THE PROCESS HYDROLOGY APPROACH TO IMPROVING PREDICTION OF UNGAUGED BASINS IN CANADA

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ABSTRACT

Numerous research basins have been instrumented and monitored for understanding the water balance and improving rainfall-runoff relationships in Canada, with mixed results and uneven improvements in our understanding and prediction of these systems. Two limitations on gaining useful results from these basins have been that their experimental designs often depended on long-term comparisons of observations and/or on calibrations of conceptual, rather than physically based, runoff models. Such comparisons and calibrations can be hampered by changes in climate and land use, measurement uncertainties, mixed sets of processes causing the basin runoff response, an over-emphasis on streamflow rather than comprehensive basin hydrology and energetics and the relatively short time period that most Canadian research basins have been operating.

An alternative to such traditional study of basin dynamics and response has been implemented where the hydrology was poorly understood and long term observations were not available or desirable. The new approach has provided rapid improvements to our understanding and prediction of these systems and is suited to application in ungauged basins. The approach consists of: i) intensive observations of the most uncertain hydrological processes or pathways in an experimental basin that represents ungauged basins in some region; ii) development of algorithms to describe the operation of the primary hydrological processes and pathways in the experimental basin, and;
iii) concurrent development of uncalibrated physically based hydrological models and their operation as diagnostic tools to determine the sensitivity of basin hydrology to specific pathways and processes.

Research basins in Wolf Creek, Yukon and the Prince Albert Model Forest, Saskatchewan were operated for several years to measure hydrological processes as well as basin runoff sensitivity and response. Processes of considerable uncertainty were focused upon and specialized observations were taken. By modelling the processes over the basin, the hydrological behaviour can be described and predicted with acceptable accuracy and increasing confidence. Because process descriptions are physically based, extrapolation beyond the region of observation is likely and a useful result of this method.

RÉSUMÉ

De nombreux bassins de recherche ont été munis d’instruments et ont été surveillés dans le but de comprendre le bilan hydrique et d’améliorer les relations chute de pluie-ruissellement au Canada, ce qui a produit des résultats mélangés et des améliorations irrégulières de la compréhension et de la prévision de ces systèmes. Deux aspects ont freiné l’acquisition de résultats utiles dans ces bassins : les conceptions expérimentales des bassins dépendaient souvent de comparaisons à long terme des observations et/ou d’étalonnages des modèles de ruissellement conceptuels plutôt que physiques. Ces comparaisons et étalonnages peuvent être gênés par des changements de climat et de l’utilisation des terres, des incertitudes dans les mesures, des jeux mixtes de processus causant la réponse du ruissellement du bassin, la surestimation des débits plutôt qu’une énergétique et une hydrologie du bassin détaillées et la période de temps relativement courte pendant laquelle la plupart des bassins de recherche canadiens ont été exploités.

On a mis en œuvre une autre façon d’étudier la dynamique et la réponse des bassins dans les endroits où l’hydrologie était mal comprise et où des observations à long terme n’étaient pas disponibles ou désirables. Cette nouvelle approche a permis d’améliorer rapidement notre compréhension et la prévision de ces systèmes et peut être appliquée aux bassins non jaugés. L’approche consiste à : i) d’intenses observations de la plupart des cheminement ou processus hydrologiques incertains dans un bassin expérimental qui représente les bassins non jaugés d’une région; ii) l’élaboration d’algorithmes pour décrire le fonctionnement des cheminement ou processus hydrologiques principaux dans le bassin expérimental; et iii) l’élaboration concurrente de modèles
hydrologiques physiques non étalonnés et leur opération comme outils de diagnostic pour déterminer la sensibilité de l’hydrologie du bassin à des processus et cheminement spécifiques.

Des bassins de recherche ont été exploités pendant plusieurs années à Wolf Creek (Yukon) et dans la forêt modèle de Prince Albert (Saskatchewan) afin de mesurer les processus hydrologiques ainsi que la réponse et la sensibilité du ruissellement du bassin. Les travaux ont été axés sur des processus d’une très grande incertitude et des observations spécialisées ont été effectuées. En modélisant les processus dans le bassin, on peut décrire le comportement hydrologique et le prévoir avec une exactitude acceptable et une confiance accrue. Étant donné que les descriptions des processus sont physiques, l’extrapolation au-delà de la région d’observation est probable et constitue un résultat utile de cette méthode.

