# Hydrologic Impacts

## Research Plan: 2015 to 2019

**December 2, 2014**

**Markus A. Schnorbus**

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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/.

## Disclaimer

## Acknowledgements

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# 1. Introduction

## 1.1 Background

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) and changes in extremes have been recently discussed by Peterson et al. (2013). 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; Dai 2013; Hirabayashi et al. 2013). 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 HIP 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 daily 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 such as changes in radiative forcing as a result of human-derived greenhouse gas (GHG) emissions. Internal processes produce *internal climate variability* that arises from natural interactions within the earth-ocean-atmosphere climate system, such as manifested in the El Niño 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 (e.g. IPCC 2013).

The activities with which HI intends to address and estimate hydrologic impacts within the short-, near- and long-term timeframes are classified into forecasting, prediction and projection, respectively. A f*orecast* 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 p*rediction* 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 GHG 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.

## 1.2 Progress to 2012-2016 Research Plan

This section provides a short summary of HI Theme research progress following the previous HI Research Plan (Schnorbus 2012), which covered the period 2012-2016.

### 1.2.1 Hydrologic Modelling

Code updates, refinements and re-engineering have been undertaken on the original VIC software in order to increase simulation efficiency, model robustness and maintainability of the code, as well as introduce structural changes to accommodate glacier mass balance and dynamics modelling. Specific changes include code conversion from C to C++, code refactoring, improved thread safety, addition of netCDF input/output, re-engineering (vectorization) to accommodate more realistic description of sub-grid land cover, and validation of code check-pointing (Stone 2013; Sharifian 2014). The updated code base is now referred to internally as VIC 4.1.2glacier. VIC 4.1.2glacier now includes algorithms to simulate glacier mass balance wherein glacier melt is realistically simulated using an energy-balance approach and glacier accumulation is tracked explicitly based on precipitation, snowpack dynamics and the conversion of snow to firn/glacier ice. The storage and drainage of melt water on and through the glacier is modelled empirically.

VIC 4.1.2glacier has been applied to a new, and much larger study domain (2,300,000 $km^2$), as shown in Figure 2. Due to significant structural changes in VIC v4.1.2glacier, the need to model over a much larger domain than previously, and in order to take advantage of updated data sources, the new VIC was re-parameterized from scratch. This included:

- Obtaining and processing updated data sources (digital elevation model, soil, land cover, stream network, and climate data)
- Creating new parameter files (soil, vegetation, snow band, vegetation library, and routing files)
- Collecting new/additional calibration data (hydrometric data, snow data, and evapotranspiration data)

The collection and pre-processing of data required for model calibration has been completed. This includes the acquisition of hydrometric, snow and evaporation data.

A long-term objective of the HI Theme is to quantify the effects of climate variability and change on water properties, such as water temperature. In order to accomplish this, the intent was to add the capability to simulate water temperature with the VIC model. However, efforts to study and assess the effects of climate change and variability on water temperature have been hampered by a lack of centralized and readily available water temperature data. Although water temperature data for the study domain exists, it is scattered among various public and private agencies, universities and individual researchers. Therefore, as an initial step, water temperature data has been collected and centrally archived for approximately 2000 locations throughout British Columbia and the Yukon (Khan 2014).

### 1.2.2 Statistical Downscaling

Based on recent inter-comparison work, the RCI theme at PCIC has developed a method of statistical downscaling that is a hybrid of BCCA (Maurer et al. 2010) and an additional quantile-mapping bias-correction step. This in-house method of downscaling substantially improves skill in day-to-day sequencing of events compared to the widely used BCSD (Wood et al. 2004), an important factor for indices of extremes (Cannon et al., in preparation; Werner and Cannon, in preparation). PCIC has since completed production of statistically-downscaled future climate projections for all of North America (Murdock et al. 2013, 2014). The technology behind these projections will be used to provide downscaled forcings specifically tailored for hydrologic projections (see Section 4.3).

### 1.2.3 Climate Model Output

Due to resource constraints, it is often impractical to conduct hydrologic impacts modelling with more than a handful of global climate model (GCM) simulations. Nevertheless, an objective means of selecting a sub-set of all available GCM projections in order to represent both internal variability and model uncertainty is a challenging task. To address this issue, the RCI theme developed an automated algorithm to select a minimal number of climate scenarios that best captures the projection uncertainty from the full range of available simulations (Cannon 2014).

### 1.2.4 Forecasting and Prediction

PCIC has developed a streamflow forecasting test-bed for the Fraser River basin. This test-bed uses VIC v4.0.7 driven by downscaled dynamic seasonal climate forecasts from the Canadian Centre for Climate Modelling and Analysis' (CCCma) Canadian Seasonal to Interannual Prediction System (CanSIPS). This application has been used to explore the skill of dynamically-based streamflow forecasts, by comparing to state-of-practice techniques, specifically Ensemble Streamflow Prediction (ESP) and conditional ESP. Forecasting skill has been assessed for monthly and seasonal streamflow forecasts for lead times of up to eleven months (Shrestha et al. 2015).

### 1.2.5 Extended Applications

In collaboration with Environment Canada's Water and Climate Impacts Research Centre (W-CIRC), work has been completed to validate the VIC model's ability to simulate Indicators of Hydrologic Alteration (IHAs) (Shrestha et al. 2014). IHAs are indices used to describe various aspects of the streamflow hydrograph (low flow, high flows, extremes, monthly flows, flow duration, etc) at various timescales, which are considered important at describing the ecological consequences of streamflow alteration. The results show generally good skill of the observation-driven VIC model in replicating most of the IHAs, although statistically significant differences in some metrics for monthly flows, number and duration of flow pulses, rise and fall rates, and flow reversals were noted.

