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PREDICTING IN UNGAUGED BASINS USING PHYSICAL PRINCIPLES OBTAINED USING THE DEDUCTIVE, INDUCTIVE, AND ABDUCTIVE REASONING APPROACH

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4.1 ABSTRACT

At the beginning of the PUB Decade the process approach to hydrological prediction was proposed as part of the solution to the problem of predicting in ungauged basins; however, persistent errors in model process descriptions continue to hamper the progress of hydrology as a science and in the development of solutions for PUB. Process algorithms developed in the last three decades of research in Canada and elsewhere provide solutions to most of these errors for cold regions environments, but the implementation of these algorithms within a predictive model is nontrivial. An approach combining deductive, inductive, and abductive reasoning for developing appropriate model process structure, basin discretization and parameterization is applied to the ungauged portion of the Smoky River Basin in Alberta, Canada. Deductive reasoning uses known physical laws and relationships to derive information from existing basin inventories and satellite imagery. Inductive reasoning is used to calibrate a small selection of sub-surface model parameters using discharge measured in a local sub-basin. Abductive reasoning is used to borrow parameters from a suite of process and modelling research basins in western Canada. The model predicted the peak spring flows on the Smoky River over several years and at two different scales with reasonable accuracy. This suggests that prediction in ungauged basins using physical principles is possible and indeed a viable alternative in regions of the world where stream gauges are sparse or non-existent. Since hydrology is a science, prediction in both gauged and ungauged basins using physical principles is not only possible, but should be the preferred approach to simulating the hydrological cycle.

4.2 RÉSUMÉ

Au début de la décennie de PBNJ, l'approche processus de la prévision hydrologique a été proposée comme élément de solution au problème qui consiste à formuler des prévisions en bassins non jaugés; toutefois, des erreurs persistantes dans les descriptions du processus du modèle continuent d'entraver les progrès de l'hydrologie en tant que science ainsi que l'élaboration de solutions pour les PBNJ. Les algorithmes de processus mis au point au cours des trois dernières décennies de recherches au Canada et ailleurs offrent des solutions à la plupart de ces erreurs pour les milieux situés en régions froides. Cependant, la mise en œuvre de ces algorithmes dans le cadre d'un modèle de prévision est non triviale. Une approche qui combine un raisonnement déductif, inductif et abductif pour l'élaboration d'une structure de processus de modèle appropriée, la discrétisation et la paramétrisation à l'échelle du bassin, est appliquée à la partie non jaugée du bassin de la rivière Smoky en Alberta, au Canada. Le raisonnement déductif fait appel aux relations et aux lois physiques connues pour extraire l'information des inventaires existants des bassins et de l'imagerie satellitaire. Le raisonnement inductif sert à l'étalonnage d'une petite sélection de paramètres de modèle de subsurface au moyen du débit mesuré dans un sous-bassin local. Le raisonnement abductif est utilisé pour emprunter des paramètres d'un ensemble de processus et à des fins de modélisation des bassins de recherche dans l'Ouest canadien. Le modèle a permis de prédire avec une exactitude raisonnable les débits de pointe du printemps de la rivière Smokey sur plusieurs années et à deux différentes échelles. Cela donne à penser que les prévisions en bassins non jaugés au moyen de principes physiques est possible et constitue en fait une solution de rechange viable dans les régions du monde où les fluviomètres sont peu abondants ou inexistants. Étant donné que l'hydrologie est une science, la prévision à la fois en bassins jaugés et non jaugés à l'aide de principes physiques est non seulement possible, mais elle devrait être l'approche privilégiée pour ce qui est de simuler le cycle hydrologique.

4.3 INTRODUCTION

Prediction in ungauged basins (PUB) has been hampered by both a lack of information on the basin and its hydrological characteristics (Sivapalan *et al.*, 2003a), and by ubiquitous misconceptions on the operation of the hydrological cycle that have persisted in many hydrological models. Almost a decade ago, the process approach to hydrological prediction was proposed as a solution to the problem of PUB (Pomeroy *et al.*, 2005); however, persistent errors in model process descriptions continue to hamper the progress of hydrology. These misconceptions cause systematic deviations of model simulations from actual hydrological processing. Calibration to streamflow observations has been used to “correct” these deviations; however, problems of equifinality cause uncertainty in parameter identification (Bevan and Freer, 2001). These create an artificial dilemma. The reliance on calibration, when streamflow observations are missing, creates the problem of predicting in ungauged basins; when observations are available the reliance on calibration supports the continuing persistence of deficient modelling approaches. This dilemma is artificial as the need for calibration is partly due to conceptual errors in hydrological model structure, form, and resolution; and partly due to an inability to identify values for certain parameters. Making progress in reducing the problems of PUB requires advances on both aspects of this problem. The objective of this paper is to demonstrate using a three-stage approach of deduction, induction, and abduction of information to identify some common misconceptions in hydrological models and how they might be readily corrected, and to show how appropriate model structure and parameters can be identified. The procedures are demonstrated in the development of a predictive system for the ungauged portions of the Smoky River Basin, Alberta, Canada.

Persistent misconceptions in hydrological modelling

Many older hydrological concepts, sometimes called “hydromythologies”, often persist in hydrological models despite being dismissed by more recent scientific investigations. This situation is not new (e.g. Klemeš, 1986). Predictive problems caused by these misconceptions are particularly evident for cold and sub-humid regions that are outside of the primary regions of hydrological model conceptualization and development, but are found in all regions. The following are but a few examples of misconceptions that are found in many hydrological models in current use; specific models using various hydromythological algorithms are not mentioned by name, but the knowledgeable reader will easily identify many examples for each point; the corrections are noted in italics and in references cited following the hydromythology.