INTRODUCTION

Basin studies are a means to an end, the end in hydrology often being an improved understanding and predictive capability for the regional hydrological system in question. Improved understanding and prediction are key goals of the new IAHS Decade for Prediction in Ungauged Basins, PUB, (Sivapalan et al., 2003), an initiative that explicitly recognises the value of research basins in developing enhanced knowledge and technology that will help to reach these goals. PUB supports improving the resiliency of hydrological predictions through the diminished use of calibration in parameterizing models, and replacing calibration with *a priori* parameter selection for hydrological models that are appropriate to the basins of interest. Parameter selection and improved hydrological models are to be developed from an increased understanding of hydrology and hydrological principles that include basin research and examining alternative basin observations. Both top-down (basin response, large-scale behaviour) and bottom-up (integration of small-scale behaviour) approaches are recognised by PUB as means to increasing the understanding of hydrology.

Given this ‘second hydrological decade’ it behoves us to reconsider the experiences of the first hydrological decade. The value of research basins for improving understanding has been understood for many years; in the International Hydrological Decade of 1965-1975 (IHD) numerous ‘representative’ and ‘experimental’ basins were instrumented and monitored for water balance and rainfall-runoff relationships. Representative basins were defined for IHD as ‘basins which are selected as representative of a hydrological region, i.e. a region
Experimental basins were defined for IHD as ‘basins which are relatively homogeneous in soil and vegetation and which have uniform physical characteristics. On such basins the natural conditions, i.e. one or more of the basin characteristics, are deliberately modified and the effects of these modifications on the hydrological characteristics are studied’ (Toebes and Ouryvaev, 1970). Some countries such as the United States and Soviet Union had already developed networks of representative or experimental research basins from the early to mid-20th C, which became IHD basins. Canada rapidly expanded its network in the mid-1960s (Canadian National Committee for IHD, 1966) though many of these basins were closed by the 1980s (Swanson et al., 1988).

The great value of the intensive observational hydrology that developed during IHD is uncontested. Basin-focussed hydrological research in this period initiated a rapid development of Canadian hydrological science. The basins were superb training grounds for students and promoted the development of enhanced observational technology. IHD-representative basin research helped to develop our first descriptions of the characteristics of runoff regimes at medium to small scales in many parts of Canada. However, research basins are expensive and many were not carried on after the end of IHD. For instance some IHD basins focussed primarily on observations and lumped catchment behaviour rather than analysis (Swanson et al., 1988); this made the findings difficult to extrapolate from one basin to others and limited the development of robust water management techniques from the observations. The limited theoretical advances simply limited the development of strong management guidelines and resulted in uneven adoption of recommendations from these programmes. These limitations contributed to the difficulty in justifying the retention of observational programmes. A particular problem of many basins was that operational monitoring requirements remained roughly stable or increased in cost whilst funding fluctuated from year to year - this added instability to the research components which were sometimes sacrificed to ‘save the research basin’.

While many valuable aspects of hydrological dynamics were learned from these basins, and important aspects of the hydrological cycle were identified, problems were experienced in closing the water balance and predicting behaviour because of uncertain estimates of evaporation and storage (e.g. Davies and Taggart, 1988) and poorly understood snow redistribution and ablation processes (e.g. discussed by Gray and Granger, 1988). The focus on potential and complementary evaporation rather than actual evaporation, and confusion over the definition of potential, ‘pan’, wet environment and open water
evaporation led to uncertainties in water balance for many IHD basins (Granger and Gray, 1990).

Two limitations in gaining useful understanding from these instrumented representative basins were that their experimental designs often depended on long-term empirical comparisons of observations and/or on calibrations of conceptual runoff models. Empirical relationships can only be extrapolated through strictly limited time or space with confidence, and their performance in extreme conditions is uncertain. Empirical comparisons and calibrations can be hampered by changes in climate and land use, variable quality and spatial coverage of measurements, and the relatively short time that most research basins were operating with intensive scrutiny. The concept of ‘equifinality’ illustrates that there are many combinations of parameters (realistic or not) that will give adequate synthesis of streamflow from models of varying conceptual derivation (realistic or not). This lends a veil of unreality to many modelling endeavours (Beven and Binley, 1992). Hence, success in simulating streamflow hydrographs does not mean that the conceptual model is correct or that parameters have been correctly selected; modelling success does not itself advance the science of hydrology.

