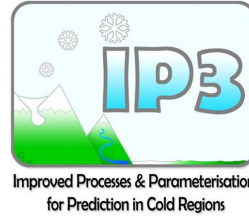




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Final Progress Report

Network Title: Improved Processes and Parameterisation for Prediction in Cold Regions

Grantee: John Pomeroy, University of Saskatchewan

1.0 Project Work

1.1 **Provide a summary description of both the nature of the science and the project work undertaken.**

IP3 was necessary and important to start in 2006 because the development of hydrological prediction in Canada had reached a serious impasse. This impasse was due to the recognition of increasing non-stationarity as accelerating climate, land use and water resource consumption changes made historical observations of climate, snowpacks, glaciers, permafrost, groundwater, lakes and streamflow more difficult to interpret and use for future hydrometeorological prediction with existing techniques. This problem was most pronounced in the sparsely gauged cold regions that form the headwaters where much of Canada's freshwater renewal occurs. Empirical methods had become recognised as unreliable for predicting future hydrological cycling in the cold regions due to the sparse observation network; non-stationarity further decreased the reliability of any predictions that could be made from existing data. The IP3 methodology was based on the belief that improved assessment of future water resources involved both deductive and inductive (top down and bottom up) approaches to prediction and that there were several serious gaps in bottom up understanding of cold regions hydrology and methods to link this understanding with existing catchment and streamflow information to develop better prediction techniques for hydrological, weather and climatological models. What was missing was parameterisation of process understanding in the context of land surface hydrological models and catchment characteristics. IP3 therefore first worked towards improving the understanding of cold regions hydrological processes relating to snow accumulation and melt, permafrost, glaciers, and cold soils and lakes, then taking this understanding to improve parameterisations of the representation of these processes in hydrological and land surface models and then changing the models themselves to take advantage of improved parameterisations by using more appropriate modelling structures and data assimilation techniques. The resulting hydrological and land surface models are sensitive to land use and are capable of being linked directly to atmospheric models and to water resource system models and so provide the interface between changing atmosphere, land cover, and water management and provide a way forward for hydrometeorological prediction in the "anthropocene", where stationarity can no longer be assumed. Process understanding enhancement, parameterisation development and model testing was done on a series of uniquely heavily instrumented research basins that spanned the Rocky Mountains, and western subarctic and Arctic with data provided by IP3, IPY, NSERC and collaborators. The progression from processes, to parameterisation and finally improved prediction is outlined here.

Theme 1 – Processes

The goal of Theme 1 was to improve the understanding of the key physical processes involved in the hydrometeorology of cold regions, through detailed studies of the nature and characteristics of climate and weather, the cryosphere, land surface and sub-surface, water bodies and the biosphere, in a group of high-latitude / high-altitude research basins. Observations made in each basin were used to derive algorithms representing a wide range of natural processes relevant to cold-regions hydrology. Issues of spatial variability in these processes were addressed by taking multiple observations within basins, and making comparisons among basins, supported by the use of remote sensing technology.

Throughout the course of the IP3 program, the Theme 1 Milestones and Deliverables (M&D) were met. Previous reports outlined the M&D for the first three years and will not be further presented here. There were no coordinated large-scale field investigations carried out in 2010, and emphasis was placed on data synthesis, archiving, and linkages with Theme 2.

A brief review of the IP3 Basins and some key Theme 1 findings are:

Trail Valley & Havikpak Creek, NWT

At these most northerly basins, research focussed on monitoring links between snow cover, blowing snow redistribution, shrubs, active layer depth and runoff. Much emphasis was placed on the reanalysis of MAGS aircraft data and the implementation of the spatially detailed model GEOTop to simulate fluxes across the catchments and for comparison to aircraft flux measurements.

Wolf Creek, Yukon

Several projects took place in Wolf Creek. The complex interactions between snow, vegetation, topography and the atmosphere were examined. Specific projects were undertaken on snow redistribution by wind and the effect of vegetation and topography; turbulent transfer of sensible and latent heat to snow, how shrub vegetation responds mechanically to intercepted snow; and how vegetation alters the radiative regimes during melt. Other projects explored issues of how ground thaw, infiltration into frozen soil and runoff combine to account for the runoff signals observed in subarctic mountainous catchments. New instrumentation to measure total frozen water content of soils was developed. The role of different water sources was identified, and process information led to new advances in process parameterization for Theme 2.

Scotty Creek, NWT

Research at Scotty Creek focussed on understanding hydrological processes in an environment that is undergoing unprecedented change from warming and human disturbance. New conceptual runoff models were developed for this landscape, highlighting the respective role of bogs, fens and peat plateaus. LiDAR imagery was used to precisely define permafrost distribution and its change through time. Process work examined fundamental hydrological processes, which led to new discoveries on preferential thaw and permafrost degradation. Theme 1 research also led to considerable parameterization and modelling advances, particularly in the area of ground thaw, organic soil hydraulic properties and energy balance. A novel experiment from Scotty Creek was the removal of a large soil monolith for experimentation in the Biotron climate simulator at the University of Western Ontario.

Baker Creek, NWT

Much of the work in Baker Creek has examined the influence of heterogeneity on runoff generation in this Canadian Shield landscape. New research on the role of landscape storage and the influence of thermal status on this has occurred, which has led to the development of implementation of new model formulation for runoff processes in this environment where previous concepts simply did not work. This improved predictive capability that encompasses

new knowledge about hydrological connectivity and how connectivity is controlled by storage dynamics and influences runoff efficiency.

Peyto Glacier, Alberta

To explore water and energy fluxes at Peyto glacier, a spatially distributed modelling framework was adopted utilizing both new and archival data. The mass balance of the glacier was linked to runoff at the catchment outlet. New research on boundary layer interactions atop Peyto Glacier were used to develop parameterization schemes of surface-atmosphere transfer from regional air mass data. A key concern, however, was a suitable atmospheric bulk transfer and katabatic flow parameterization scheme to estimate sensible and latent heat transfer, the most likely candidate being one wherein the regional wind and the katabatic wind are arranged as parallel conductances to heat flow.

Lake O'Hara, BC

Research in Lake O'Hara closely examined the role of groundwater storage in alpine aquifers, which act to alleviate the impacts of climate warming on water resources. Research in both Lake O'Hara watershed and Yoho National park investigated the occurrence of groundwater in the glaciated alpine basin and focussed on parameterization of subsurface hydrological processes. Key results indicate a substantial portion of water input to alpine lakes is provided by groundwater, which is stored in moraine and talus deposits. These geological units, very common features in the Canadian Rockies, have an ability to store snowmelt and rain waters for a time scale of several weeks to several months, thereby delaying the release of these waters.

Marmot Creek, Alberta

Specific research at Marmot Creek included investigation of wind redistribution, transport and sublimation of snow in high relief alpine areas; snow interception, sublimation and unloading by evergreen forests, snowmelt energetics under forest canopies on steep slopes, turbulent transfer of sensible and latent heat to snow in complex terrain, snow accumulation and ablation regimes in forested vs. non-forested mountain areas through modelling, and innovative snow observation techniques through development testing of an acoustic "snow sonar" snow properties measurement device. Other research examined runoff processes at the hillslope scale and snowmelt infiltration. Much of this work was used directly for the development of new parameterization techniques in Theme 2.

Crean Lake and Landing Lake (NWT, Saskatchewan)

Research on open-water evaporation was conducted at Crean Lake, SK, and Landing Lake, NWT. Instrument towers were set up at both sites on and off-shore, and all turbulent and radiative exchanges measured. This data was used to develop new parameterization schemes for open-water evaporation conditions under different stability parameterizations in Theme 2.

Theme 2 – Parameterisation

A parameterisation is a means of describing a complex phenomenon in relatively simple mathematical form so that it can be used in a computer simulation. Parameterisations are increasingly important in environmental science as they provide the means of representing at the basin scale, processes operating at the relatively small scales of plots and hillslopes. Parameterisations in hydrology therefore attempt to link the understanding of processes operating at relatively small spatial scales with the prediction of the hydrological response of larger systems of which the latter is a component. They are a crucial linchpin in the inductive-deductive approach that characterises IP3 and link process and prediction, point measurements and basins behaviour, understanding and water management capability.