1. Solar and net radiation are impossible to estimate with normal meteorological data and so energy balance formulations for evapotranspiration, sublimation, soil thaw, snowmelt, and glacier melt cannot be operated in hydrological models and must be replaced by empirical temperature index formulations. [*There are several relationships to estimate solar and long-wave radiation from latitude, time of year, air temperature, and humidity which can be used to drive energy balance snowmelt and combination type evapotranspiration algorithms, (Walter et al., 2005; Sicart et al., 2006; Shook and Pomeroy, 2011a).*]
2. Vegetation is not a dynamic mediator of hydrology and can be represented by simple fixed boundary conditions or constant unresponsive functions. [*There are many dynamic vegetation growth and rooting algorithms available to provide resistance to potential evaporation, and complementary feedback relationships are available for when vegetation, roots, and soils are relatively unknown (Granger and Gray, 1990; Brimelow et al., 2010; Armstrong et al., 2010).*]
3. Snowfall and rainfall can be distinguished by a simple temperature threshold. Snowfall gauge undercatch is not important, and most snow that falls is the snowpack available for melt because sublimation losses are negligible. [*Precipitation phase is controlled by the psychrometric equation, snowfall gauge undercatch can be very substantial but is correctable, and sublimation can consume a substantial proportion of snowfall in dry environments. Sublimation can be estimated using energy balance and aerodynamic approaches (Pomeroy and Gray, 1995; Goodison and Metcalfe, 1992; Harder and Pomeroy, 2013).*]
4. Soils can be adequately represented by a fully-connected uniform porous media with horizontally layered properties, and without macropores and vertical structure. The hydraulic properties of soils change with scale by some unknown scaling mechanism, but are temporally invariant, fixed over hillslopes and little affected by vegetation, animals, and tillage. [*Macropores caused by plants, animal and mankind can provide a primary soil flowpath and infiltration equations can be modified for macropore flow. The*

variance of soil properties over a hillslope is a critical influence on variable contributing areas, fill and spill mechanisms control saturated flow at the soil-bedrock interface (Beven and Kirkby, 1979; Beven and Germann, 1982, 1985; Tromp-van Meerveld and McDonnell, 2006; Craig et al., 2010).]

5. Drainage basins are definable in that sub-surface flow drains within the drainage basin, all land surfaces can always drain freely to a stream, and all parts of the basin are always fully contributing to streamflow via overland or sub-surface flow. As a result, drainage of stored water produces basin discharge via unique functions that are often linear. [*Contributing areas expand and contract as depressional storage and saturated flow pathways fill and empty; the relationship between contributing area and storage is non-linear hysteretic but can be modelled using network connectivity concepts (Spence and Woo, 2003; Phillips et al., 2011; Shook et al., 2013).*]
6. Overland flow is the dominant runoff mechanism and so open channel hydraulic equations can be used to calculate the celerity of runoff from land. [*Sub-surface flow abounds and its velocity is controlled by soil and topographic parameters (Henderson and Wooding, 1964; Sabsevari et al., 2010).*]
7. Water movement into, through, and above frozen soils behaves in a similar manner to unfrozen soils. [*Infiltration and soil hydraulics are controlled by the interaction of soil ice content and porosity over time which is controlled by coupled energy and mass balance equations and influenced by the depth of freezing and the presence of permafrost (Zhao and Gray, 1999; Gray et al., 2001; Quinton and Gray, 2001).*]

The Cold Regions Hydrological Modelling platform (CRHM) was created as a set of algorithms that could be used to address such problems in a flexible, modular hydrological modelling context (Pomeroy *et al*., 2007). The application of CRHM in this paper shows how most of these hydromythologies can be overcome with modern, flexible, modelling technologies, based on scientific principles.

Deduction, induction, and abduction and the cold regions hydrological model

Inductive (bottom up) and deductive (top down) approaches to environmental prediction have abounded for many years and the application of these approaches to hydrology are reviewed in Dornes (Chapter 10).

Philosophically, they go back to the reasoning of Ancient Greece, but similar concepts can be found in Chinese philosophy (Liu *et al*., Chapter 2) and are perhaps common to the experience of humanity in solving problems. Unfortunately in hydrology, there has been persistent confusion about what these terms mean and they have been commonly misapplied in the field. For instance, Sivapalan *et al*. (2003a) and Littlewood *et al*. (2003) define the top down or downward approach in hydrology to be driven by observation and moving from general observations to specific rules and therefore deductive, whilst in the study of scientific philosophy it is accepted that data driven approaches are inherently inductive and bottom up (Vickers, 2013). Physics-based approaches are in fact deductive and top down as they derive from application of accepted rules (Holyoak and Morrison, 2005). Further, what has been referred to in the PUB decade as the top down approach in hydrology, is not only inductive and empirical, but can lead to serious errors in conclusions, the dangers of which have been known since the writings of the classical philosopher Sextus Empiricus in the 3rd C AD (Romesburg, 1981; Popper and Miller, 1983). Dornes (Chapter 10) shows the benefits of combining top down and bottom up approaches for hydrological prediction. In this paper, deductive and inductive approaches follow the accepted conventions of philosophy (Vickers, 2013) and correspond to physics-based and empirical approaches respectively.

Whilst it has become clear in PUB that both induction and deduction are needed to develop robust and appropriate hydrological models, the role of abduction (inference) has not been widely discussed despite its great utility to PUB and heretofore unrecognized use in hydrology (Magnani, 2001; Couclelis, 2003). Abduction follows a logic where the major premise is true but the minor premise is probable; here it begins with an incomplete set of observations from a wide range of sources and proceeds to the likeliest possible explanation. It does its best with the information at hand which is often incomplete – a typical situation that hydrologists face. Combining the three approaches in hydrology can be termed the “DIA Approach” and can be quite powerful. A simple example of the DIA approach applied to snowmelt runoff follows:

1. Deduction (rule based / top-down): allows deriving *b* from *a* only where *b* is a formal logical consequence of *a*. Given a rule, based on the continuity equation, that whenever the snow melts in a basin that streamflow must result, the deductive statement is: snow is melting in a basin, therefore there must be streamflow.