As part of the Mackenzie Global Energy and Water Cycle Experiment Study (Mackenzie GEWEX or MAGS), two research areas were established and instrumented by the federal government and the University of Saskatchewan in the 1990s: Wolf Creek Research Basin in the sub-arctic mountains of the Yukon Territory and the Prince Albert Model Forest (several small basins in the southern boreal forest of central Saskatchewan). Besides core support from Environment Canada and Indian & Northern Affairs Canada (Wolf Creek), the basins also received support from programmes such as the Prince Albert Model Forest and the Arctic Environmental Strategy and subsequently from NSERC, NERC, US-NWS and CFCAS. In all cases the funding programmes required rapid improvements in the understanding of hydrological processes, pathways and hydrological response of the basin to precipitation inputs. This precluded long-term comparative and/or empirical approaches that would have relied primarily upon estimating long-term water balances and relating meteorology to stream discharge through some rainfall-runoff transfer functions or statistical analysis. In such a situation there was no ‘top’ for a top-down ‘numerical experiment’ approach. Instead, a bottom-up approach to rapidly increase scientific hydrology knowledge of these basins was used to complement what was known from gauging records and previous research.
Existing knowledge at the time of basin establishment (Gray, 1970; Gray and Male, 1981) was:

1) the spring freshet was normally the largest runoff event of the year and was followed by much smaller summer flows,
2) large changes in snow accumulation did not always correspond to large changes in the magnitude of the spring freshet,
3) the impact of heavy rainfall on summer flows was variable and often modest.

As such, particular attention was paid to improving the understanding and calculation of the following processes

1) snow accumulation (redistribution, interception and sublimation)
2) snowmelt,
3) infiltration to frozen soils,
4) evaporation.

This required very specific process research strategies. The advantage was that a good understanding of these processes could be developed in just a few years, sufficient to assemble and evaluate physically based models of the hydrological system. This paper will describe how a process hydrology approach was applied to these basins and was used to develop a quick understanding of their hydrological systems.

RESEARCH BASINS

Research basins at Wolf Creek, Yukon and the Prince Albert Model Forest, Saskatchewan were instrumented in 1993 as part of MAGS.

Wolf Creek, Yukon

The Wolf Creek Research basin (drainage area about 195 km$^2$) lies in southern mountainous headwaters of the Yukon River basin in north-western Canada and is considered representative of non-glacierized northern cordilleran headwater basins (Figure 1). The sub-arctic continental climate is characterized by a large seasonal variation in temperature (-50°C to +25°C), low relative humidity and relatively low precipitation (300-400 mm/year). The basin consists of three principle ecosystems; boreal forest, sub-alpine taiga (shrub-tundra) and alpine tundra, with proportions of 22%, 58% and 20% respectively of the total basin area. Instrumented study plots are located within each of the ecosystems at
elevations of 750, 1250 and 1615 m respectively. The forest site is relatively level with gently undulating terrain consisting of an alternating hummock and hollow landscape. The canopy is dense, consisting primarily of white spruce to heights of approximately 20 m, with sparse poplar trees to approximately 15 m. The sub-alpine taiga site is located on an east-facing moderate hillslope of approximately 15 degrees. The hillslope itself consists of undulating terrain with numerous hummocks and depressions. The site is vegetated with shrub alder and willow to heights of approximately 2 m. The alpine tundra site occupies a windswept ridge-top plateau. Approximately 50% of the site is relatively level, with the balance sloping at approximately 15 degrees to the south. Vegetation is sparse, consisting of mosses, some grasses and lichens with occasional patches of scrub willow no more than 0.2 m high.