Work has been completed to assess the effects of projected climate change on streamflow extremes, particularly high streamflow extremes (e.g. peak annual streamflow). Work has been completed for the Fraser and upper Columbia basins (Shrestha et al. 2012; Werner et al. 2013). In both the Fraser and upper Columbia basins annual maximum peak flow, which is predominantly snowmelt driven, is projected to occur earlier in the year (by as much as several weeks on average by end-century). Annual maximum peak flow is expected to increase in the Columbia, but results are ambiguous for the Fraser.

Recent streamflow projections produced by PCIC were based on downscaled output from GCMs contributing to Coupled Model Inter-comparison phase 3 (CMIP3) experiments. Given that GCM uncertainty is a large part of projection uncertainty, the question arises: do the new GCMs contributing to the Coupled Model Inter-comparison phase 5 (CMIP5) experiments, based on new emissions scenarios, present a different picture of future streamflow change? To quickly update previous work with the new CMIP5 projections we used a statistical model to emulate the CMIP3-based projections made by the VIC model. This was then applied to the new CMIP5 climate change projections. This method was applied to produce CMIP5-based monthly streamflow projections for the Fraser and Peace River basins (Schnorbus and Cannon 2014).

# 2. Research Plan

## 2.1. Purpose

The purpose of this Research Plan is to provide strategic program definition to the Hydrologic Impacts (HI) Theme at PCIC and to guide applied research activities over the coming five years. The Research Plan defines the major HI objectives and indicates 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, with planned updates every two years. The current document is an update to the previous Hydrologic Impacts Research Plan detailed in Schnorbus (2012).

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 2012).

## 2.2. Research Objectives

The four HI Theme objectives 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 intended that all four objectives will address, when practical, the expanded spatial domain described in Section 2.3.

Table 1. Hydrologic Impacts Program Research Objectives

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

The purpose of Objective 1 is to expand upon the previous hydro-climate projection work of the HI Theme, as reported by Schnorbus et al. (2014), Shrestha et al. (2012) and Werner et al. (2013). 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. 2012), 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 2005 to 2100. These projections will cover the full range of potential future climates encompassed by the various RCP scenarios, but with greater emphasis on RCP4.5 and RCP8.5. 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). This objective is the top priority for the next five years.

Recent examinations of decadal prediction skill based on CMIP5 models (Boer et al. 2013; Meehl et al. 2013) indicates that predictive skill for temperature and precipitation is low for western Canada. This leads us to the conclusion that there is, at present, little to be gained by exploring potential skill in hydrologic decadal prediction. Hence, this objective is deferred over the next five years, at which time we anticipate that we will have access to updated CMIP6-based decadal prediction results (Meehl et al. 2014).

Based on recent research conducted at PCIC for the Fraser River (Shrestha et al. 2015), seasonal hydrologic forecasts driven by deterministic climate models currently offer some skill improvement over more traditional methods based on Ensemble Streamflow Prediction (ESP). Seasonal hydrologic forecasting skill depends upon both uncertainties in specified initial conditions (for shorter lead times) and climate forecast skill (for longer lead times) (Li et al. 2009; Shukla and Lettenmaier 2011). Hence improvements in forecast skill may be possible via applied research into snow and soil moisture assimilation techniques (Han et al. 2012; Magnusson et al. 2014), or by assessing the effects of using a larger ensemble of dynamic climate forecasts (e.g. such as those available through the North American Multi-Model Ensemble (NMME) (Kirtman et al. 2013). We could also pursue additional improvements in forecast skill by investigating the use of statistical post-processing techniques, such as bias-correction (Shi et al. 2008) and ensemble post-processing (van Andel et al. 2013). Nevertheless, based on stakeholder feedback, this objective is not considered a high priority for the next five years.

The purpose of Objective 4 (Extended Applications) is to extend the results from Objectives 1, 2 and 3 (but primarily Objective 1), which focus exclusively on hydrologic changes, to more specifically address impacts on water and its properties (e.g. temperature) 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. This objective is the second priority for the next five years.

## 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. The proposed spatial domain is shown in Figure 2.

Prioritization of basins within the spatial domain will be required for work planning purposes. At this time the Columbia basin (including the Okanagan and Similkameen), north-eastern BC (including the upper Peace, upper Slave and Liard basins) and the Fraser have been identified as priority regions and would be addressed first, second, and third, respectively. These priority regions will be followed by the remaining drainages in (or flowing into) BC, followed by YK drainages. However, order of priority is also subject to stakeholder requirements.

Note that the extent of the spatial domain for any particular study may be governed by additional constraints such as the domain of high-resolution dynamically-downscaled RCM output(s) and the availability of hydrometric data required for model calibration and validation.

# 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 3, 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 3 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 4, 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 3. However, as much of the expertise required to address specific water resource impacts does not currently reside at PCIC, 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 – Projection

The PCIC HI Theme will adopt a comprehensive approach characterized by the use of leading-edge methodology and tools. For Objective 1 the approach shown schematically in Figure 1 will be followed. The proposed method will generally involve three steps (Figure 1):

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

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).