2. Induction (observation based / bottom-up): allows inferring *b* from *a*, where *b* does not follow necessarily from *a*. Given the observation that the stream flows only when there is snowmelt in a particular basin, the inductive statement is: the stream is observed to be flowing, therefore there must be snowmelt in the basin.
3. Abduction (opportunistic / lateral): allows inferring to the best explanation even when information is incomplete. Given the inference that when the regional snowcover melts there is streamflow in many local streams in springtime and that this can occur without rainfall, the abductive statement is: streamflow is observed without rainfall in springtime, therefore it is likely that snow is melting in the basin.

A weakness of the inductive approach in this example is that streamflow can be derived from sources other than snowmelt in the spring, and a weakness of the deductive approach is that the rule might be misapplied and snowmelt water might evaporate, infiltrate, or form depressional storage, rather than forming streamflow. The flexibility and ability to bring in auxiliary information of the abductive approach is appealing for complex hydrological problems, but it also has weaknesses, such as the situation where the basin of interest is not like others in the region. Clearly, the use of any reasoning approach by itself can lead to misconceptions and errors, but the combined DIA approach can be powerful when the availability of observations, the applicability of rules, and the reliability of regional inference are limited, as is often the case in hydrology. The application of physical laws by deduction permits rigorous enforcement of continuity of mass and energy and the laws of thermodynamics and kinematics. Using fundamental observations by induction to develop rules of hydrological behavior is how hydrological science often advances. Inferring missing observations or unknown hydrological behavior by abduction of rules or induced behavior is how the hydrological response can be determined with inadequate knowledge or information. There are clearly parallels between the DIA approach and the traditional Chinese housewife approach outlined by Liu *et al*. (Chapter 2).

CRHM is a modular modelling system that permits appropriate hydrological processes for the basin, selected from a library of process modules, to be linked to simulate the hydrological cycle as a purpose-built model (Pomeroy *et al*., 2007). CRHM is very well suited for the DIA approach as an initial selection of process laws can be considered deduction, the evaluation of process performance, inclusion and model redesign based on learning from model failure can be considered induction, and the use of regional analogues for structure and parameters from research basins can be considered abduction.

From its inception, CRHM has focused on the modular incorporation of physically based descriptions of cold regions hydrological processes, but it also includes a full range of temperate regions modules. Recent developments include options for treeline forest effects from alpine blowing snow (MacDonald *et al*., 2010), improved soil moisture accounting and fill and spill depressional storage (Fang *et al*., 2010), variable rooting zones for evapotranspiration calculations (Armstrong *et al*., 2010) and enhanced forest canopy interception and radiation modules (Ellis *et al*., 2010). CRHM has a suite of process modules including calculation of solar radiation using diurnal temperature ranges, direct and diffuse radiation to slopes, long-wave radiation in complex terrain, intercepted snow, blowing snow, sub-canopy turbulent and radiative transfer, sublimation, energy balance snowmelt, infiltration to frozen and unfrozen soils, rainfall interception, combination-type evapotranspiration, sub-surface flow, depressional storage fill and spill, saturation excess overland flow, and separate routing of surface, sub-surface, and streamflow. The selection of modules is an inductive exercise, depending on the biophysical environment and data availability. CRHM uses an object-oriented structure to develop, support, and apply dynamic model routines. Existing algorithms can be modified or new algorithms can be developed and added to the module library, which are coupled to create a purpose-built model, suited for the specific application. It is particularly useful to replace hydromythologies with modules based upon physical principles.

CRHM operates on the spatial discretization of the hydrological response unit (HRU) which has been found optimal for modelling in basins where there is a good conceptual understanding of hydrological behaviour, but incomplete detailed information to permit a fully distributed fine scale modelling approach (Dornes *et al*., 2008). The level of disaggregation into HRUs is guided not only by the spatial variability of biophysical attributes and drainage conditions in the basin, but by the available information to describe these attributes as parameters and so is simultaneously an inductive and deductive exercise. Being physically based, the majority of CRHM modules do not require calibration against gauged flows and therefore are suitable for parameterization in ungauged basins. Parameters are typically selected *a* *priori* from soil/land cover characteristics, vegetation cover, drainage networks, and other basin information – a deductive exercise. Some unmeasured parameter values can be transferred from hydrologically similar basins – an abductive exercise. Calibration of unknown parameters against gauged flows is possible using trial and error methods – an inductive exercise.

4.4 APPLICATION OF THE DIA APPROACH TO HYDROLOGICAL PREDICTION FOR THE SMOKY RIVER BASIN

The Province of Alberta needs to predict spring streamflow for the ungauged portion (46%) of the 51 839 km^2 Smoky River Basin as the ungauged flows have been implicated in exacerbating river ice jams and floods on the Peace River, downstream. The Smoky River flows north out of the Canadian Rocky Mountains into the Peace River lowlands which are the northernmost agricultural region in Canada. The region is remote; weather and climate stations are sparse in the basin and require substantial interpolation and infilling of data for use in hydrological modelling. There are 26 ungauged and 14 gauged sub-basins in the Smoky River Basin and these vary from mountain headwater basins dominated by alpine tundra and sub-alpine forest, upland boreal forest sub-basins to lowland agricultural and forested sub-basins.

Model process structure by deduction

Known hydrological characteristics of the region are long periods of winter (usually five months) and snowcovers heavily modified by wind redistribution and sublimation of blowing snow (Pomeroy and Gray, 1995). The blowing snow process is affected by the interaction of local topography and surficial vegetation cover with regional wind flow patterns (Pomeroy *et al*., 1993; Fang and Pomeroy, 2009). High surface runoff derives from spring snowmelt, which is 80% or more of annual local surface runoff in the Prairies (Gray and Landine, 1988), and occurs as a result of frozen mineral soils at the time of melt and a relatively rapid release of water from melting snowpacks (Gray *et al*., 1985). Snowmelt timing and meltrate are primarily controlled by the net inputs of solar radiation, thermal radiation, energy advected from rainfall, and turbulent transfer of sensible and latent heat. These net inputs are controlled by the storage of internal energy in the snowpack and the snow surface albedo, both of which change rapidly in the pre-melt and melt period. Meltwater infiltration into frozen soils can be restricted, limited, or unlimited depending on soil infiltrability (Gray *et al*., 1985; Zhao and Gray, 1997).