IP3 has undertaken fundamental research on processes and parameterisations in Canada's cold regions. This research was accomplished through specialised observations in a set of research basins where the key components of the natural water and energy cycles and

associated flow and storage processes were observed and used to develop and test mass and energy flow concepts and equations. The research basins span high altitude and high latitude environments in western and northern Canada and include the partly glaciated mountains of the western cordillera as well as the sub-arctic/arctic Canadian Shield to the lowlands of the Mackenzie River Basin. It is expected that these concepts and equations can form the basis for the development of physically-based hydrological models and integrated atmospheric water cycle models for small basin to large area water resource assessments. One of the main scientific objectives of IP3 was to improve mathematical parameterisations of land surface cold regions hydrological processes and incorporate the new parameterisations into coupled land surface–hydrology models at scales between 10 and 100 km².

The objective of Theme 2 was to integrate the individual natural process identified and described in Theme 1, through improving the basin-scale parameterisation of the cold regions hydrological processes which control the coupled atmospheric-hydrological system. Processes associated with surface hydrology works in different ways on landscapes with different biogeoclimatic characteristics: forest, tundra, wetlands, and lakes all require different strategies to describe the unique water and energy flowpaths in each ecosystem.

The IP3 strategy involved describing processes within Hydrological Response Units (HRU's), small landscape units which possess essentially homogenous conditions and characteristics, but with allowances for subtle variability; examples might be a section of hillside, a forest stand or a wetland area. The HRU is treated as a control volume for mass and energy budgeting, and is represented by average state variables for the unit as a whole. Observations of exchanges between HRUs enable descriptions to be derived of the amalgamation of their individual response into those of sub-basins (small catchments), and from there to basin-groups (larger watersheds). By evaluating these models against observations made in the wide variety of natural contexts found in the IP3 research basins, parameterisations have been developed which are transferable from the point scale (at which observations are made) to small and large basins (at which predictions are required).

The principal modeling tool used in IP3 to develop and test new process algorithms and parameterisations is the Cold Regions Hydrological Model (CRHM). CRHM was developed through IP3 as a framework for the representation of algorithms based on physical hydrological processes, and their integration into more complex models of natural systems at a range of resolutions. CRHM was used to develop and test IP3's mathematical descriptions of the natural world, allowing parameterisations to be tested alone, and then together with others, to demonstrate by evaluation against the collected data whether the process-descriptions were complete and could be applied to various combinations of environmental conditions and characteristics. After parameterisations were successfully evaluated in CRHM, they were incorporated into IP3's strategic coupled hydrological-atmospheric model, MESH, covered in Theme 3 – Predictions.

CRHM was set-up at selected test sites in each of the four regions (arctic, alpine, wetland and shield). Existing parameterisations were assessed against archives of mass and energy balances over complex terrain and an assessment of MAGS aircraft flux measurement was done to determine an upscaled "observation" for use in determining regionally averaged turbulent fluxes. Performance evaluations of CRHM process parameterisation against field and distributed modelling data were conducted, and evaluations of MESH performance in respect to mass and energy balances, CRHM and distributed modelling data were made. This led to the development of improved parameterisations for radiation, turbulent transfer, snow dynamics, melt, soil thaw, subsurface flow and lake evaporation.. The numerical representations of snow redistribution, melt, canopies, lakes, landscape and water course connectivity were incorporated into CRHM and MESH, and used to develop up-scaled mass and energy balance representations for cryospheric processes in complex vegetated terrain and representations of

regionally averaged fluxes over lake and snow dominated terrain. The testing of CRHM and MESH (CLASS) with new algorithms, permitted comparison of model outputs to observations, distributed models and previous version outputs, with the appropriate code revisions taking place. Parameterisations were implemented in coupled models after complete testing and revision as necessary.

Theme 3 – Prediction – Using MESH/MEC modelling system

The focal point for Theme 3 was on testing and evaluating results from the process based, basin scale experiments. The focus was on scaling, segmentation and parameterization of hydrological-land-surface models for application in the regimes considered by IP3. The platform for model evaluation was the hydrological land surface scheme H-LSS (MESH) hydrological system that is part of Environment Canada's Modélisation Environnementale Communautaire (MEC) modelling platform. A close partnership between this activity and scientists supported by the first two themes of this program was essential to the success of IP3. The objective of this research was three-fold. The first (Optimization) was to examine the potential of multi-objective optimization for model parameterization at the basin scale. There has been significant advancement in this area through the PhD work of Pablo Dornes. Using field estimates of SWE and streamflow hydrographs, both inductive and deductive approaches to hydrological simulations were used. In the inductive approach, optimisation using a multi-objective approach was required. Both MESH and CRHM models were used and optimization used the optimization techniques developed by Bryan Tolson. The second objective (Basin Segmentation) was to examine different combinations of tile and tile connectors that could best explain the variations in the water cycle. Segmentation within MESH is based on the GRU approach which focuses on land-cover as the method for segmentation. Forcing is consistent with the model grid. Although this is a well-established protocol, it is based on the assumption that variability (both atmospheric forcing and hydrological response) are consistent with land-cover. There is still much research in assessing the appropriate level and type of segmentation required in order to capture the sub-grid variability of the energetics and hydrology of the basin. In this part of the study, the importance of representing topographic variability within a model grid was examined. It was well understood that variations in forcing data and initial conditions required a level of segmentation in the GRU approach. However a methodological approach based on inductive reasoning, small scale modelling with CRHM provided a framework and systematic process for establishing the appropriate level of basin segmentation. The current operational framework for atmospheric forcing in MESH does not take this into account, and advances made in this research will need to be operationalized into the EC system. Moreover, snow accumulation is not only a function of land-use, but also a function of local topographic effects. The MEC-MESH framework is designed to allow for various combinations of grouped units to be established. Optimum and appropriate basin segmentation schemes for various cold-region domains were proposed and evaluated at the GEM-LAM scale. This third objective (MESH Development) has largely been achieved through the assistance of Bruce Davison, an IP3 collaborator. On this objective, there was significant progress made. Close collaboration with E.D. Soulis and Frank Seglenieks (U of Waterloo), Diana Versegny and others has allowed for a software group to be developed. A stand-alone version of the MESH modelling system is available to all IP3 investigators, and is supported largely through in-kind EC contributions, but also substantially through efforts of this study. Some changes still required focus on vertical water and energy budget deficiencies within CLASS (in the context of MESH), tile sequencing requirements within MSC and some changes in the MESH interface to deal with distributed inputs, parameters and initial conditions based largely on the findings from this work.

A physically based blowing snow model, the Prairie Blowing Snow Model (PBSM), initially developed for prairie environments was used to model snow redistribution and sublimation by wind over two sites representative of mountainous regions in Canada: Fisera Ridge in Marmot Creek Research Basin and Granger Basin in Wolf Creek Research Basin. Blowing snow algorithms were incorporated into MESH to create MESH-PBSM. Snow redistribution by wind

was shown to cause mountain snow accumulation to vary from 10% to 161% of seasonal snowfall within a headwater catchment in the Canadian Rocky Mountains, and blowing snow sublimation losses ranged from 10 to 37% of seasonal snowfall. Matthew MacDonald has extended his M.Sc. contribution by evaluating and improving MESH in mountainous regions. The transferability of parameter sets derived from using observed meteorological forcing data and from using numerical weather prediction model output is examined. The Canadian Land Surface Scheme version 3.5 (CLASS) was used to model snowcover and soil moisture at Marmot Creek Research Basin. Parameters were calibrated using both field data and GEM/CaPA as meteorological forcing. This work will also assist in parameterising MESH for large scale application. Ongoing is the evaluation of the importance of including blowing snow transport and spatially variable solar radiation on simulating discharge in mountainous terrain.

1.2 Explain whether the project milestones originally proposed were met.

Theme 1 – Processes

Year 4 Milestones and Deliverables

Two main tasks remained for Year 4:

- Incorporation of all new numerical process descriptions into CRHM complete
- Continued refinement of numerical process descriptions as they are tested across all research catchments.