Methodological details include:

1. Use of ensemble simulations to quantify uncertainty due to emissions, variation in climate sensitivity to a given radiative forcing between individual GCMs, and internal climate variability.
2. Selecting and processing global and/or regional climate data from the CMIP5 long-term experiments (Taylor et al. 2012).
3. Downscaling to produce a set of consistent domain-wide climate projections. The downscaling must be tailored and/or appropriate to addressing the effects of climate change and variability on hydrologic phenomena at a daily timescale.
4. High resolution (1/16-degree), spatially-distributed, process-based 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).

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 (see Figure 1).

## 3.3. Objectives 2 and 3 – Prediction and Forecasting

The intent is that hydro-climate assessments at all time frames (whether projections, predictions, or forecasts) will utilize the same methodological approach and tools. Hence, the approach to be used for Objectives 2 and 3 will be very similar to that described for Objective 1. The main distinction between forecasting, prediction or projection problems is largely addressed by selecting the appropriate source global climate data (step 1 in Figure 1). Hydrologic forecasts would employ hindcast and forecast output from dynamical forecasting systems, such as the Canadian Seasonal to Interannual Prediction System (CanSIPS) (Merryfield et al. 2013) and the North American Multi-Model Ensemble (NMME) (Kirtman et al. 2013). Hydrologic predictions would potentially employ decadal climate prediction results from the upcoming CMIP6 experiment (Meehl et al. 2014).

## 3.4. Objective 4 – Extended Applications

The approach required to address Objective 4 is yet to be determined in detail, but will involve various types of impact modelling (e.g. reservoir modelling, analysis of in-stream flow indices, habitat suitability modelling, etc.) as well as water properties modelling, such as water temperature. Additional activities may include extending the hydrologic modelling work conducted under Objectives 1, 2, and 3 to include scenarios dealing with land use change, current or planned flow regulation and diversion projects, and water abstraction for irrigation. While simple land use change scenarios can be dealt with in a straightforward manner with current hydrologic modelling tools, incorporation of the effects of flow regulation, diversion and irrigation would require access to alternative models or upgrades to PCIC's current hydrology modelling. The scope and priorities 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 Requirements

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 and extended applications. 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 milestone.

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 external collaborators; these are also anticipated and identified for each commitment. The other themes at PCIC include the 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). Potential external collaborators include the Water and Climate Impacts Research Centre (W-CIRC), the Canadian Centre for Climate Modelling and Analysis (CCCma), 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 and through the Western Canada Research Grid (WestGrid; http://www.westgrid.ca/). Data management and storage will utilize PCIC data and computing resources.

## 4.1. Requirement 1 - Hydrologic Modelling

This requirement includes improvements to PCIC's hydrologic modelling capability and technology, predominantly as it pertains to satisfying Objectives 1, 2 and 3. This will be affected exclusively by upgrades to the VIC model over the next two years; but if merited, will also include adopting alternative models or technologies over the next five years. Immediate capability improvements include explicit representation of glacier dynamics and consideration of frozen soil and permafrost in the northern portion of the study area (Zhang et al. 2008). Additional activities revolve around model set-up, parameterization and calibration to the expanded spatial domain.

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 4. 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. An initial step will involve digitization, validate and organization of a substantial amount of water temperature data. Subsequent research can then focus on exploring and testing the implementation of water temperature modeling with the VIC platform for a case study basin such as the Fraser River, which contains the majority of water temperature observations (see Section 1.2.1). If successful, future work in three- to five-years' time would potentially involve a regional application of the water temperature model (see Section 4.4).

Additional research will seek to exploit the availability of dynamically downscaled (using a regional climate model (RCM)) climate projections from experiments such as Coordinated Regional Climate Downscaling Experiment (CORDEX) as well as from other research partners, such as CCCma, UVic and Ouranos. Such dynamically downscaled data would be used to augment existing hydrologic projections, most likely by serving as input to a hydrologic model (following suitable bias-correction and downscaling if necessary). Supporting research might also involve diagnosis of the raw RCM output to determine if recent models demonstrate improved suitability to directly drive a hydrologic model in order to quantify climate change impacts.

Although explicit modelling of lakes, wetlands and groundwater have also been identified as necessary components to improve the realism and accuracy 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 over the next two years, but opportunities to address these specific issues over the next five years may be possible via opportunistic collaborative arrangements.

At the local scale there can be important feedbacks between vegetation dynamics (forest succession, forest disturbance, species migration, etc.) and hydrologic process. Although GCMs attempt to model these dynamics of the terrestrial ecosystem under non-stationary climate, they are unable to consider the effects of regional and local variation in important hydro-climatic processes. Consequently, there is a recognized need for higher resolution hydrologic modelling to capture the dynamic response of vegetation to, and subsequent impact on, local and regional hydrology. However, due to limited resources and expertise this activity is identified as a low priority over the next five years. A more modest effort would be to assess VIC model sensitivity to changes in vegetation parameters, an activity that can be undertaken as part of the hydrology model calibration process.

This requirement identifies what will essentially be the core responsibilities of the HI theme at PCIC over the next two years, with some more generalized and opportunistic goals identified for the remaining three years. Specific commitments, given in order of priority, are as follows.