**Prince Albert Model Forest, Saskatchewan**

The Prince Albert Model Forest (PAMF) is an area in central Saskatchewan, Canada, containing both conserved and harvested forests in and near Prince Albert National Park, the adjacent provincial forest and Montreal Lake First Nation (Figure 2). Observations were made in the small basins of Beartrap Creek, Bittern Creek, Waskesiu River and Snowfield Lake and are representative of the southern margin of the western boreal forest of North America. The area has a continental, sub-humid climate with winter and summer extremes of -45°C

![Map showing location of Wolf Creek Research Basin near Whitehorse, Yukon, location of main instrumented meteorological station and snow survey sites and their associated vegetation cover.](image)
and 35°C, respectively. Annual precipitation is 450 mm, with approximately one-third falling as snow. The snow-covered season extends approximately from November through April, though there is substantial variation from year to year.

Meteorological, hydrological and soils data were collected from five stands, namely:

- Mature jack pine (*Pinus banksia*), LAI = 2.4, tree height = 18 m, sandy soil
- Mixed-wood aspen/white spruce (*Populus tremuloides, Picea glauca*), Summer LAI = 2.5, tree height = 20 m, silty-clay till soil
- Mature black spruce (*Picea mariana*), LAI = 4.1, tree height = 10 m, organic/silty soil
- Recently, completely burned black spruce, LAI = 0.23, tree height = 10 m, silty soil.
• Regenerating jack pine plantation (*Pinus banksia*), LAI = 1.7, 
  tree height = 7 m, sandy-clay soil

• Recent clear-cut (*Populus tremuloides*), Summer LAI = 0.5, 
  tree height = 1.5 m, silty-clay soil.

One river basin, Beartrap Creek was intensively mapped and monitored for 
stream discharge and was used for the hydrological model evaluation.

**RESEARCH BASIN OBSERVATIONAL STRATEGIES**

Providing instrumentation in a basin for process hydrology studies requires the 
deployment of a large number and variety of instrumentation. In order to go 
beyond the development of empirical relationships between standard 
meteorological parameters (requiring only one “standard” station) and basin 
discharge, one needs to measure and observe those parameters that directly 
affect the various processes that control the capture, redistribution, storage and 
release of the water. Since the vegetation can play a significant role in many of 
these processes, its physical state and properties are important. As well, the 
description of the hydrological processes generally requires that the 
meteorological parameters be measured at several locations, heights and degrees 
of exposure (relative to the vegetation), and that the fluxes or processes be 
measured directly where possible.

**Basic Research Basin Observations**

Approximately 390 and 240 hydrometeorological instruments were deployed 
simultaneously in the PAMF and Wolf Creek respectively (Pomeroy *et al*., 1997; 
Pomeroy and Granger, 1999). These were most certainly gauged basins. Most 
variables were measured at multiple levels in and above the canopy and in the 
soils to provide a vertical structure to the hydrometeorological conditions found 
at each site. Both research areas were instrumented to provide a basic description 
of the water budget and its spatial variability with intensive examination of snow 
accumulation, snowmelt, infiltration and evaporation processes. Instrumentation 
was clustered in intensive study plots in the major land cover types noted above. 
At forested sites, canopy access towers (triangular or square ‘walk-up’ type) 
were installed to permit measurements both above and below canopy processes. 
Sites were visited at least weekly in the PAMF and at least monthly in Wolf 
Creek. A diagram of a typical forest tower with full instrumentation is shown in 
Figure 3, whilst an alpine tower is shown in Figure 4.
Stream Gauge/Water Level Recorder Period of Record

Four streamflow gauges captured the relative contribution of flow from each ecozone and the basin outlet at Wolf Creek. These gauges have been in operation from 1993-present. Stream velocities were measured throughout the year using drillholes in the ice. Special twice-daily rating curves were developed for specific stream gauging sites in spring where snow dams and channel ice change the depth discharge relationship very rapidly. A streamflow gauge at a road crossing of Beartrap Creek, south of Waskesiu Lake, was operated by Water Survey of Canada with the help of Prince Albert National Park staff (since discontinued) and the basin characterized a natural landcover. In the forestry lease area, nearby Whitegull Creek encompassed some of the disturbed sites in the PAMF and represented a basin subject to forest harvesting.