Considerable process has been made regarding new numerical process descriptions with respect to frozen ground heat and mass movement, runoff, lake evaporation and snow processes. Publications in the IP3 Hydrology and Earth System Science special issue and other international peer-reviewed journals highlight this work. Ground thermal and soil water algorithms described by Zhang et al. (2008, 2010) have been imported to the CRHM platform for testing by Dr. Chad Ellis. Runoff routines developed earlier have already been incorporated into CRHM and tested at appropriate IP3 basins. A new “fill and spill” scheme has been incorporated in CRHM and tested against field data at a number of appropriate sites. New schemes for snow energy, snow redistribution and snow interception routines have been incorporated in CRHM, including the effect of stand type, slope and aspect on snow interception and melt, and mountain slope on blowing snow transport. Other models such as GEOtop have also been utilized to refine process description and understand interactions. Where appropriate, CRHM has been used in various forms in all catchments.

Theme 2 – Parameterisation

The milestones and objectives of Theme 2 were met. The first one was to: ***test and evaluate CRHM and MESH (CLASS) with new algorithms, and compare model outputs to observations, distributed models and output of previous version. Revise code.***

A summary of some of the main areas of advancement is given below:

Runoff: A new hydraulic conductivity (K) – depth association was incorporated into CRHM in which the user defines the K value at the upper and lower extremes of the profile, and the depth of the transition. This method of defining K increases the transposability of the model amongst cold regions site types. CRHM was tested with the new representation of hydraulic conductivity using archived data collected at Scotty Creek for the period 2001-2010. These tests showed that the CRHM estimates of runoff closely matched observed values in terms of both timing and amount.

Ground thaw: A new soil thaw algorithm has been coded into CRHM based on Hayashi et al. (2007). New algorithms were also developed that simulate the downslope movement of energy with subsurface flows. This has led to a new capacity to simulate the linkage between preferential flow and preferential ground thaw. The new algorithms have been tested as stand alone models and incorporated into CRHM.

Connectivity: New relationships between frost depth and surface soil moisture have been identified and parameterised with a modified form of the Peclet number. The identification of storage – discharge curves at the basin scale may prove useful for catchment classification and the prediction of streamflow. A new basin-scale connectivity metric has been developed and this index has been shown to be related to both streamflow and runoff ratio. The shape of the relationship depends on the configuration of HRUs within the basin. Both CRHM and MESH experienced problems simulating streamflow in Baker Creek.

Fill and Spill: A new “fill and spill” scheme has been incorporated into CRHM and has been tested not only at Baker Creek but in other landscapes (e.g., Canadian Prairies). Initial results are promising, but the relative influence of the scheme on simulations has not been fully tested. MESH remains with its original tile connector.

Snow: New releases of the Distributed Blowing Snow Model (DBSM) and PBSM were prepared, including the implementation of two different methods for simulating wind flow over complex topography. These were tested against wind measurements from Wolf Creek and Marmot Creek and implications for the modelling of snow redistribution were investigated. A deterministic model for the bending of shrub branches under applied snow loads was developed. This process is important because the degree to which shrubs are buried by snow is an important control on the radiative characteristics of tundra landscapes. A new parameterisation of snow unloading from coniferous forest canopies was developed and tested with a revised interception routine. A parameterisation for radiative transfer through discontinuous forest canopies on steep mountain slopes has been developed and used in an improved snowmelt algorithm. Parameterisations for turbulent heat and moisture fluxes to the atmosphere over heterogeneous vegetation, glaciers and complex snowcovers have been evaluated. A parameterisation for the landscape fraction of exposed vegetation is being developed from the shrub bending process model. Each of these new parameterisations has been coded into CRHM.

Model tests indicate that the delineation of HRUs introduces complexity to models that was not anticipated. HRUs should not be viewed as the components of a landscape classification, but as a delineation based on hydrological response along a flow sequence, and this delineation may vary among processes. For instance, the source areas of blowing snow will be different from those of hillslope runoff, since wind can transport snow across drainage divides. Likewise, the HRUs used for snowmelt and groundwater flow are often different, as the landscape properties of importance vary among processes. For some processes, it is also necessary to define flow sequences among HRUs. For example, one HRU may produce surface runoff and convey it to another HRU, from where it flows to a third HRU. This sequence is likely different for other flow processes (e.g. blowing snow or groundwater flow), and may vary with time over the thaw season as the meltwater supply dwindles and the active layer develops, causing alterations in drainage pathways.

Another crucial milestone was to *implement parameterisations in coupled models*.

During the last year parameterisations have been incorporated into CLASS as a first step toward incorporation in MESH. The new parameterisations are currently being tested in CLASS off-line, so that model performance can be evaluated before the new parameters are

incorporated into MESH. Examples of this step toward implementation in MESH are given below:

Energy-based framework for runoff generation: The distribution of energy-based runoff-contributing areas in catchments persists from year to year, since spatial variations in aerodynamic and radiant energy are strongly controlled by surface topography, namely aspect and slope angle. The LiDAR-based DEMs for Trail Valley Creek, Granger basin and Scotty Creek were used to define the topography of the ground surface and of the impermeable frost table at several stages of active layer thaw. The frost table topography defines the spatial distribution of K_s , local hydraulic gradients, and the location of preferential flowpaths. Modelling runs have produced frost table depths and frequency distributions that compare well with field measurements. Since arctic and alpine tundra, taiga, and the forests and peatlands of the boreal zone support a similar suite of peat-forming species, there are strong similarities in the hydraulic and thermal properties of organic soils of these terrains, which adds to the transferability of the new framework.

Spatial variation of ground thaw: New parameterisations were developed that reflect the coupling of the subsurface drainage and thaw processes. Thinning of the tree canopy by natural or anthropogenic processes leads to increased radiation loading at the ground surface, which produces local increases in thaw depth. These areas develop higher soil moisture values as water drains toward them, which increases the bulk thermal conductivity of the peat in the depression, allowing transfer of more thermal energy from the surface to further deepen the depression. As this process continues, the remaining trees in the area may be unable to survive due to water-logging, thinning the canopy further and increasing radiation loading of the ground surface above the depression. This sequence of events describes how the local site characteristics may need to be updated during model runs.

Theme 3 – Prediction

Major improvements have been made in representing important physical processes in MESH, automating model testing, model input/output processing, visualization and general model development practices.

1. The CRHM's Frozen Soil Infiltration Algorithm has been smoothly incorporated into MESH and has produced considerable improvements in the head waters of the South Saskatchewan River basin and in the Upper Assiniboine River basin. An abstract has been submitted for the 2011 CWRA conference and publication is expected in 2011,
2. The interflow algorithm is aligned with the advanced interflow algorithm from the University of Waterloo and Recherche Prévision Numérique (RPN),
3. Adaptation of the well tested automated testing system that has long been in use at the Institut National de la Recherche Scientifique (INRS), Université de Quebec, into the MESH modeling system,
4. Many of the tools to set up and run the MESH modeling system in any of the Canadian basins are now in place and functional. These include; a pre-processor to extract land cover, soil and digital elevation data from the Canadian GeoBase data source, programs to process forcing data from reanalysis products such as the Canadian Precipitation Analysis (CaPA), the North American Regional Reanalysis (NARR) and from the Global Environmental Multiscale (GEM) model, a connector program for auto calibration runs using the Dynamically Dimensioned Search (DDS) Algorithm (and many other calibration algorithms on the way), and batch files and scripts to run the MESH model either in personal computers or at any node in the halsasgrid cluster system of the Hydrometeorology and Arctic Lab. The current version of MESH also allows the production of model outputs in a format that can be

visualized using the Canadian Hydraulics Centre's Green Kenue software (advanced data preparation, visualization and analysis tool for hydrological models).

5. Improved model development practices continue to be incorporated into the development of MESH. In addition to the testing procedures already described, these practices include regular code reviews, software configuration management, and better developer and user documentation.