- **Modelling of glacier dynamics -** complete the VIC model upgrade to include the ability to represent glacier volume and area changes. *Milestone*: March 2015 • *Lead*: HI • *Support*: CSG + CAM + UBC/UNBC
- **Hydrology model parameterization -** finalize set-up and parameterization of the upgraded VIC hydrology model to the expanded spatial domain (Figure 2), including completion of the surface drainage network. *Milestone*: July 2015 • *Lead*: HI •*Support*: n/a
- **Frozen soil and permafrost -** test and implement the VIC model's routines for simulating frozen soil and permafrost. *Milestone*: July 2015 • *Lead*: HI •*Support*: n/a
- **Hydrology model calibration and validation** – calibration and validation of the upgraded VIC hydrology model, including validation against snow and evapotranspiration data and sensitivity analysis of vegetation parameters. The priority regions for this activity will be the Columbia, north-eastern BC and the Fraser. *Milestone*: 2015/16 • *Lead*: HI • *Support*: CSG
- **Hydrologic projections for study domain -** complete CMIP5-based transient hydrologic projections based on an ensemble of GCMs and RCP scenarios and deliver data via web-based portal. The priority regions for this activity will be the Columbia, north-eastern BC and the Fraser. *Milestone*: 2016 • *Lead*: HI • *Support*: CSG
- **Stream temperature model -** test coupling or integration of water temperature model with the VIC hydrology model in order to model water temperature in a spatially distributed manner using a case-study watershed such as the Fraser. *Milestone*: 2016/17 • *Lead*: HI • *Support*: W-CIRC + DFO + UBC/UW/OSU
- **Utilize dynamically downscaled driving data** – use available RCM results to augment existing hydrologic projection ensembles. *Milestone*: 2017/18 • *Lead*: HI • *Support*: RCI**Lakes and wetlands modelling -** seek opportunities, via collaboration, to implement lakes and wetlands modelling. *Milestone*: 2018 • *Lead*: HI • *Support*: unknown
- **Groundwater modelling** – seek opportunities, via collaboration, to implement regional groundwater modelling. *Milestone*: 2018 • *Lead*: HI • *Support*: collaboration required

- **Dynamic vegetation -** seek opportunities, via collaboration, to implement dynamic vegetation modelling as part of hydrologic models. *Milestone*: 2018 • *Lead*: HI • *Support*: collaboration required

## 4.2. Requirement 2 – Baseline Historical Climate Data

Calibration of hydrology models and statistical downscaling techniques rely on the use of gridded historical climate data. It was originally intended to utilize an off-the-shelf daily gridded climate product produced by Natural Resources Canada based on the ANUSPLIN thin-plate smoothing spline algorithm (Hutchinson et al. 2009; McKenney et al. 2011). However, the daily gridded data are still not available for the United States. Consequently, the required gridded historical temperature and precipitation data that encompasses the spatial domain given in Figure 2 will be generated in-house using the same ANUSPLIN algorithm. Some preliminary hydrologic modelling work with the current ANUSPLIN-based product for British Columbia indicates the presence of precipitation and temperature biases, likely the result of low station density and under-representation of high elevation regions. In order to correct these biases, the ANUSPLIN-based data will be corrected to PRISM-based climatologies. The assumption is that PRISM-based climatologies, which typically use more station data and are an expert-based system, provide a more accurate representation of the spatial distribution of temperature and precipitation, which can be used to adjust the daily information provided by the ANUSPLIN-based daily grids.

Although any work conducted in support of this requirement will overlap considerably with the activities of the CAM theme, the immediate need for daily baseline data is currently a requirement unique to, and as such falls under the lead of, HI. The following commitment has been identified:

- **Create gridded daily climate data** – interpolate station data using ANUSPLIN methodology to create gridded data consistent with the latest ClimateWNA 1971-2000 monthly climatology. *Milestone*: July 2015 • *Lead*: HI • *Support*: RCI + CAM

## 4.3. Requirement 3 - Downscaling

Short-term forecasts, near-term predictions and long-term projections will all be driven by outputs downscaled from coarse resolution global climate models. Therefore, leveraging off the testing and development work conducted by the RCI Theme over the past two years, we will use statistical downscaling to produce forcing data tailored to satisfy the requirements of HI (i.e. daily data at 1/16-degree spatial resolution over the spatial domain shown in Figure 2 and using the baseline climatology developed as per Requirement 4.2.1). The following commitment has been identified:

- **Downscaling** – statistically downscale a select subset of CMIP5 GCM experiments to accurately estimate the daily (including extremes) projected climate response, including changes in the variability of daily phenomena. *Milestone*: 2016 • *Lead*: HI • *Support*: RCI

## 4.4. Requirement 4 – Extended Applications

It is intended that the latter period the Research Plan (i.e. years three to five) will focus on using the hydrologic data, generated primarily under Objective 1 (Long-term Projections via Requirements 1, 2 and 3) to more deeply analyse changes in specific aspects of the hydrologic cycle as well as to directly assess impacts to various water-related activities. Proposed research activities include 1) a region-wide analysis of changes in hydrologic extremes, specifically changes in flood and meteorological, agricultural and hydrologic drought hazard, 2) a regional analysis of projected changes in water temperature, 3) projected changes in river ice, stream hydraulics and water level, and 4) analysis of water resource impacts on such sectors as irrigated agriculture, power generation, domestic and industrial water supply, fisheries management, public safety, recreation and tourism and ecological health.

To date hydrologic projections have only considered anthropogenic climate effects on the hydrologic cycle in terms of global systemic changes (i.e. change to the climate system), treating the modelled drainage basins in all other respects as unmodified by human activity. However, for many regions of BC, anthropogenic activities (such as forest harvesting, urbanization, irrigation withdrawal, flow regulation and flow diversion) also condition the hydrologic system (Montanari et al. 2013), such that many rivers in North America are subject to multiple sources of stress (Palmer et al. 2009). Consequently, it is recognized that in order to more realistically model the hydrologic system, it is crucial to include human dynamics as an integral part of the hydrologic cycle. Such an approach to hydrologic systems modelling would serve to place the effects of climate change and climate variability in a more relevant local context.