Frozen mineral soils usually have limited infiltration characteristics, which means that the infiltrability is controlled by the degree of saturation of the soil pores with water and ice. The degree of saturation can be estimated from the soil porosity and the volumetric moisture content of the preceding fall if overwinter soil moisture changes are minimal. Substantial mid-winter melts or rain events can cause restricted infiltration, in which most snowmelt water goes directly to runoff (Gray *et al*., 2001) due to the presence of ice layers at the snow-soil interface. Heavy clay soils can crack when frozen, resulting in nearly unlimited infiltration; hence little to no runoff generation (Pomeroy *et al*., 1990). Deep prairie soils are characterized by good water-retaining capacity and high unfrozen infiltration rates (Elliott and Efetha, 1999). Most rainfall occurs in spring and early summer from large frontal systems and the most intense rainfall in summer is associated with convective storms over small areas (Gray, 1970). During summer, most rainfall is consumed by evapotranspiration associated with the growth of crops and perennial grasses (Armstrong *et al*., 2008). Evapotranspiration occurs quickly from wet surfaces such as water bodies, wetted plant canopies, and wet soil surfaces, but relatively slowly from unsaturated surfaces such as bare soils and plant stomata (Granger and Gray, 1989). Any physically based runoff model for this region must correctly resolve these hydrological processes.

Deduction based on the experience of the modellers in constructing models in western Canada with the known physical processes in the region, informed the construction of a model using physically based modules in a sequential manner to simulate the dominant hydrological processes for the Smoky River. Appropriate modules were selected that could be run to robustly forecast the hydrological cycle of the region in a physically based manner. Figure 4.1 shows the schematic setup of these modules. The following list describes the methods that are included in each module:

1. Observation module: reads the meteorological data (temperature, wind speed, relative humidity, vapour pressure, precipitation, and radiation) used to operate CRHM, adjusting temperature with environmental lapse rate and precipitation with elevation and wind-induced undercatch, and providing these inputs as the "driving meteorology" to other modules as required by the module calculations.
2. Radiation module based upon Garnier and Ohmura (1970): calculates the theoretical global clear-sky radiation as direct and diffuse solar radiation to slopes based on latitude, elevation, ground

slope, and azimuth, providing radiation inputs to the energy-budget snowmelt module, and the net all-wave radiation module. Transmittance is estimated using a diurnal temperature range method (Annandale *et al*., 2002; Shook and Pomeroy, 2011).

3. Long-wave radiation module based upon Sicart *et al*. (2006): estimates incoming long-wave radiation using vapour pressure, air temperature, and the short-wave transmittance estimated from the short-wave radiation module. This feeds into the energy-balance snowmelt module.
4. Albedo module based upon Gray and Landine (1987): estimates areal snow albedo throughout the winter and into the melt period and also indicates the beginning of melt for the energy-balance snowmelt module.
5. Canopy module based upon Ellis *et al*. (2010): estimates the snowfall and rainfall intercepted by the forest canopy and updates the under-canopy snowfall and rainfall and calculates short-wave and long-wave sub-canopy radiation. This module has options for open environment (no canopy adjustment of snow mass and energy), small forest clearing environment (adjustment of snow mass and energy based on diameter of clearing and surrounding forest height), and forest environment (adjustment of snow mass and energy from forest canopy).
6. Blowing snow module based upon the method of Pomeroy and Li (2000): simulates the inter-HRU wind redistribution of snow transport and blowing snow sublimation losses throughout the winter period.
7. Energy-Budget Snowmelt Model based upon Gray and Landine (1988): estimates snowmelt by calculating the energy balance of radiation, sensible heat, latent heat, ground heat, advection from rainfall, and change in internal energy.
8. All-wave radiation module using the method of Granger and Gray (1990): calculates the net all-wave radiation from short-wave radiation for input to the evaporation module for snow-free conditions.
9. Infiltration module using Gray's snowmelt infiltration algorithm (Gray *et al*., 1985): estimates snowmelt infiltration into frozen soils; Ayers' infiltration (Ayers, 1959): estimates rainfall infiltration into unfrozen soils based on soil texture and ground cover. Both infiltration algorithms link moisture content to the soil column in the soil module. Surface runoff forms when snowmelt or rainfall exceeds the infiltration rate.

10. Fall soil moisture module: sets the fall soil moisture status for running multiple-year simulations. The amount of soil moisture and the maximum soil moisture storage in the soil column are used to estimate the fall soil moisture status, which provides the initial fall soil saturation for the infiltration module.

11. Evaporation module using Granger's evaporation expression (Granger and Gray, 1989; Granger and Pomeroy, 1997): estimates actual evapotranspiration from unsaturated surfaces using an energy balance and extension of Penman's equation to unsaturated conditions; Priestley and Taylor evaporation expression (Priestley and Taylor, 1972): estimates evaporation from saturated surfaces such as stream channels. Both evaporation algorithms modify moisture content in the interception store, ponded surface water store, and soil column and are restricted by water availability to ensure continuity of mass; the Priestley and Taylor evaporation also updates moisture content in the stream channel.

12. Soil & Hillslope module: calculates sub-surface flow and simulates groundwater-surface water interactions using physically based parameters. The present module was revised from an original soil moisture balance routine developed by Leavesley *et al*. (1983) and modified by Pomeroy *et al*. (2007), Dornes *et al*. (2008), Fang *et al*. (2010), and Fang *et al*. (2013) and now calculates the soil moisture balance, groundwater storage, subsurface and groundwater discharge, depressional storage, and runoff for control volumes of two unsaturated soil layers, the groundwater layer and surface depressions. Groundwater recharge occurs via percolation from the soil layers or directly from depressional storage via macropores. Subsurface discharge occurs via horizontal drainage from either soil layer; groundwater discharge takes place through horizontal drainage in the groundwater layer. Surface runoff occurs when inputs from snowmelt or rainfall exceed subsurface withdrawals from saturated soils or if the rate of snowmelt or rainfall exceeds the infiltration rate. The drainage factors for lateral flow in soil layers and groundwater layer (i.e. subsurface and groundwater discharges) as well as vertical flow of excess soil water to groundwater (i.e. groundwater recharge) are estimated based on Darcy's flux. The Brooks and Corey (1964) relationship is used to calculate the unsaturated hydraulic conductivity.