1.3 **Describe the tangible results or the measurable outputs generated by the project and how these results have been taken up by user groups for policy development or operational improvements.**

- At the end of the project, Baker Creek remains as a very well instrumented basin useful for expanding knowledge of hydrological processes that can be applied to water management across the region. Site operations are now shared between Environment Canada and Indian and Northern Affairs. Data from Baker Creek is being used for managing the abandoned Giant Mine near the mouth of the creek. New lateral transfer schemes in CRHM may prove useful when the model is applied for water management purposes in both northern and prairie Canada.
- The Lake O'Hara study is still generating new understanding of groundwater processes in alpine headwaters. No policy development or operational improvements have been made.
- Marmot Creek research is being used to develop policy for Alberta Sustainable Resource Development on allowable forest harvesting and on the impact of pine beetle on water resources. Marmot Creek results have been relayed to the Parliament of Canada, Prairie Provinces Water Board, Environment Canada, Alberta Environment and Saskatchewan Watershed Authority for policy in response to climate change impacts. Marmot Creek has been sustained by Alberta SRD funding after IP3 to use as a benchmark laboratory for forest hydrology in Alberta. Parameterisations developed here have substantially developed CRHM for general use in mountain environments.
- The tremendous losses of seasonal snow to sublimation from both alpine blowing snow and forest snow interception in the Rocky Mountains have been quantified and used to improve water balance assessments in the region and globally.
- Parameterisations developed in the Wolf Creek project are being implemented in the UK community land surface model, which is used for both operational weather forecasting and climate modelling.
- Research at the Wolf Creek Research Basin has resulted in the further development of CRHM which has in turn been used by numerous public and policy groups in western Canada. Information from this project has also led to an international collaboration entitled North-Watch (Funded by Leverhulme Trust, UK). This work has also been used as the basis for understanding cold-region processes associated with oil sands reclamation activities in Fort McMurray, Alberta. Work on CRHM and other IP3 projects is being reviewed by Indian and Northern Affairs Canada (INAC) as part of their technical advisory group on northern mines, which represent a large liability to the Government of Canada. Information from IP3 research is being used to better understand and steward the closure of mine sites in cold regions.
- The field studies at Scotty Creek led to a new understanding of the hydrological functioning of the wetland-dominated discontinuous permafrost terrain that predominates throughout much of the southern extent of permafrost. The landcover consists of three hydrological units: permafrost plateaus, channel fens and flat bogs, occurring in a mosaic of different size patches. Permafrost plateaus function as runoff generators, owing to their relatively large end-of-winter snow water equivalent moisture supply, limited active layer water storage capacity, and relatively large hydraulic gradient directed toward the surrounding bogs and fens. Channel fens convey water along their broad, hydraulically

rough channels, thus plateau runoff entering these features flows toward the basin outlet. Flow through the extensive networks of interconnected wetlands is highly diffuse and practically impossible to gauge accurately. However, water level monitoring stations located along main drainage ways showed that the propagation velocity of storm pulses can be used to estimate the bulk hydraulic roughness of channel fen networks. Analysis of water samples collected along fens indicates that they receive groundwater discharge, whereas the water chemistry of bogs indicates they recharge groundwater systems. Bogs that are completely surrounded by permafrost plateaus are hydrologically isolated from other wetlands, so that water entering such bogs is stored until removed by evaporation or groundwater recharge. Water entering bogs with connections to channel fens will flow to the latter during periods of high water supply only and is otherwise stored as in isolated bogs. Overland flow from plateaus is rare owing to the very high permeability of their surfaces. Lateral drainage is therefore conveyed through a subsurface flow zone with a lower boundary defined by the impermeable frost table. The spatial pattern of soil thaw over a permafrost plateau is largely controlled by the spatial pattern of soil moisture, as wet peat is a better conductor of energy to the thawing frost table than dry peat. These studies were a critical first step towards developing numerical simulations and predictive tools needed by water scientists and water managers in the region.

- A new method that combines LiDAR with other aerial and satellite imagery was developed to accurately delineate the edges of terrain underlain by permafrost. This method enables delineation of runoff producing areas as needed by water managers, and allows for monitoring annual changes in permafrost coverage. IP3 collaborated with the Forest Management Division (FMD) of the Government of the Northwest Territories (GNWT) to develop an archive of historical aerial photographs and satellite images over the study region in order to obtain current and historical “snapshots” of permafrost distribution. The Scotty Creek project also developed new techniques for obtaining consistent results among photographs and images of different resolution and spectral characteristics.
- The runoff generation process of individual permafrost plateaus is now well understood. Numerical representations of such processes in the Cold Regions Hydrological Model (CRHM) produced accurate runoff simulations from peat plateaus for a range of hydrological input, soil moisture and thaw conditions. Simple Fill and Spill Hydrology (SFASH), a quasi 3D coupled heat and water transfer model, was developed to simulate the thawing of the active layer and runoff generation in an individual peat plateau. This is an application of the fill-and-spill hypothesis for organic covered permafrost since water stored in frost table topographic depressions can be released due to melt-out of the impounding ground ice without precipitation forcing, as the frost table topography evolved with soil thaw. Snow accumulation, melt and evapotranspiration from individual plateaus and wetlands are also now reasonably understood from the IP3 field studies.
- The development of a simple, reliable model capable of calculating lake evaporation rates for hourly time periods was achieved with model validation demonstrating accurate and reliable results. Relationships were also developed between the wind speed over open water and wind speed over the land surface, which may be useful in cases where measurement over water is not possible. The initial progress made with this project has encouraged other researchers to attempt the direct measurement of evaporation from the Great Lakes. Interest has been expressed by users of other models such as WATFLOOD for incorporating this procedure. Lakes in other jurisdictions (eg. Okanagan Water Management Board) are interested in carrying on this field work in their locations.
- Software development of CRHM, MESH, interfaces and coupling systems has led to substantial improvement in cold regions hydrological modelling.
- Theoretical advances have been made in developing a subsurface inflow parameterisation for sloping aquifers, as well as a new approach to defining field capacity for sloping soils and improved Green-Ampt infiltration algorithms for shallow soils.
- Water balance assessments have been constructed for Lake O'Hara, Marmot Creek, Wolf Creek and Scotty Creek basins.

- Mesoscale modelling improvements led to the land surface model being tested by other research groups including the Drought Research Initiative (DRI) and the University of British Columbia (WC2N).

1.4 Explain any significant delays or departures from the research plan, or the rescheduling of activities, and how they were addressed.

There were no significant delays or departures from the overall research plan.

1.5 Explain any significant deviations from the budget (changes of 20% or more).

There were no significant deviations from the budget.

1.6 Describe how the work of co-investigators was integrated or coordinated.

IP3 investigators' work was integrated across all three themes with many investigators contributing to more than one theme area. Network activities were coordinated through monthly Scientific Committee teleconferences with the Principal Investigator, Theme Leaders, Network Manager, Financial Manager and Data Manager. Data sharing was facilitated through posting of observational datasets and modelling outputs to the IP3 ftp server.

Multiple inter-institutional visits were made between all universities involved in the network: University of Calgary (Pomeroy), Carleton University (Essery, Pomeroy), University of Saskatchewan (Carey, Marks, Link, Essery, Janowicz), Wilfrid Laurier/University of Waterloo (Soulis, Quinton, Pietroniro, Pomeroy, Hayashi, Carey), University of Edinburgh (Carey, Janowicz, Pomeroy)

Field work collaboration was a cornerstone of the IP3 network. Wolf Creek Research Basin field research and analysis was carried out by Carey, Essery, Janowicz, Pomeroy, Quinton, Pietroniro, and many of their students and technical staff, with planning and coordination of all Wolf Creek research activities carried out through Yukon Environment. Marmot Creek research and analysis was carried out by Pomeroy, Pietroniro and Snelgrove with numerous student research projects focussed on this site. Other fieldwork collaborations included Peyto Glacier (Munro and Pomeroy), Lake O'Hara (Hayashi and Pomeroy), Baker Creek (Spence, Granger and Pomeroy) and Scotty Creek (Quinton and Hayashi). Data collected from each basin was shared with students pursuing specific research in modelling and parameterisation. Investigators working in the same basin were able to share research equipment and field gear, field camp operations, and coordination of field logistics. Graduate students were often co-supervised by investigators at the same research basin. Co-supervision also occurred between multiple themes with Quinton and Soulis co-supervising students for process and parameterisation work, and Pomeroy and Pietroniro co-supervising students for parameterisation and modelling.

The MESH modelling system was applied on many of the basins with collaboration between investigators collecting field data and investigators working on the modelling systems, specifically Pietroniro, Soulis and Versegby.

Several investigators also relied on working relationships with IP3 collaborators; Marsh and Blanken (for aircraft flux data analysis), Soulis and Craig (MESH drainage algorithm), Soulis and Tolson (adding DDS to MESH and running DDS on various IP3 basins), Quinton and Schincariol (laboratory studies of frozen peat at the BIOTRON facility), Quinton and Heck (using 3-dimensional analysis for defining flowpaths through peat), Pomeroy, Link and Marks

(development of new snow parameterisations and models), Pomeroy and Westbrook (flowpaths and hyporheic exchange) Marsh and Mackay (analysis of flux data from snow covered sites and comparison with CLASS), Versegby and Mackay (incorporating developmental lake model into CLASS), and Essery and Marks (canopy radiative transfer modelling).