Extended application projects will be regionally prioritized consistent with Requirement 1 (Hydrologic Modelling), and as detailed in Section 2.3. It is reiterated that the scope of applied research activities will rely upon guidance from stakeholders and the availability of expertise from external agencies and researchers, and may well rely upon exploiting opportunistic research partnerships. Although several activities are proposed, the HI theme will remain receptive to additional or alternative topics and projects that fall within the mandate of the theme. The following commitments, in order of priority, are proposed:

- **Regional analyses of hydrologic extremes** – quantify changes in flood and drought hazard for defined sub-regions as determined by stakeholder interest. *Milestone*: 2017 • *Lead*: HI • *Support*: RCI + stakeholders
- **Regional analysis of water temperature change -** quantify changes in water temperature for lakes and streams for defined sub-regions as determined by stakeholder interest. *Milestone*: 2017/18 • *Lead*: HI • *Support*: EC/DFO/USFS + UBC/SFU + stakeholders
- **Sectoral and ecological analysis of water resources impacts** – impacts of hydrologic change (due to climate change and variability) on various sectors. *Milestone*: 2018 • *Lead*: relevant stakeholder(s) • *Support*: HI + collaborators
- **River ice and hydraulic modelling -** seek opportunities, via collaboration, to assess changes in lake and river ice cover, ice breakup and river hydraulics (e.g. water level and flow velocity). *Milestone*: 2018 • *Lead*: relevant stakeholder(s) • *Support*: HI + collaborators
- **Hydrologic systems modelling** – investigate collaborative opportunities and/or new technologies to model the dynamics of anthropogenic activities (land management, water extraction, reservoir management, etc.) and climate-driven human feedbacks on the hydrologic cycle. *Milestone*: 2018 • *Lead*: HI • *Support*: unknown

## 4.5. Requirement 5 – Delivering Information

Over the course of this research, a large volume of data and information will be produced. Hence, online dissemination of model data will be a key aspect of information delivery. Data delivery will include gridded (e.g. runoff, snow, evaporation, soil moisture) and station (e.g. streamflow) hydrology model output, gridded climate forcings (e.g. temperature, precipitation, wind speed, etc.) and glacier mass, volume and area data.

Building upon recent work at PCIC (see Section 1.2.5), it is proposed to conduct continuing research into using model emulation as a means to operationalize hydrologic projections (see Figure 1). The intent is to provide external users the flexibility to generate on-demand hydrologic projections for a customised regions/time periods using specified CMIP3- and CMIP5-based (and possibly upcoming CMIP6-based) global climate experiments. An additional online tool will allow users the ability to generate routed streamflow at custom locations within the hydrologic modelling domain based on gridded model output. Given the anticipated resources required, any work in this regard would not be considered until years three through five.

- **Data portal** – contribute CMIP5-based hydrologic model results and accompanying driving data sets to the PCIC data portal. *Milestone*: 2015/16 • *Lead*: CSG • *Support*: HI
- **Develop online tools -** Develop tools to operationalize hydrologic streamflow projections and generate routed streamflow time series data at custom locations. *Milestone*: 2018 • *Lead*: HI • *Support*: CSG

## 5. References


Van Andel, S. J., A. Weerts, J. Schaake, and K. Bogner, 2013: Post-processing hydrological ensemble predictions intercomparison experiment. *Hydrol. Process.*, **27**, 158–161, doi:10.1002/hyp.9595.

Barnett, T. P., and Coauthors, 2008: Human-Induced Changes in the Hydrology of the Western United States. *Science*, **319**, 1080–1083, doi:10.1126/science.1152538.

Boer, G. J., V. V. Kharin, and W. J. Merryfield, 2013: Decadal predictability and forecast skill. *Clim Dyn*, **41**, 1817–1833, doi:10.1007/s00382-013-1705-0.

Bonfils, C., and Coauthors, 2008: Detection and Attribution of Temperature Changes in the Mountainous Western United States. *Journal of Climate*, **21**, 6404–6424, doi:10.1175/2008JCLI2397.1.

Bray, D., and H. von Storch, 2009: "Prediction" or "Projection"? *Science Communication*, **30**, 534–543, doi:10.1177/1075547009333698.

Cannon, A. J., 2014: Selecting GCM Scenarios that Span the Range of Changes in a Multimodel Ensemble: Application to CMIP5 Climate Extremes Indices. *J. Climate*, doi:10.1175/JCLI-D-14-00636.1. http://dx.doi.org/10.1175/JCLI-D-14-00636.1.

Dai, A., 2013: Increasing drought under global warming in observations and models. *Nature Clim. Change*, **3**, 52–58, doi:10.1038/nclimate1633.

Hamlet, A. F., and D. P. Lettenmaier, 2007: Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resour. Res.*, **43**, W06427, doi:10.1029/2006WR005099.

Han, E., V. Merwade, and G. C. Heathman, 2012: Implementation of surface soil moisture data assimilation with watershed scale distributed hydrological model. *Journal of Hydrology*, **416–417**, 98–117, doi:10.1016/j.jhydrol.2011.11.039.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae, 2013: Global flood risk under climate change. *Nature Clim. Change*, **3**, 816–821, doi:10.1038/nclimate1911.

