ *Lead*: HI ▪ *Support*: CAM ▪ *Collaboration:* CCCma/UW

4.5.2 **Forecast/prediction skill -** Evaluation and assessment of various measures of hydro-climatic and streamflow forecast and prediction skill. This work will be closely tied to parallel efforts by other groups within and external to PCIC to directly assess the skill of climate forecasts and predictions ▪ *Timeline*: 2013/14 ▪ *Lead*: HI ▪ *Support*: RCI ▪ *Collaboration:* CCCma

4.6 Requirement 6 – High-resolution Modelling

The reliance on the VIC model applied at a spatial resolution of 1/16-degree essentially constrains the spatial scale of impact assessment to watersheds no smaller than roughly 500 km^2. Nevertheless, users have identified the requirement to understand the potential consequences of climate change and variability on hydrology (including extremes) at very small spatial scales (in some cases down to a mere several square kilometres). Consequently there is a need to explore means to explicitly address the effects of climate change and variability at very small spatial scales (i.e. < 1/16-degree). The following approach will be considered:

4.6.1 **High-resolution hydrology model(s)** – Direct application of a high-resolution hydrologic model (e.g. WaSIM-ETH or DHSVM) to a limited number of case-study watersheds ▪ *Timeline*: 2013/14 ▪ *Lead*: HI ▪ *Support*: RCI ▪ *Collaboration:* UBC/other

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Appendix 1: Schematic of proposed approach