Workshops and conferences offered many venues for investigators to meet together over the four years of IP3. Annual IP3 meetings (2006-Saskatoon, 2007-Waterloo, 2008–Whitehorse, 2009–Lake Louise) allowed network research progress to be shared; while many investigators also attended and presented their IP3 research at the annual CGU Assemblies (2007-St. John's, 2008–Banff, 2009-Toronto, 2010–Ottawa, 2011-Banff). Several investigators and students attended the 17th International Northern Research Basins (NRB) Symposium and Workshop, Iqaluit-Pangnirtung-Kuuujuaq, Canada (August 2009). A Theme 2 Parameterisation Workshop held in Waterloo in June 2008 allowed an improvement in coordination and advancement in developing model parameterisations. The success of the Prediction theme involved substantial collaboration between many of the investigators. A Theme 3 Prediction workshop in Waterloo in 2009 allowed IP3 investigators the opportunity to summarize modelling progress and produce a plan for completion of modelling goals through the end of IP3. Pomeroy coordinated CRHM development including the addition of new parameterisations with Spence, Essery, Marks, Carey, and Quinton. Spence, Quinton and Pomeroy's work has allowed advancement in parameterisations in CRHM for lateral runoff transfers, and radiation through forest canopies. Five CRHM workshops were held over the term of the network (Waterloo-June 2008, Calgary-June 2008, Winnipeg-June 2009, Red Deer-January 2010, and Yellowknife-October 2010) with large contingents of user groups from government water resource managers to engineering consultants being introduced to the CRHM model. Pietroniro coordinated MESH development with close collaboration between Pietroniro, Soulis, Pomeroy and Versegby, with Soulis and students providing support to numerous IP3 investigators in setting up and running the MESH model in their basins. Versegby worked with investigators and students to set up CLASS for research basins after adding new parameterisations on cold regions into CLASS. Two MESH workshops were held (Waterloo-March 2009, Edmonton-October 2009) to review model improvements and transfer technology throughout the network and to users.

1.7 Describe the participation of government (federal, provincial or local), university, industry or foreign researchers in the project.

Canadian federal government scientists, as both investigators and collaborators, were involved in all stages of IP3, from field work to data analysis, model development and testing, and student supervision. Staff from Environment Canada's National Hydrology Research Centre (NHRC) contributed to the Trail Valley Creek research basin by collecting and analyzing data and carrying out CRHM model runs. Indian and Northern Affairs Canada (INAC) participated in field data collection at the Baker Creek research site, using the information in its site management plans for the Giant Mine site downstream from Baker Creek. The Northwest Territories Power Corporation (NWTPO) discussed the possibility of using the remote sensing methodologies developed at Baker Creek in a similar watershed under their regulation. The Hydrology Manager for Yukon Environment was a key investigator with IP3 allowing access and monitoring in the Wolf Creek research basin. Alberta SRD assisted and provided funds to keep Marmot Creek running in the later part of IP3. Provision of data from Reynolds Creek, Idaho from the USDA ARS was responsible for a substantial improvement in the ability to test models. Success in Theme III – Predictions – would not have been possible without assistance from the Hydrometeorology and Arctic Lab located in Saskatoon and the RPN lab located in Dorval – staff from both labs was heavily involved in providing assistance to the prediction phase of the IP3 research. Environment Canada/NWRI provided access to EC/NWRI data collected at key research sites near Inuvik – data included snow surveys, discharge data and meteorological data collected on site as well as satellite images, LIDAR and NRCC Twin Otter flux data. NWRI staff collected data, carried out initial analysis and ran CRHM model runs. Funding for a PDF for

the Trail Valley project allowed for expanded contacts with the University of Colorado in Boulder, Agriculture Canada, and the NRC.

2.0 Impact

2.1 Describe short and medium term objectives that have been achieved.

- CRHM is now a fully developed and tested cold regions hydrological model that can interface with atmospheric models and has provided a simulation platform for dozens of IP3 students and investigators as well as many more collaborators and IP3 users throughout Canada, USA, UK, Germany, France, Switzerland, Spain, Argentina, Chile and China.
- Baker Creek has been fully instrumented. Field studies of ground frost/runoff processes used a diversity of hydrometric, hydrochemical and remote sensing techniques. Model tests have begun using CRHM. Communication with industry and government on the study progress and results continues.
- We have improved the understanding of groundwater in the alpine environments, where very little knowledge existed prior to IP3. We have also developed parameterisations for groundwater flow and storage in moraine and talus deposits dominating alpine watersheds.
- A study of the spatial scaling of topographic characteristics controlling snow accumulation and melt (elevation, slope and drift profiles) was conducted, comparing topographic statistics for the Wolf Creek Research Basin with Marmot Creek Research Basin and the Reynolds Creek Experimental Watershed, Idaho.
- A new release of the Distributed Blowing Snow Model was prepared, including the implementation of two different methods for simulating wind flow over complex topography (Mason-Sykes and Ryan) and two different methods for calculating blowing snow fluxes (PBSM and simplified blowing snow model). These were tested against wind measurements from Wolf Creek and implications for the modelling of snow redistribution were investigated.
- A deterministic model for the bending of shrub branches under applied snow loads was developed. This process is important because the degree to which shrubs are buried by snow controls the radiative characteristics of tundra landscapes.
- Ray-tracing radiative transfer models were developed for complex shrub and forest vegetation.
- A scheme for the simultaneous calculation of turbulent fluxes over snow and exposed shrub vegetation was developed, and datasets were prepared for further evaluation of this scheme.
- Simple wind flow models were found to give useful results in terrain steeper than that in which they had previously been evaluated. Wind flow models giving similar performance in comparison with mast measurements were found to be capable of predicting quite different snow distributions, identifying an area for further investigation. Surface elevation information from LiDAR was found to improve simulations of snow distribution and revealed that more work is required on interactions between sparse vegetation and windblown snow in high-resolution simulations.
- Two parameterisations for radiative transfer through discontinuous forest canopies were developed, one fitting the outputs of ray-tracing models with an expansion in terms of hemispherical harmonics and the other representing shading by blocks of trees. The latter approach can easily be extended to include topographic shading for mountain forests.
- A parameterisation for heat and moisture fluxes to the atmosphere over heterogeneous vegetation and snow cover was evaluated.
- A parameterisation for the landscape fraction of exposed vegetation was developed from the shrub bending process model.

- Parameterisations of snow redistribution, shading, wind flow, surface fluxes and shrub burial were combined in a high-resolution distributed model for complex snow-covered landscapes.
- At Scotty Creek, the medium term goal of the project was to develop a suite of models for predicting the response of discontinuous permafrost in the Hay River Lowland to climate warming and human disturbance from oil and gas exploration, and the subsequent change in landcover and river flow regime. This goal has largely been achieved through meeting the following short-term objectives: mapping the spatial distribution of permafrost and its change over the past 60 years; developing conceptual and mathematical models of hydrological process; developing a new model of permafrost to simulate its response to climate warming and human disturbances; and coupling the hydrological model with the permafrost model to predict the spatial distribution of permafrost and river flow regime under possible scenarios of climate warming and human disturbance.
- Work in Granger Basin (Wolf Creek) was done on developing and testing an energy-based framework for simulating the volume and timing of basin runoff in alpine and arctic tundra.
- A simple, reliable model for hourly lake evaporation has been developed and tested.
- Substantial improvements to the MESH model have been made through a better understanding of processes and the demonstrated importance of field data for model verification.
- Historical MAGS and CFCAS data for Wolf Creek has been reviewed and archived.
- A data repository has been developed for use in future studies.
- Support for two major Canadian models has been institutionalized.
- Analyses of lake flux data, flux data over snow covered terrain, and comparison of aircraft, tower, and modelled fluxes has been achieved.
- A strategy has been developed and implemented for improved land-surface modelling in two basins that could be applied operationally to the Canadian Land Surface Scheme and eventually in the context of the operational NWP (Numerical Weather Prediction model) within Environment Canada. Software version control and scaling and segmentation issues within the context of H-LSS (Hydrology Land Surface Scheme) development are moving forward. This work will be used by Environment Canada to re-think both the parameterization and approach it currently uses in representing cold-region, high-latitude regimes in its current modelling system for the NWP.