Precipitation Gauges

Meteorological Service of Canada (MSC) Nipher-shielded snowfall gauges were located at each tower site along with tipping bucket and MSC standard rain gauges and were monitored year round. Snow particle detectors (Brown and Pomeroy, 1989) provided high-resolution snowfall rates for each of these sites. At the forested sites, precipitation was measured above and beneath the forest canopy.
Micrometeorological Data

Dataloggers recorded measurements of radiation (incoming and outgoing shortwave, net), sub-canopy shortwave and net radiation, air temperature (multiple heights), relative humidity (multiple heights), atmospheric pressure, wind speed (multiple heights), wind direction, snow particle flux, soil temperatures (multiple depths), volumetric soil moisture content (multiple depths), snowpack temperature, and snow depth on a half-hourly basis (See Figures 3, 4).

Specialised Hydrological Process Measurements

Leaf Area Index

Leaf area index is an important parameter for rain and snow interception and canopy radiation transmission studies. Effective leaf area index and canopy coverage were measured at all sites in both summer and winter using a LI-COR LAI-2000 Plant Canopy Analyser. Effective leaf area index is a useful measure of canopy structure because of its physical meaning as the cumulative horizontal area of canopy stems and leaves over a unit area of ground. The LAI-2000 uses the optical density of the canopy and view angle to determine effective leaf area index and canopy coverage. To prepare the instrument for measurements, the LAI-2000 was calibrated to sky brightness at the top of the tower on a day with
uniform cloud or clear skies, while using a 90° view-limiting cap to shield measurements from the operator and the sun. Measurements were then taken (roughly 10 randomly selected spots per site) at ground level with the same view cap and orientation, within two minutes of the calibration readings (Pomeroy and Dion, 1996; Hedstrom and Pomeroy, 1998; Pomeroy et al., 2002).

**Snow Accumulation, Redistribution and Melt Measurements**

Snowfall was estimated at both sites using specialized techniques that permitted great accuracy. Nipher-shielded MSC copper-cylinder snowfall gauges (Nipher gauge) were installed either above canopy (tundra, clearcuts, clearings, shrub tundra) or below canopy (forests) at all sites. Where installed below canopy, a reference above canopy Nipher gauge measurement was made nearby (Hedstrom and Pomeroy, 1998). Snowfall collected in Nipher gauge cylinders was removed, melted and measured in a graduated cylinder weekly (PAMF) or monthly (Wolf Creek), minimising wetting losses that occur from 6-hourly emptying. Next to each Nipher gauge was an anemometer to measure wind speed and an opto-electronic snow particle detector (Brown and Pomeroy, 1989). The opto-electronic snow particle detectors were built by the Division of Hydrology, University of Saskatchewan to measure the threshold conditions for blowing snow and the horizontal snow mass flux in the near surface layer of the atmosphere. However they also provided the particle flux of falling snow by using the ratio of particle counts per half hour to that over the time the Nipher gauge was exposed; they could then be used to apportion the weekly or monthly snowfall measurements from the Nipher gauge to half-hourly snowfall rates. Snowfall was then corrected for Nipher shield undercatch by applying the corrections of Goodison et al. (1988) using the wind speeds at the time of snowfall. Blowing snow was estimated by the particle flux at wind speeds in excess of about 5 m/s; blowing snow was distinguished from falling snow by the strong non-linear relationship between snow particle flux and wind speed, which is not apparent for falling snow (Pomeroy and Li, 2000; Pomeroy et al., 1998). Further confirmation of the occurrence of blowing snow was made by examining rapid deviations from snow depth or corrupted signals from the ultrasonic snow depth gauge which were very evident during blowing snow events in signals from the model UDG01 ultrasonic depth sounder made by Campbell Scientific.