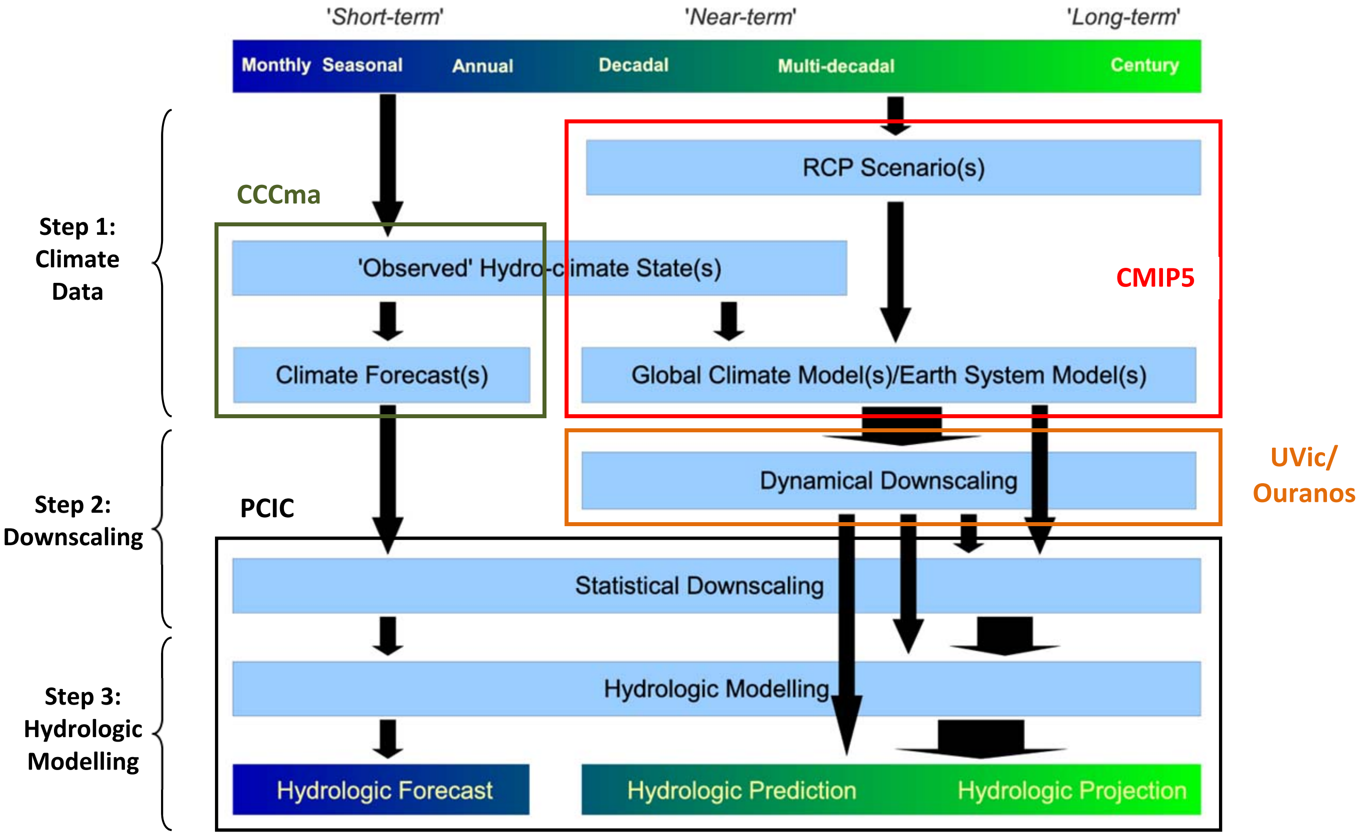

Figure 1. Schematic of proposed approach to address hydrologic impacts due to climate variability and climate change by means of "short-term" (monthly to annual) forecasts, "near-term" (decadal to multi-decadal) predictions and "long-term" (multi-decadal to century) projections. Global climate data will be obtained from external agencies, namely CCCma for monthly, seasonal and decadal forecasts and CMIP5 for decadal climate predictions and multi-decadal and century climate projections (step 1). Dynamical downscaling results will be obtained from a UVIc/Ouranos collaboration (or other sources subject to availability) (step 2). PCIC's in-house efforts will focus primarily on analysis and diagnosis of dynamically downscaled results, statistical downscaling (step 2), and hydrologic modelling (step 3).

Appendix 2: Proposed spatial domain of the Hydrologic Impacts theme

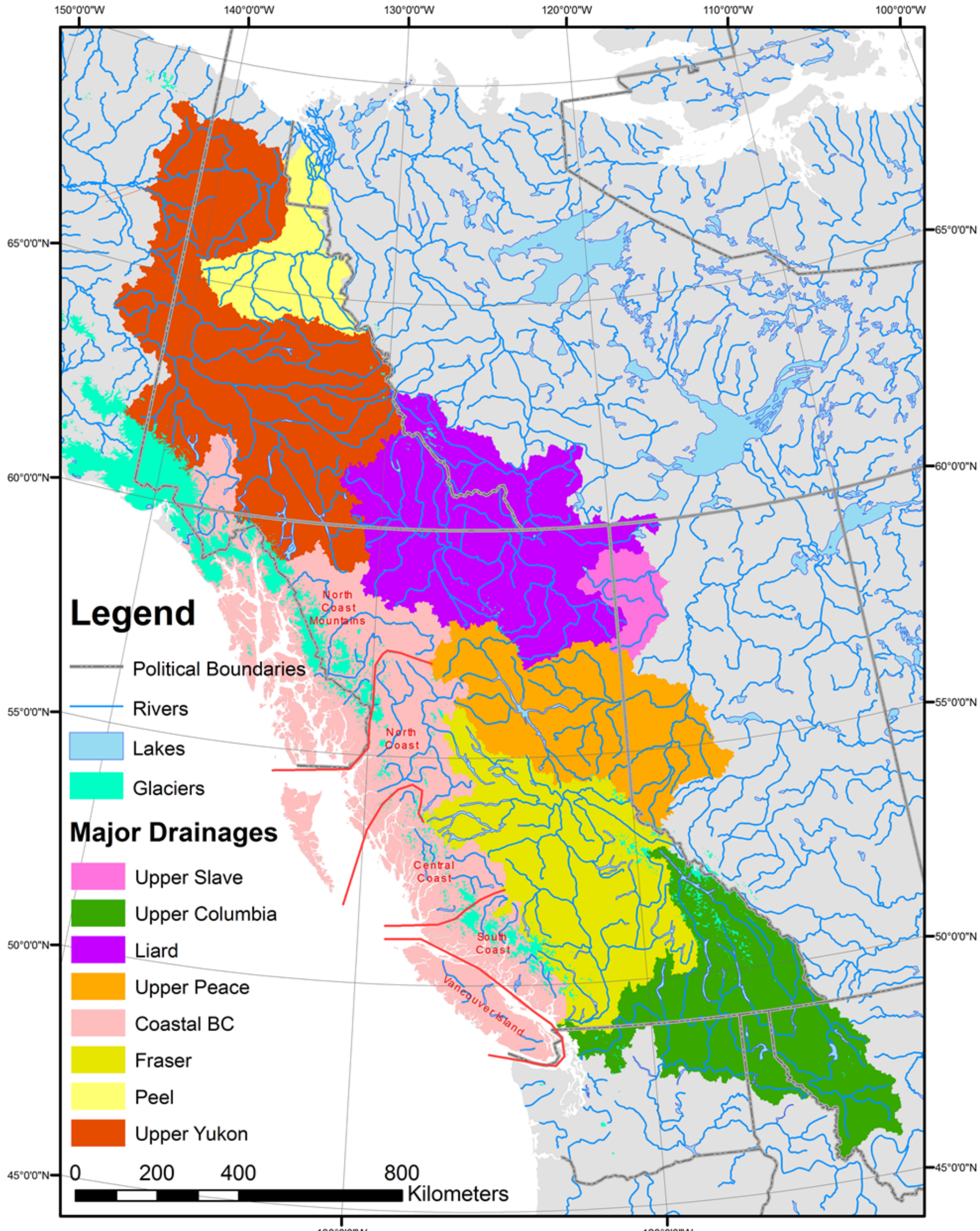

Figure 2. Proposed spatial domain of the Hydrologic Impacts theme, organized by major drainages (see text). Also shown are major hydrographic features (rivers and lakes) and glaciers within the study region. Note that Coastal BC is further sub-divided into (from south to north) Vancouver Island, South Coast, Central Coast, North Coast and North Coast Mountains.