2.2 Describe the significance / impact of the results achieved to date. Describe, as appropriate:

The impact of the project on government policy development (federal, provincial or municipal);

- The project has provided guidance and feedback for the Government of the Northwest Territories (GNWT) Strategy Development. Work at Baker Creek has not had direct results on policy, but it has helped local water management downstream with improved cooperation among partner organizations in the operation of the Baker Creek Research Basin, and collaborative studies are continuing between Environment Canada, and Indian and Northern Affairs.
- The IP3 project brought significant activity and resources to Whitehorse and the Yukon Territory, which was acknowledged by the Yukon government, which in turn led to a willingness to participate and contribute to the project. State of the art knowledge of hydrometeorological process developed by the IP3 research at Wolf Creek is being used in other Yukon locations for operational purposes. As the Wolf Creek Research Basin is in the upper headwater regions of the Yukon River Basin, IP3 research activities were viewed

favourably by government water management agencies, NOAA, the State Hydrological Institute (Russia) and the University of Alaska.

- IP3 development of CRHM is leading to its use in calculating hydrological impacts to determine the allowable area of forest disturbance in Alberta.
- The involvement of Al Pietroniro as a principal scientist with the Hydrometeorology and Arctic Lab (HAL) was by design with the IP3 project highlighting deficiencies in current Environment Canada modelling systems such as insufficient simulation abilities in high-relief, high-latitude regions. Advances in IP3 science will be incorporated into the MESH modelling systems which form the basis for future hydrological prediction, data assimilation and climate modeling as it relates to water. Innovations in IP3 will also influence a number of aspects of land-surface modelling used within the Canadian NWP and RCM modelling systems.

How the project has expanded contacts in partner organizations, or increased cross-disciplinary cooperation;

The IP3 network helped to integrated federal and territorial government agencies with a common interest in water resources management by bringing the agencies into a common research/outreach program. The research at Baker Creek has helped local water management downstream through improved cooperation among partner organisations in the operation of the Baker Creek Research Basin and continuing collaborative studies between Environment Canada (EC) and Indian and Northern Affairs (INAC). INAC has shown interest in the results of IP3 through development of a working document relating hydrological issues of abandoned mines and mine closures in the north. The IP3 project increased contacts and collaboration at Carleton University through internal partnerships to examine the efficacy of LiDAR and other remote sensing (QuickBird) data to discriminate HRU's via image classification. Observation techniques used, and progress made in the lake evaporation project has encouraged Environment Canada and US researchers to attempt the direct measurement of evaporation from the Great Lakes. Researchers studying Lake Okanagan in British Columbia have also requested information on using the research knowledge gained in lake evaporation studies for their use. Demonstration of the model capability has encouraged Parks Canada at Prince Albert National Park to collaborate in a program for assessment of the evaporative losses from Waskesiu Lake.

Whether and how it has enhanced or improved the reliability of predictive methods related to the science;

IP3 has been a leader in hydrological modelling in Canada with benefits ranging from legacy field data sets to institutionalized models (CRHM) and (MESH) which will provide modelling frameworks for a wide variety of applications. Improved algorithms in CRHM and GEOtop have led to improved prediction capabilities. The optimization studies involving DDS and the comparison of the MESH processes with detailed numerical simulations establish the limits of the current model structures and thus provide sign posts for the next modelling initiatives. Specific additions to current predictive methods include a bulk radiative transfer model for use in satellite image analysis that is interactively adjustable to in-basin global radiation measurements and has shown that in comparison with the MODTRAN (MODerate resolution atmospheric TRANsmission) standard atmospheres, performs well without the need for radiosonde data. A procedure for removing noise from recording precipitation gauge data, such that predictions of glacier snow pack build-up from off-glacier data compares well with glacier AWS (automated weather station) measurements of snow pack growth has been applied to data with further improvements to be achieved by filtering noise from snow depth sounder data. Future opportunities to explore the data collected will continue to unfold leading to improved predictions.

The impact of the project on your own institution (e.g. helped attract new students or personnel);

IP3 led to a substantial increase in research and training capacity at the University of Saskatchewan and the NHRC, leading, in part, to the success recruitment of a hydrologist for the Canada Excellence Research Chair in Water Security and establishment of the Global Institute for Water Security at the University of Saskatchewan, co-located at NHRC. IP3 has played a major role in recruiting quality graduate students and Post Doctoral Fellows (PDF's). It has also helped to nurture new research collaborations within institutions. For example, there is much interest at Wilfrid Laurier from non-IP3 collaborators in the water quality implications of permafrost thaw. Several seasons of field data collection have led to the training of students from the Universities of Toronto, Saskatchewan and Calgary in glacier basin field techniques. One example of many for student recruitment for graduate studies is demonstrated by an undergraduate student at the University of Toronto who spent a summer as an IP3 research assistant at Peyto Glacier retrieving archived Peyto Glacier Basin outflow data against which to compare outflow simulations; the student is now using this knowledge to pursue graduate studies. The high quality data sets collected by IP3 will go beyond the research needs of the current investigators leaving legacy data for future graduate student work at multiple institutions.

Whether it has improved or increased the acquisition of funds from other agencies, or led to new partnerships;

The IP3 project was critical to the acquisition of Natural Sciences and Engineering Research Council (NSERC) Strategic Grant funds for Scotty Creek, NSERC RTI for Marmot Creek, and helped in the acquisition of additional funding from the Canada Foundation for Innovation (CFI). The new Laurier-GNWT Partnership Agreement is a major legacy of the IP3 programme. Funding at the University of Edinburgh has been obtained from the UK Natural Environment Research Council for a two-year project employing two PDF's on terrestrial Arctic responses to climate change and a three-year project employing one PDF on snow-vegetation-atmosphere interactions – both of these will draw on IP3 results and encourage further collaboration with IP3 investigators. Processing and interpretation of LiDAR data to obtain surface parameters has expanded contacts with partner organizations and prompted discussion with USDA collaborators on further applications. IP3 provided leveraged funding of a federal government funded IPY project and facilitated NSERC-RTI grants to build heat-pulse probes and acoustic snow sensors. Progress in lake evaporation studies funded through IP3 also enabled leveraging for increased acquisition of funds through IPY. IP3 also provided leverage funding for the NORTH-WATCH (Northern watershed ecosystem response to climate change) proposal funded by the Leverhulme Trust (UK) which has dramatically improved the ability to predict ground freezing/thawing and infiltration, and redistribution of water in frozen soils.

Any links with international initiatives and the potential impact of these (e.g. profile of Canadian science, influence on international programs);

Results disseminated through the International Association of Hydrological Sciences (IAHS) Prediction in Ungauged Basins (PUB) initiative will influence international scientific efforts. IP3 not only contributes to PUB, but the IP3 PI is currently the Chair of PUB and so there is direct injection of the IP3 approach into international approaches for prediction in ungauged basins. Having an IP3 investigator in the UK offered many opportunities for dissemination of IP3 science including: an invited presentation at the European Centre for Medium-Range Weather Forecasts to advise on the reliability of predictive methods for cold regions; advice given to UK and Norwegian meteorological services on operational forecasting of snowmelt; advice on the necessary resolution for remote sensing of snow processes provided for a mission assessment group of the European Space Agency (Canadian associate membership); the acceptance of Marmot Creek, Wolf Creek and Trail Valley Creek as potential ground calibration / evaluation

sites for a proposed dual-band radar snow mapping instrument. IP3 was accepted as a collaborator with the Geneva-based ACQWA (Assessing Climate impacts on the Quantity and quality of Water) project with the Project Coordinator – Martin Beniston presenting as the invited keynote speaker at the IP3 Theme 3 workshop. A postdoctoral fellow was attracted to the project from Switzerland, resulting in a research link with the Swiss Federal Institute for Technology, Swiss Federal Institute for Aquatic Science and Technology, and Swiss Federal Institute for Forest, Snow and Landscape Research focussing on hydrological research in alpine environments.

Any commercial or social application the results may have had or could have;

Analysis of lake flux data and snowmelt runoff components and developments in CRHM, MESH and GEOtop have made significant contributions to Environment Canada research which includes considerations of the impact of the proposed Mackenzie Gas Project on the northern environment. Many consultants have taken the IP3 CRHM and MESH courses and these models and components of these models are used in industry for engineering and environmental consulting dealing with oilsands impact mitigation, climate change impact assessment, forest disturbance planning and hydroelectricity capacity assessment. There has been interest expressed in commercial development of the snow acoustic sonar probe.