13. Routing module: the Muskingum method is based on a variable discharge-storage relationship (Chow, 1964) and is used to route runoff between HRUs in the sub-basins. The routing storage constant is estimated from the average distance from the HRU to the main channel and average flow velocity; the average flow velocity is calculated by Manning's equation (Chow, 1959) based on the average HRU distance to the main channel, average change in HRU elevation, overland flow depth, and HRU roughness.

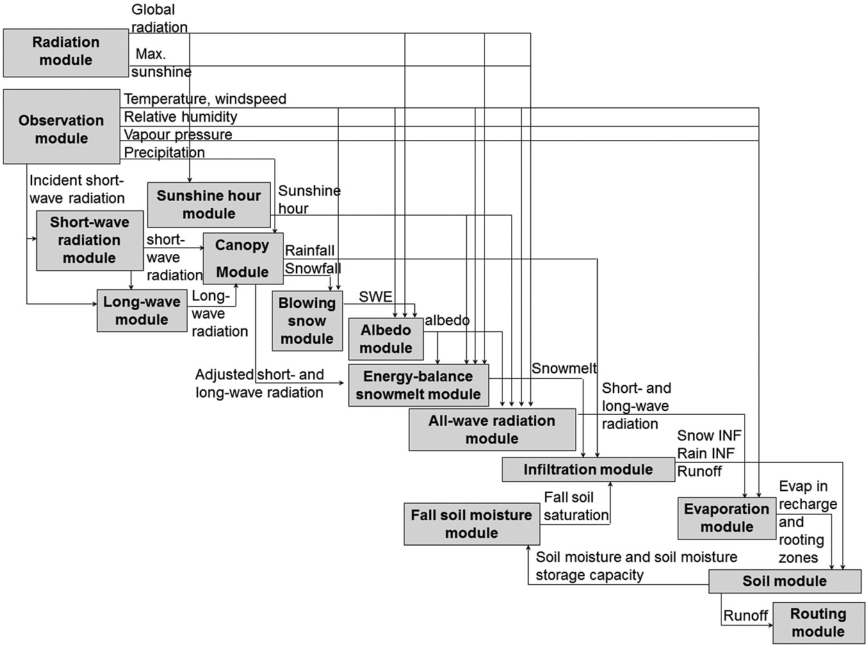

Figure 4.1 *Flowchart of physically based hydrological module used in the Lower Smoky River Model created using CRHM.*

Model HRU structure by induction

Hydrological response units (HRU) are based on combinations of vegetation, soils, drainage, waterbody, and topographic parameter information. Sub-basins of the Smoky River Basin span the mountains and foothills, boreal forest, boreal forest – agricultural transition, and agricultural ecoregions. The boreal forest has been heavily impacted by forest harvesting and disturbance for oil and gas production platforms and pipelines, and agricultural regions are heavily cultivated to cereal and oilseed crops. HRU delineation varied by ecoregion; in all areas land cover and drainage were important; however, in alpine areas slope, aspect, and elevation were included whereas in the flatter agricultural areas soil texture was used. Figure 4.2 shows how an overall delineation of land cover from a satellite image classification was used to delineate HRU specific to each ecoregion, by induction informed by a site visit and field observation of how satellite-derived land cover classifications corresponded to suitable landscape units for hydrological simulation. Figure 4.3 presents a map of the HRUs for the ungauged portion of the basin and of the drainage pattern.

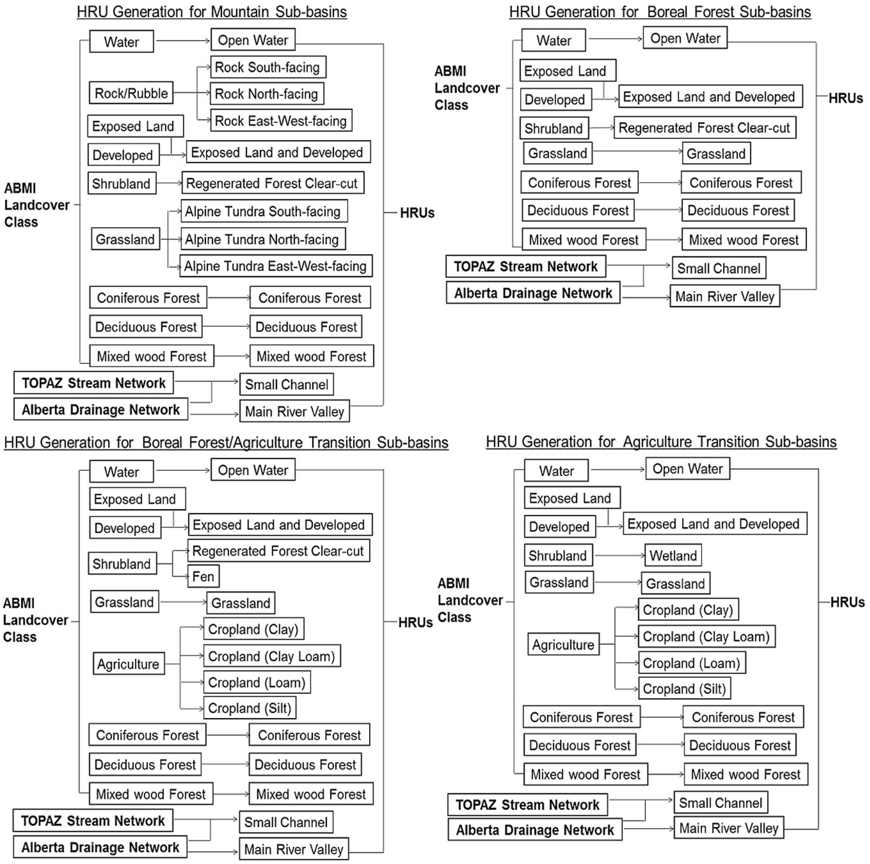

Figure 4.2 *HRU generation for the Smoky River modelled sub-basins.*

Model parameterization by DIA

Deduction

The sub-basin network was extracted using an automated basin delineation tool, TOPAZ, which uses rules to decide on drainage patterns from the digital elevation model (Garbrecht and Martz, 1997). For HRU, the corresponding area, elevation, aspect, and slope for the HRUs were