Hutchinson, M. F., D. W. McKenney, K. Lawrence, J. H. Pedlar, R. F. Hopkinson, E. Milewska, and P. Papadopol, 2009: Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum–Maximum Temperature and Precipitation for 1961–2003. *J. Appl. Meteor. Climatol.*, **48**, 725–741, doi:10.1175/2008JAMC1979.1.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker et al., Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Keenlyside, N. S., and J. Ba, 2010: Prospects for decadal climate prediction. *WIREs Clim. Chg.*, **1**, 627–635, doi:10.1002/wcc.69.

Khan, A., 2014: *Collection of Stream Temperature Data for British Columbia and Preliminary Analysis of Fraser River Basin*. Pacific Climate Impacts Consortium, University of Victoria, 36 pp.

Kirtman, B. P., and Coauthors, 2013: The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction. *Bull. Amer. Meteor. Soc.*, **95**, 585–601, doi:10.1175/BAMS-D-12-00050.1.

Lettenmaier, D. P., and E. F. Wood, 1993: Hydrologic forecasting. *Handbook of Hydrology*, D.R. Maidment, Ed., McGraw-Hill, 26.1–26.30.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. *Journal of Geophysical Research-Atmospheres*, **99**, 14415–14428, doi:10.1029/94JD00483.

Li, H., L. Luo, E. F. Wood, and J. Schaake, 2009: The role of initial conditions and forcing uncertainties in seasonal hydrologic forecasting. *J. Geophys. Res.*, **114**, D04114, doi:10.1029/2008JD010969.

Magnusson, J., D. Gustafsson, F. Hüsler, and T. Jonas, 2014: Assimilation of point SWE data into a distributed snow cover model comparing two contrasting methods. *Water Resour. Res.*, **50**, 7816–7835, doi:10.1002/2014WR015302.

Maurer, E. P., H. G. Hidalgo, T. Das, M. D. Dettinger, and D. R. Cayan, 2010: The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrol. Earth Syst. Sci.*, **14**, 1125–1138, doi:10.5194/hess-14-1125-2010.

McKenney, D. W., and Coauthors, 2011: Customized Spatial Climate Models for North America. *Bulletin of the American Meteorological Society*, **92**, 1611–1622, doi:10.1175/2011BAMS3132.1.

Meehl, G. A., and Coauthors, 2013: Decadal Climate Prediction: An Update from the Trenches. *Bull. Amer. Meteor. Soc.*, **95**, 243–267, doi:10.1175/BAMS-D-12-00241.1.

——, R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony, and B. Stevens, 2014: Climate Model Intercomparisons: Preparing for the Next Phase. *Eos Trans. AGU*, **95**, 77–78, doi:10.1002/2014EO090001.

Merryfield, W. J., and Coauthors, 2013: The Canadian Seasonal to Interannual Prediction System. Part I: Models and Initialization. *Mon. Wea. Rev.*, **141**, 2910–2945, doi:10.1175/MWR-D-12-00216.1.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, 2008: Stationarity Is Dead: Whither Water Management? *Science*, **319**, 573–574, doi:10.1126/science.1151915.

Montanari, A., and Coauthors, 2013: "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, **58**, 1256–1275, doi:10.1080/02626667.2013.809088.

Moss, R. H., and Coauthors, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756, doi:10.1038/nature08823.

Murdock, T. Q., A. J. Cannon, and S. R. Sobie, 2013: *Statistical downscaling of future climate projections*. Pacific Climate Impacts Consortium, University of Victoria, 16 pp.

——, ——, and ——, 2014: *Statistical downscaling of future climate projections for North America*. Pacific Climate Impacts Consortium, University of Victoria, 38 pp.

Palmer, M. A., D. P. Lettenmaier, N. L. Poff, S. L. Postel, B. Richter, and R. Warner, 2009: Climate Change and River Ecosystems: Protection and Adaptation Options. *Environmental Management*, **44**, 1053–1068, doi:10.1007/s00267-009-9329-1.

PCIC, 2012: *The PCIC Strategic Plan 2012-2016*. Pacific Climate Impacts Consortium, Victoria, B.C.,.

Peterson, T. C., and Coauthors, 2013: Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States: State of Knowledge. *Bull. Amer. Meteor. Soc.*, **94**, 821–834, doi:10.1175/BAMS-D-12-00066.1.

Pierce, D. W., and Coauthors, 2008: Attribution of Declining Western U.S. Snowpack to Human Effects. *Journal of Climate*, **21**, 6425–6444, doi:10.1175/2008JCLI2405.1.

Rodenhuis, D., K. E. Bennett, A. T. Werner, T. Q. Murdock, and D. Bronaugh, 2009: *Climate overview 2007: Hydro-climatology and future climate impacts in British Columbia*. Pacific Climate Impacts Consortium, Victoria, B.C.,.

Schnorbus, M., 2012: *Hydrologic Impacts Research Plan for 2012 - 2016*. Pacific Climate Impacts Consortium, University of Victoria, 23 pp.

——, A. Werner, and K. Bennett, 2014: Impacts of climate change in three hydrologic regimes in British Columbia, Canada. *Hydrological Processes*, **28**, 1170–1189, doi:10.1002/hyp.9661.

Schnorbus, M. A., and A. J. Cannon, 2014: Statistical emulation of streamflow projections from a distributed hydrological model: Application to CMIP3 and CMIP5 climate projections for British Columbia, Canada. *Water Resour. Res.*, **50**, 8907–8926, doi:10.1002/2014WR015279.