The anticipated impact of the work on Canadians and their well-being;

The uncertainty of the rates and mechanisms of permafrost degradation, its impact on water drainage, storage patterns and processes, and appropriate mitigation strategies is a great challenge facing north-western Canada, and one which underscores the need for scientific research to provide the knowledge base for informed and sustainable management of northern water resources. Engineering design, resource exploration and extraction, forest land practises, mining, ecosystem management, hydroelectric facilities, water management strategies and water policy are all predicated on managing risk with respect to ensuring adequate water supply for users and the environment. Improved information is therefore needed so that federal and territorial agencies can more confidently develop guidelines and codes of practise for northern water resources. This project continues to respond to this need by contributing an improved science-based understanding and new predictive tools needed to guide economic development and sustainably manage northern water resources.

The shortage of available water in the South Saskatchewan River was identified by the Royal Canadian Geographical Society as one of the most serious water issues facing Canada and IP3 research at Marmot Creek in the river headwaters is directly addressing this problem and was featured in an October 2010 issue of *Canadian Geographic*.

4.0 Reverse Impact Statement

4.1 Provide a reverse impact statement, describing what would have happened in terms of the project and resulting science, if the work had not been funded by CFCAS.

Much of the science could not have been completed without CFCAS funding. IP3 funding meant more students involved in field work – at Baker Creek, the identification of hysteretic behaviour between basin storage and discharge would not have been identified without the level of field studies that were completed. Much of the results that now show how heterogeneity influences connectivity and runoff response would not have been developed. Key findings that will influence how hydrological model structures need to be updated would not be available without funding for extensive fieldwork campaigns. Alpine groundwater is another topic of research that

would not have been conducted without the substantial CFCAS funding necessary for the hours needed to fund students in collecting large quantities of field data. Work would have been carried out at a much lesser level of activity. Without access to this funding, there would have been a considerable lack of progress with regards to our understanding of hydrological and land-surface processes in cold environments. From process through prediction, we would not have achieved the detailed level of understanding regarding how water cycles through subarctic catchments and the development of appropriate techniques and methodologies necessary to model heat and mass transfer in northern soils. In addition, there would be no foundation upon which to build future projects underway such as the development and testing of new technologies to measure total moisture content below zero-degrees Celsius (heat-pulse probes). If this work had not been funded by CFCAS, the high rate of permafrost thaw along the southern margin of permafrost might not have been demonstrated, and its hydrological and water resource implications interpreted. Permafrost thaw might not have had as much emphasis in the GNWT policies related to climate change adaptation and mitigation. Furthermore, other research funding and collaboration opportunities such as the NSERC Strategic Grant, CFI Grant and the Laurier-GNWT Partnership Agreement would likely not have come about if CFCAS had not funded IP3. A consistent attempt to develop a Canadian model would not have occurred; though other cold regions models do exist they do not model cold conditions with the thoroughness necessary for Canada's diverse cold regions. Canada's international leadership in snow science would have withered without this funding. Without this funding, Canada's cold regions research would have become inconsequential at a time of critical importance. Participation of UK scientists and students in IP3 would not have been possible without the provision of travel money by CFCAS.

5.0 Dissemination

5.1 Provide information on the dissemination of the research results (publications, including journal names and whether refereed), conference contributions, seminars, workshops or videos, websites or other methods of transferring the results.

A full listing of publications and presentations is provided in Appendix A. In summary, IP3 members published more than 80 refereed publications and 50 other publications including books chapters and conference proceedings. Over two hundred presentations were given at conferences, workshops and public events by the IP3 community over its four year mandate. Appendix B lists all workshops and training courses provided by IP3. The IP3 website was redesigned in 2010 to reflect its legacy status as an archived website which will be maintained by the University of Saskatchewan at www.usask.ca/ip3. The website provides access to all IP3 outreach publications including newsletters and brochures, as well as presentations from workshops. Further dissemination of modelling results will continue after the official conclusion of IP3.

5.2 Describe data management/sharing activities including organization of the metadata. Also is the data being archived, and how will it be made available to other researchers?

- Hydrometeorological field data and metadata from the six principal research basins have been collated by the IP3 Network Manager for archiving. These data have been written to relational databases, and are being made available for download from the IP3 website in a universally accessible format that should be available over the long term.
- Data collected by Spence, Granger and Marsh are also archived at the National Hydrology Research Centre, and data for Wolf Creek has also been archived at Carleton University.

- The MESH repository has been transferred to the Meteorological Service of Canada.
- CRHM will continue to be available through the University of Saskatchewan's Centre for Hydrology.
- All model and source code information managed by the HAL lab will be archived within Environment Canada. All research conducted by Environment Canada researchers is archived at Environment Canada.

5.3 **Comment on any outreach or public information activities, including press interviews or other media interest or reports. Has the project helped to popularize science or increase public awareness?**

- There have been regular communications with user groups through an active Users Advisory Committee which adopted the name Cold Regions Hydrology Users Group (CHRUG) and is chaired by Mr. Robert Reid of INAC Water Resources, Yellowknife who is also a member of the IP3 Board of Directors. The Committee has representatives from INAC, Parks Canada, Alberta Sustainable Development, Alberta Environment, Manitoba Hydro, BC Hydro, Yukon Energy, NWT Power, Environment Canada, Yukon Environment, Alberta Parks, and the Columbia Basin Trust. Twenty-two teleconference meetings were held with the group over the term of the network and members actively participated in all IP3 workshops, giving feedback to IP3 for the most relevant types of network science results and providing advice on effective dates, locations, and potential participants for CRHM and MESH model training workshops.
- A Users Advisory Workshop attended by 58 representatives from all levels of government, private consultants, industry, non-profits and academics, was held in Canmore, Alberta, in March 2008 to meet with both private and public sector users to discuss the transference of new research results and products. The workshop involved a well-attended public talk by John Pomeroy and was cosponsored by Lafarge Canada and the Western Watersheds Climate Research Collaborative.
- Grad students and research scientists have given many public presentations to interested parties in venues close to their research sites. Public presentation highlights include: Masaki Hayashi's research group giving public presentations at the Lake O'Hara Le Relais day shelter one day each summer for 2006-2009 along with a public presentation for Parks Canada for the Parks Canada Research updates Speaker Series in Banff in May 2010; The Lake O'Hara Trails Club newsletter carried two different articles; in the 2007 issue – "Hidden pathways of water in the Lake O'Hara Basin" and in the 2010 issue – "Groundwater: Natural water reservoir in the alpine"; and The Alpine Club of Canada 2010 issue of the Canadian Alpine Journal included an article "Secret Water" – contributed by Masaki Hayashi.
- The Canadian Rockies Snow and Ice Speaker Series was presented by IP3 in Canmore, Alberta, from January to May 2010. Eight public lectures were given by visiting academics with events attended by 50 to 100 people. Lectures were given by John Pomeroy (University of Saskatchewan) "Canadian Rockies Snow and Ice Initiative: creating a Canadian Davos in the Bow Valley"; Juan Ignacio Lopez-Moreno (Instituto Pirenaico de Ecologia, Zaragoza, Spain) "Environmental change and water resources in the Pyrenees: facts and future perspectives for Mediterranean Mountains"; Gwenn Flowers (Simon Fraser University) "Water under glaciers: why some glaciers flow fast and what this means for their survival"; Robert Sandford (Western Watershed Climate Research Collaborative) "Corralling the water hole: dispute and potential conflict over water in the Canadian West"; Matthias Bernhardt (Ludwig-Maximilians University, Munich, Germany) "Research on snow and glaciers in the European Alps"; Danny Marks (Northwest Watershed Research Center, Boise, USA) "The Impact of climate warming on snow, climate, and streamflow in a North American mountain basin"; Tobias Jonas (WSL Institute for Snow and Avalanche Research, Davos, Switzerland) "Research, monitoring and warning services related to snow"

and avalanches in Switzerland"; and Shawn Marshall (University of Calgary) "Glacier fluctuations: what glaciers tells us about climate change".