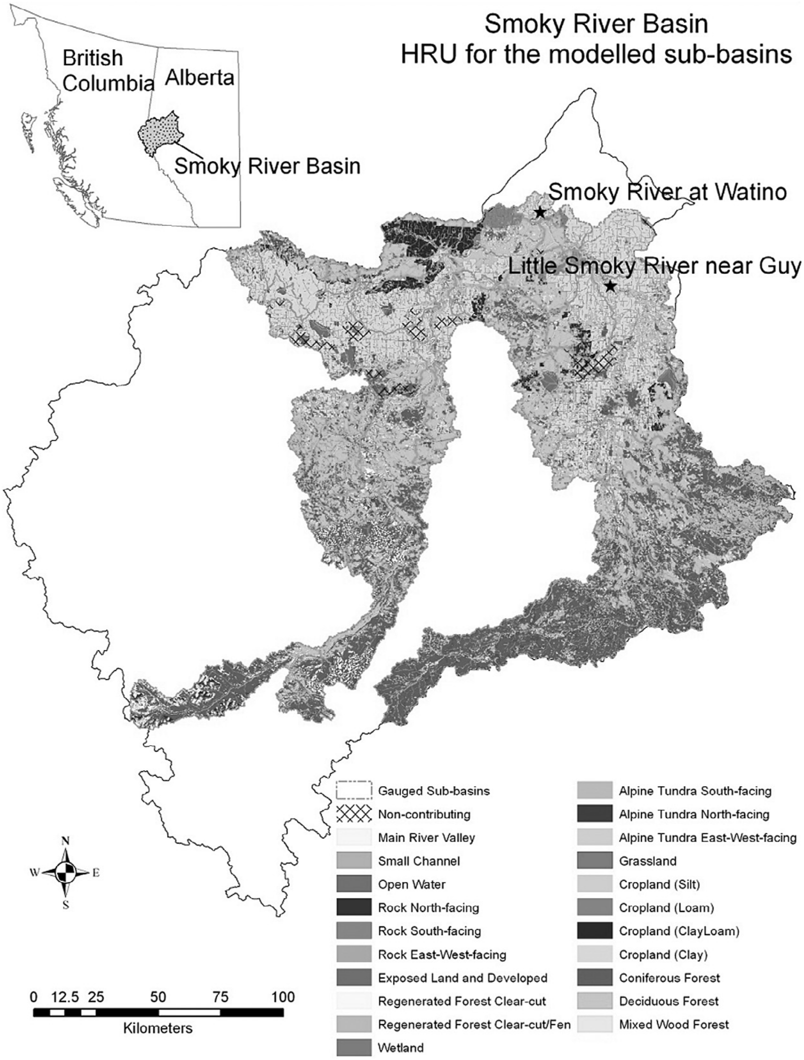

Figure 4.3a *HRU for the modelled sub-basins in the Smoky River Basin.*

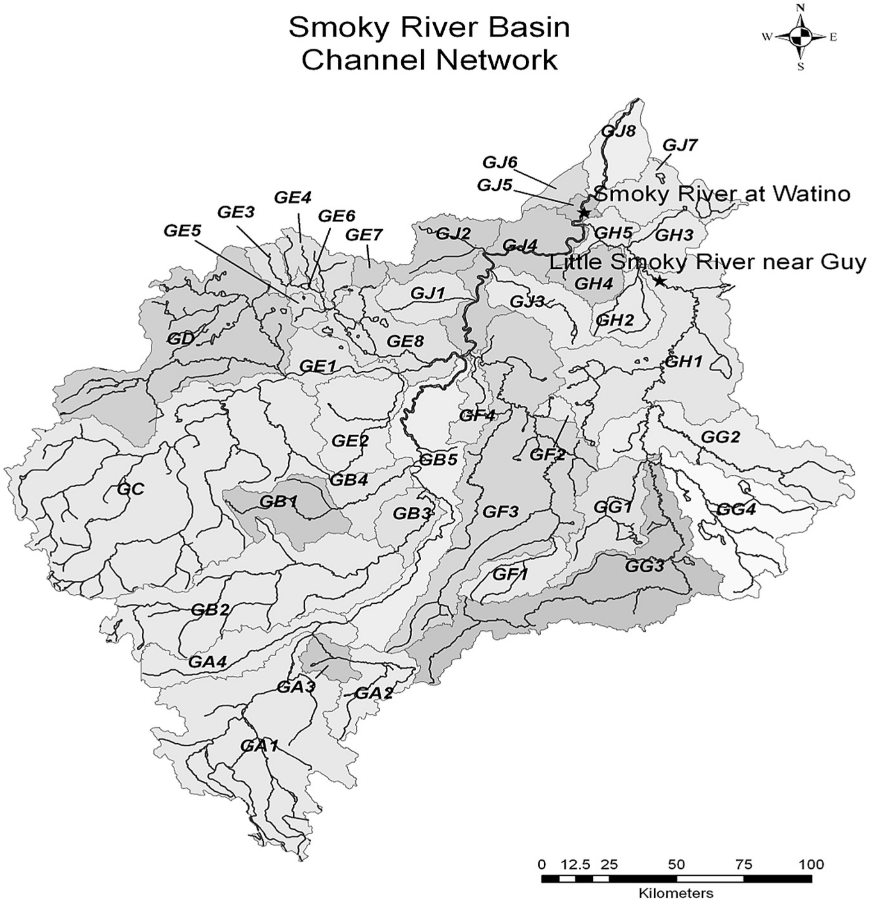

Figure 4.3b *Smoky River Basin channel network and sub-basins.*

computed using the SAGA GIS (Conrad, 2006) terrain "analysis profile tool" and the ArcGIS (Environmental Systems Research Institute, 2012) "extract by mask" tool, as described by Fang *et al*. (2010). This was largely a deductive exercise obtained from existing information using rules. Vegetation and soils were determined by Alberta Biodiversity Monitoring Institute satellite remote sensing vegetation classifications and soil surveys and were interpreted to leaf area index, vegetation height, and soil texture classes using rules developed from field studies in western Canada over many years (e.g. Pomeroy and Gray, 1995; Pomeroy and Brun, 2001;

Pomeroy *et al.*, 2002). These rules were modified by ecoregion as it is understood from ecological principles that a "grass" classification in an alpine ecoregion corresponds to tundra, whilst in a prairie ecoregion it corresponds to grassland. Hydraulic parameters such as Manning's n and channel shape were estimated from observations made during site visits.