Sharifian, S., 2014: *Variable Infiltration Capacity (VIC) Hydrology with Glacier Mass Balance and Dynamics*. Pacific Climate Impacts Consortium and Faculty of Engineering, University of Victoria, 44 pp.

Sheffield, J., and E. F. Wood, 2008: Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, **31**, 79–105, doi:10.1007/s00382-007-0340-z.

Shi, X., A. W. Wood, and D. P. Lettenmaier, 2008: How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting? *J. Hydrometeor*, **9**, 1350–1363, doi:10.1175/2008JHM1001.1.

Shrestha, R. R., M. A. Schnorbus, A. T. Werner, and A. J. Berland, 2012: Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada. *Hydrological Processes*, **26**, 1840–1860, doi:10.1002/hyp.9283.

——, D. L. Peters, and M. A. Schnorbus, 2014: Evaluating the ability of a hydrologic model to replicate hydro-ecologically relevant indicators. *Hydrol. Process.*, **28**, 4294–4310, doi:10.1002/hyp.9997.

——, M. A. Schnorbus, and A. J. Cannon, 2015: A Dynamical Climate Model-Driven Hydrologic Prediction System for the Fraser River, Canada. *J. Hydrometeor*, doi:10.1175/JHM-D-14-0167.1. http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0167.1.

Shukla, S., and D. P. Lettenmaier, 2011: Seasonal hydrologic prediction in the United States: understanding the role of initial hydrologic conditions and seasonal climate forecast skill. *Hydrol. Earth Syst. Sci.*, **15**, 3529–3538, doi:10.5194/hess-15-3529-2011.

Stone, J., 2013: *Variable Infiltration Capacity Software Improvements*. Pacific Climate Impacts Consortium and Faculty of Engineering, University of Victoria, 35 pp.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Van Vuuren, D. P., and Coauthors, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109**, 5–31, doi:10.1007/s10584-011-0148-z.

Werner, A. T., M. A. Schnorbus, R. R. Shrestha, and H. D. Eckstrand, 2013: Spatial and Temporal Change in the Hydro-Climatology of the Canadian Portion of the Columbia River Basin under Multiple Emissions Scenarios. *Atmosphere-Ocean*, **51**, 357–379, doi:10.1080/07055900.2013.821400.

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, doi:10.1023/B:CLIM.0000013685.99609.9e.

Zhang, T., R. G. Barry, K. Knowles, J. A. Heginbottom, and J. Brown, 2008: Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography*, **31**, 47–68, doi:10.1080/10889370802175895.