- The Government of Yukon occasionally issued press releases about work in the Wolf Creek Research Basin; as there is strong local interest in the project, Rick Janowicz participated in several media interviews about ongoing work in the basin.
- At the Peyto Glacier research site – many visitors hike near the research site and the researchers were asked to always take the time to speak to people curious about the research activities. The involvement of Scott Munro in publishing a chapter in the book "Peyto Glacier: One Century of Science" and collaborator Mike Demuth in editing the book would seem to have had an impact on public awareness as the Peyto Glacier Basin is now a key element in current planning for water resource research in the Rocky Mountains.
- Sean Carey presented a public lecture "Water in the changing north" to the Yukon Science Institute in November 2008 concurrent with IP3's annual workshop which was attended by more than 60 interested parties. Radio interviews and newspaper articles followed from the public lecture and workshop.
- CFCAS organised "The Lowdown on the Meltdown" Arctic research symposium in Ottawa in November 2008. John Pomeroy presented "Wetter, wilder, warmer" detailing IP3's Arctic research.
- The CFCAS and Environment Canada organized "Water Security: The Critical Role of Science" symposium in Ottawa in May 2010 saw several IP3 researchers take part as invited speakers: John Pomeroy presented "Where are the snows of yesteryear? The effects of snow on water supplies"; Sean Carey presented "Water in the changing north" and Phil Marsh presented "The Mackenzie Delta: changing water supply in a sensitive arctic ecosystem".
- John Pomeroy and Bob Sandford participated in several water resource vignettes produced by The Weather Network in conjunction with CFCAS.
- Sean Carey, IP3 Theme 1 Leader, was the recipient of the Canadian Geophysical Union's Young Scientist Award in 2010 and during two CBC interviews for the awards, CFCAS and its role in the work funded to aid Carey in achieving this award was mentioned.
- Work in the Scotty Creek Research Basin has led to the opportunity for many public interactions including: scientific advice to the Government of the Northwest Territories for use in developing public policy documents in water resource management and climate change impact and adaptation, forest resource assessment and guidance for protection of land, forest, and wildlife in oil and gas seismic exploration; regular communication with local municipal governments and First Nations; grad student - Ross Phillips giving both a public lecture and detailed research lecture to INAC staff in Yellowknife; scientific interpretation by request for public media including CBC-North, The Globe and Mail, the Province (Vancouver), The Record (Kitchener) and the Deh Cho Drum (Northwest Territories).
- Public media articles have been written about IP3 research and include "It's all about water" published in Research at Laurier's – Summer 2008, "Unlocking the secrets of climate change" in the Northern News Services December 2007 and "Problems ahead for Canada's water supply" in the Kitchener Record December 2007. Many IP3 researchers have been invited guest lecturers for public talks – Quinton on "Permafrost melt in wetland basins: Implications for Water Resources in the NWT" – invited by GNWT – Department of Environment and Natural Resources – March 2009 and November 2009; "Climate Warming and water resources in the northern boreal forest" – invited by Liddli Kue First Nations - August 2009.
- Bill Quinton gave a public lecture on "Permafrost thaw impacts on northern water resources" in Yellowknife in October, 2010 as part of a two-day CRHM workshop and northern research seminar. Thirty government water practitioners and private consultants attended the CRHM workshop, with 35 participants attending the second day presentations on IP3 research in the north. John Pomeroy was interviewed by both CBC North radio and television during the event.

- Sean Carey participated as a panel member in a public discussion at the University of Toronto on the Athabasca Tar Sands as an expert in cold regions hydrology.
- Parks Canada has been given photos and a project description for lake evaporation research for inclusion in a Parks Canada newsletter.
- John Pomeroy was interviewed multiple times for newspaper articles relating IP3's work to the Saskatoon Star-Phoenix, Ottawa Citizen, Calgary Herald, and the Rocky Mountain Outlook. Topics covered included the dwindling freshwater supply, the relationship between Rocky Mountain runoff and prairie water resources, the importance of research funding, research at Marmot Creek and the Principles of Hydrology course offered at the Biogeoscience Institute at Kananaskis.
- A MESH workshop was held in Edmonton in October 2009 at the request of water resource practitioners with the government of Alberta. The two day event attracted 18 participants.
- IP3 supported outreach activities by several IP3 investigators and students during the 17th Annual Northern Research Basins (NRB) Symposium in Nunavut in August 2009.
- A CRHM workshop attended by 24 participants held in Winnipeg in June 2009 was followed by meetings with Manitoba Water Stewardship and Parks Canada to discuss applications of CRHM to hydrological prediction of ungauged watersheds.
- A CRHM workshop followed by a water management workshop was held in Red Deer in January 2010, with 35 participants attending the CRHM workshop and 33 individuals from provincial and federal government agencies, universities, regional watershed alliances and local community organisations attending the second days discussion on application and improvement of CRHM and water management in the Prairies.
- The Saskatoon Star-Phoenix printed articles on several students whose research fell under the auspices of IP3 including Nicholas Kinar's work on sonar measurements of snow water equivalent and Stacey Dumanski's fieldwork for Parks Canada in the Yukon.
- John Pomeroy presented to parliamentarians in Ottawa in May 2010, as part of the Bacon and Eggheads lecture series. His presentation "Water prescriptions for a dry land-how the West can prepare for drought" was heard by over 175 government policy experts, scientists, Members of Parliament and Senators.
- A workshop and public presentation on "Glaciers in the Columbia Basin – glacial recession research" was held in Golden, BC in February 2010 to share WC²N and IP3 research with the Columbia Basin Trust and interested members of the public. Twenty water resource practitioners attended the workshop while the public presentation attracted a large local audience of 70.
- Robert Sandford is contracted to write a popular science book based on the results of both IP3 and WC²N research. The finished manuscript should be in the hands of publisher Rocky Mountain Books for September 2011.

5.4 Describe how you have acknowledged CFCAS support.

CFCAS support has been recognized by IP3 members through acknowledgments and display of the CFCAS logo in conference and other meeting presentations, posters, published articles, reports, and on network and investigator websites. The CFCAS logo was always included in the first slide of oral presentations and on all poster presentations with written acknowledgment in all manuscripts. Interviews with media were always used to highlight the generous support of CFCAS in providing funding for specific research projects. Larger venues such as the joint AGU-CGU meeting in Toronto in May 2009, joint IAMAS-IAPSO-IACS assembly in Montreal in July 2009 and the joint CGU-CMOS meeting in Ottawa in June 2010 were excellent venues for very public acknowledgment of CFCAS support.

5.5 Attach copies of any papers published or accepted for publication. Alternatively, if the work resulted in a large number of publications, please provide a reference list and if possible, a copy of each publication's title page.

As the work of IP3 has resulted in an extremely large number of publications, including a special issue of the European Geoscience Union's journal, *Hydrology and Earth System Science*; a complete reference list has been included in Appendix A.

6.0 Training

6.1 Quantify student and PDF involvement (indicate the level of each: undergraduate, masters, doctorate or PDF). If possible and within the Federal Privacy Act rules governing the collection of personal information, provide a general indication of their subsequent employment (i.e., university, industry, government, other, etc.), and indicate whether the employment was foreign or domestic.

This project has produced graduates with a readily employable level of theoretical and practical capability gained through field and lab work, and analytical and modelling/quantitative training by offering a rich pedagogical environment for high-quality training. Students benefitted from rich data archives, expertise and equipment at the various research basins, and from interactions with scientists and technicians at collaborating institutions. Student supervisory committees often included investigators and collaborators from multiple universities, modelling collaborative approaches to research that students will transfer to their future employment. Over the life of the IP3 network, investigators have directed or supervised 10 Postdoctoral Fellows, 26 PhD students, 39 M.Sc. students, 34 undergraduate students, and 10 research employees and staff. A full listing of personnel, their roles and where graduates are now can be found in Appendix B.

7.0 Other

7.1 Provide suggestions on how CFCAS could enhance its contribution to university based research in climate and atmospheric sciences, or otherwise assist the community. Provide any remarks or additional suggestions for CFCAS.

IP3 is an excellent example of university and government collaboration. It should be cited as an example of how things can work. Innovation needs to come from the University sector however, the aspects of innovation that can make a real difference in mandated programs within government also need to move from research to operations in a cohesive and comprehensive way. The ability to provide funding for ongoing baseline data collection activities for climate monitoring purposes is a key requirement for ongoing research.