Induction

The need to adjust some model parameters was informed by induction since the initial sub-basin modelled flows matched observed streamflows very poorly. Induction with respect to sub-basin streamflow was used to adjust the vertical profile of saturated hydraulic conductivity in soil, and the sub-surface travel time parameter, as these parameters were not measured. No other parameters were calibrated.

Abduction

As local measurements of many parameters were not available, their values were abducted from detailed observations in four Canadian ecoregions as explained in Pomeroy *et al*. (2005). For instance, abduction was used to set fall soil moisture parameters to address the impact of macropores in soil (Darwent and Baily, 1982) and the snow interception parameters to address the effects of strong winds on interception efficiency (Pomeroy and Gray, 1995). Additional information was extracted from studies of Prairie agricultural fields (Knapik and Lindsay, 1983; Pomeroy *et al*., 2007; Armstrong *et al*., 2008; Fang and Pomeroy, 2009; Fang *et al*., 2010; Pomeroy *et al*., 2010); from alpine tundra in Alberta and Yukon (MacDonald *et al*., 2009; 2010; Fang *et al*., 2013), and from boreal forest in Saskatchewan and Yukon (Granger and Pomeroy, 1997; Hedstrom and Pomeroy, 1998; Pomeroy *et al*., 2002). The set of model parameters and the parameterization process are described in detail by Pomeroy *et al*. (2013).

4.5 IMPLICATIONS OF MODELLING RESULTS

Simulations of ungauged streamflows are by definition impossible to evaluate directly. In an attempt to evaluate the model against gauged flows, nine years of local simulated ungauged inflows were added to routed gauged upstream flows and compared to the gauged downstream flows on the Little Smoky River at Guy and the Smoky River at Watino in Figure 4.4. The gauged upstream flows were routed so that the discharges of gauged and modelled flows were synchronized. The predicted seasonal spring discharges (modelled plus routed gauged flows) from 15 March to 31 May were compared to the gauged flows for both rivers for nine spring periods and are shown in Figure 4.5. For the Little Smoky River simulations, the mean bias ranged from -0.60 in 2007 to 0.76 in 2010, indicating the cumulative spring discharge ranged from 60% underestimation to 76% overestimation with an average seasonal underestimation of 3%. Cumulative spring flows were underestimated by 18.5% over the nine springs. For the Smoky River simulations, the mean bias ranged from -0.07 in 2008 to 0.41 in 2009, indicating the cumulative spring discharge ranged from a 7% underestimation to a 41% overestimation with an average seasonal overestimation of 12%. Cumulative spring flows were overestimated by 9.7% over the nine springs. These statistics, when evaluated along with the Nash-Sutcliffe coefficient for the Little Smoky River and Smoky River daily hydrographs of 0.41 and 0.87, suggest good model performance in hydrograph prediction and in estimating the water balance, with model performance improving with increasing basin size and distance downstream. This is partly due to the contribution of the routed gauged flows to the modelled flows and partly due to the effect of increasing basin size on masking unmeasured and missing precipitation data and errors in parameterization and model structure. Overall, it is a confirmation that a physically based model with minimal calibration can provide good simulations of ungauged basins when the DIA approach is used to develop and parameterize the model.

The success of the abductive approach to model development and parameterization in this example was due to the availability of information from intensive research basins in similar ecoregions to those occurring in the basin (Pomeroy *et al.*, 2005). These research basins were not nearby, in some cases being over 1000 km away from Alberta, in Saskatchewan and the Yukon Territory, but the similarity of vegetation form and structure, soil structure, drainage basin spatial arrangement, and climate across these biomes permitted the transfer of certain conceptual approaches and physically identifiable parameters over vast distances. Kouwen *et al*. (1993) suggested this approach for parameterization of grouped response units in large scale hydrological models, and Pietroniro and Soulis (2003) demonstrated application of the parameter regionalization concept to water