## 6. Figures

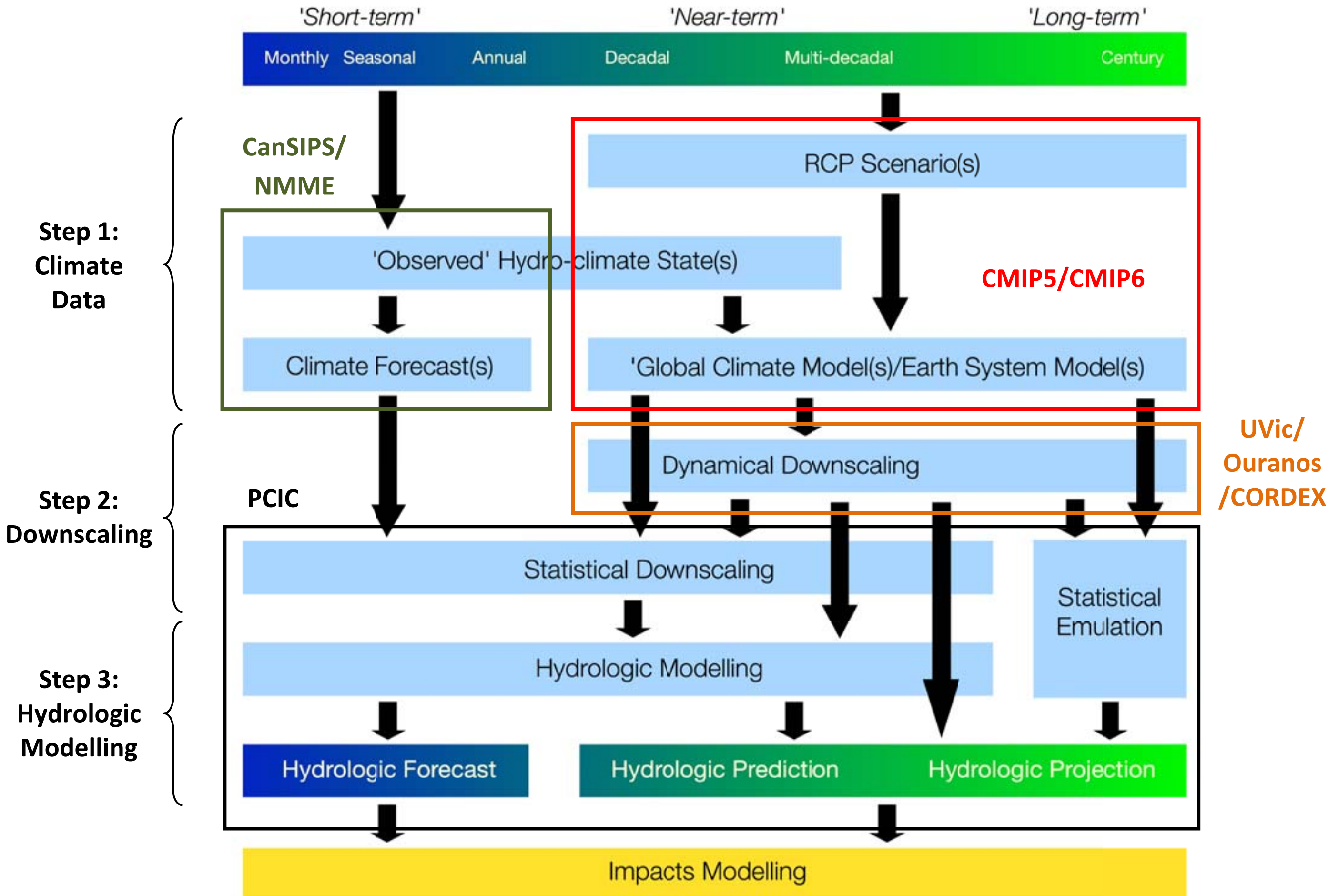


**Figure 1**. Schematic of proposed approach to address hydrologic impacts due to climate variability and climate change by means of "short-term" (monthly to annual) forecasts, "near-term" (decadal to multi-decadal) predictions and "long-term" (multi-decadal to century) projections. Global climate data will be obtained from external agencies, such as CCCma or NMME, for monthly, seasonal and decadal forecasts and CMIP5 or CMIP6 for decadal climate predictions and multi-decadal and century climate projections (step 1). Dynamical downscaling results will be obtained from external agencies such as UVIC, Ouranos or CORDEX (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).

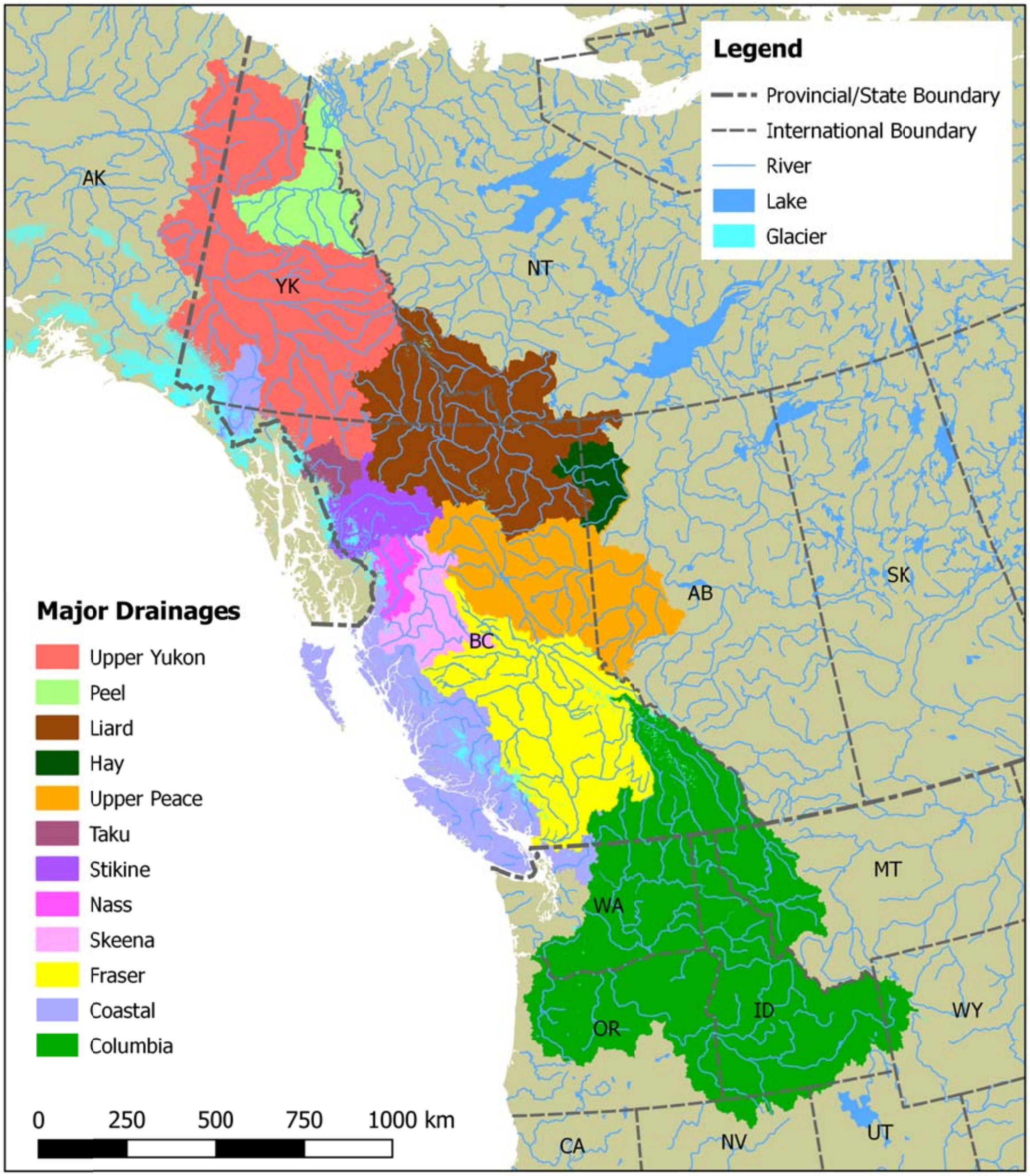


**Figure 2**. Proposed spatial domain of the Hydrologic Impacts Program, organized by major drainages (see text). Also shown are major hydrographic features (rivers and lakes) and glaciers within the study region.