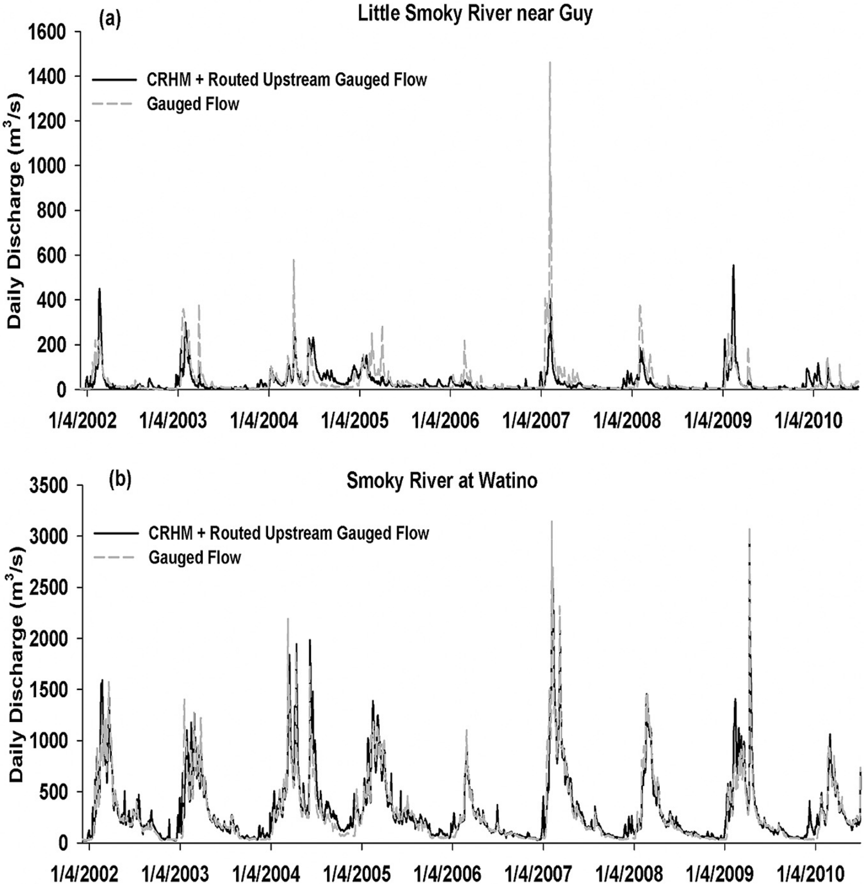

Figure 4.4 *Comparisons of CRHM simulated plus routed real-time upstream gauged streamflows and gauged daily streamflows from 4 March 2002 to 30 September 2010 for:* ***(a)*** *Little Smoky River near Guy and* ***(b)*** *Smoky River at Watino.*

and energy cycle calculations over large areas of Canada. This suggests that regionalization of modelling approaches on ecological, hydrological, and climatic principles is viable and that this abductive approach can be employed where there are networks of research basins from which detailed hydrological relationships and parameter values can be obtained. These research basins were established around the world in the International Hydrological Decade of 1964-1975, and archives or recent studies from those basins that still exist are invaluable resources for abductive contributions to PUB.

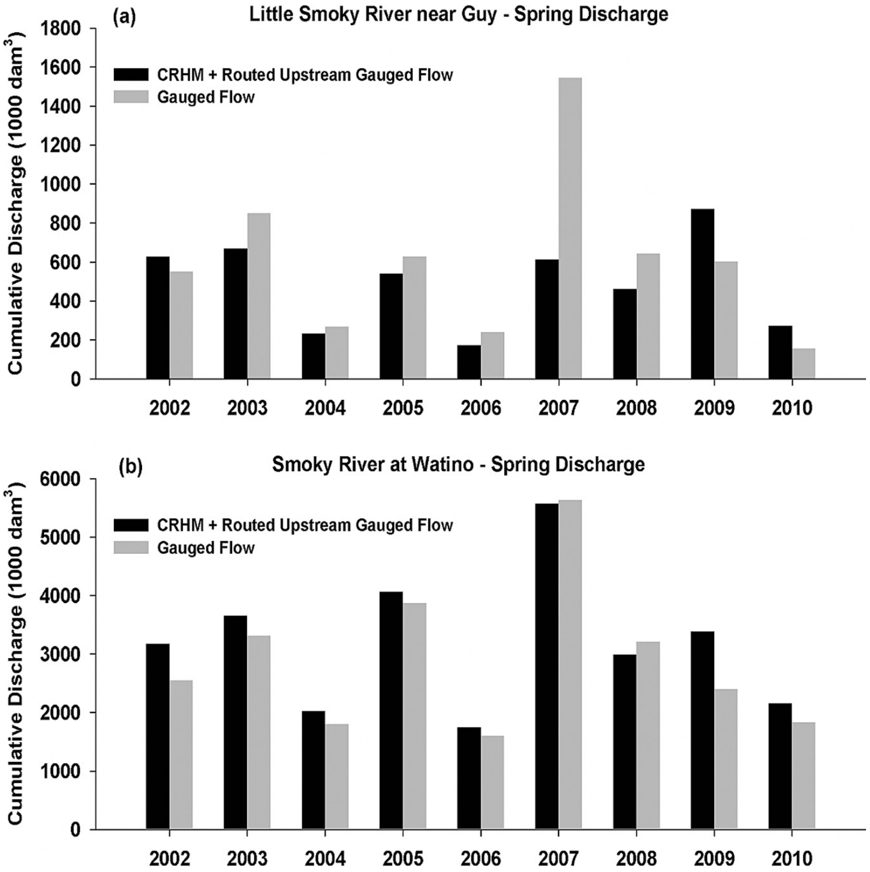

Figure 4.5 *Comparisons of CRHM simulated plus real-time upstream gauged streamflow and observed gauged cumulative spring discharge from during 15 March-31 May in nine springs from 2002 to 2010 for:* ***(a)*** *Little Smoky River near Guy and* ***(b)*** *Smoky River at Watino.*

4.6 CONCLUSIONS

Persistent errors in model process descriptions have hampered the progress of hydrological prediction as has the over reliance on either data-driven inductive approaches or physically prescribed deductive approaches to model derivation. Modelling errors can be corrected using process algorithms developed from the last three decades of integrated, strategic field and modelling research. Models including these process descriptions may be capable of prediction in ungauged basins with minimal calibration if parameters can be identified and appropriate model structures created. The use of a combination of deductive, inductive, and abductive reasoning is recommended for prescribing both an appropriate level of complexity and process inclusion in model structure and in parameterizing process algorithms. An example of the deduction, induction, and abduction approach was shown in the development of model process structure, basin discretization and parameterization and was applied to the ungauged portion of the Smoky River Basin in Alberta, Canada. Deductive reasoning used known laws to deduce information from existing basin maps and satellite imagery. Inductive reasoning was used to calibrate certain model parameters from a test sub-basin. Abductive reasoning was used to borrow parameters from a suite of intensive research basins in western Canada. The model was able to achieve good performance in predicting the peak spring flows on the river over several years and at two different scales. This suggests that in remote regions of the world where stream gauges are sparse or non-existent, prediction in ungauged basins using physical principles is a possible, viable, and preferable alternative.

4.7 ACKNOWLEDGEMENTS

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