Snow survey networks were designed to provide a spatial representation of snow cover at each research site (Pomeroy and Gray, 1995). In the PAMF, a 10–point (100 m) snow-survey line was marked at each site and weekly measurements made of snow depth and snow density using a ruler and ESC-30 snow density gauge. The snow-survey lines crossed representative terrain and vegetation and
sampled both near to and remote from individual trees. Snow surveys usually commenced in November and ceased with the end of snowmelt in April. The surveys were supplemented by half-hourly single point depth measurements from an ultrasonic snow-depth gauge. When snow density estimates were multiplied by the snow depth, then a point snow water equivalent could be estimated on a half-hourly basis from this gauge. In Wolf Creek snow-course observations were taken monthly up to the time of spring melt (April) and then every few days during melt. They consisted of 25 depth points spaced 5 m apart with a snow density every 5th depth (25 m apart). Changes to snow water equivalent in characteristic landscape types were measured intensively before and during the melt period at many sites in the basins at intervals of 5 m for depth and lengths up to 1 km (Faria et al., 2000; Pomeroy et al., 2001; Pomeroy et al., 2003). Granger sub-basin and the spruce forest in lower Wolf Creek were used for these intensive melt measurements. In PAMF these intensive surveys were based on the standard transects (Pomeroy and Granger, 1997); in Wolf Creek standard transects were used as well as transects of valley sides. Techniques are described in detail by Pomeroy and Gray (1995). Snow-covered area was measured using digital cameras located on towers, hillsides and remote-controlled helicopters (Faria et al., 2000; Pomeroy et al., 2004).

Interception

Interception controls the precipitation delivery to the soil surface and is an important storage mechanism for both snowfall and rainfall. Interception processes were measured using sub-canopy rain and snowfall gauges, a weighed suspended tree and a stem-flow gauge attached to an aspen tree. Rate rainfall gauges, or tipping bucket rain gauges were located above the canopy at forested and shrub sites and provided a measure of the gross rainfall intensity. Standard MSC rain gauges were used to provide a test or calibration of cumulative rainfall derived from the tipping bucket gauges, to determine sub-canopy rainfall and to provide a better spatial representation of precipitation. To evaluate and develop interception models, tipping bucket and standard MSC rain gauges were installed below canopies to give a measure of throughfall and drip (Elliott et al., 1998).

To measure stem-flow in the PAMF mixed wood stand, a small trough was wrapped around one aspen tree and funnelled into a 70 litre carboy. Any water flowing down the aspen stem was diverted into the carboy, which was emptied weekly (Granger and Pomeroy, 1997).

The weight of intercepted snowfall on a single tree was measured by cutting, sealing the cut end and suspending a local tree from a cable with an in-line force
transducer (Pomeroy and Schmidt, 1993). A triangular tower equipped with an aluminium boom and davit system was used to suspend each cut tree within the canopy. The base of the weighed tree was stabilized by an aluminium frame attached near the bottom of the tower. The base was inserted in a collar with Teflon rollers that allowed for vertical movement of the tree as snow accumulated on or ablated from the hanging tree branches. The datalogger performed a four-wire bridge measurement of the intercepted mass (g). Tests of the repeatability of measurement of the transducer with the tree attached were better than 70 g. Weighed trees were installed at several forested sites in both basins. Trees were calibrated to provide areal interception by examining the ratio of change in snowfall-SWE to the change in weight of the tree + snow for weeks where there was little unloading, melt and sublimation (Hedstrom and Pomeroy, 1998). Further information on the presence of snow in the canopy was gained from time-lapse digital camera photographs, and relationships between area of snow patches and snow sublimation rates were obtained (Pomeroy and Schmidt, 1993; Pomeroy et al., 1998).

Snowfall was measured with MSC Nipher-shielded cylinders under the canopy and in open locations. One sub-canopy snowfall measurement was made at each forested site with open canopy references collected in adjacent open areas. The snow collected in the cylinders was emptied weekly (PAMF) and monthly (Wolf Creek), melted and measured as liquid water equivalent. All snowcover and snowfall amounts were expressed as SWE, snow water equivalent (mm), which is the equivalent depth of water covering the ground.

**Frozen Soil Infiltration**

Frozen soil moisture content was determined using twin-probe gamma attenuation techniques at all sites in both basins, except the grass and burn in PAMF (Pomeroy et al., 1997; Zhao and Gray, 1999). The technique indicates density of material between radioactive source and detector using the principle that attenuation of radiation emitted by a source follows an exponential decay whose rate depends on the density, absorptivity and length of the intervening material. To obtain the density from a measured gamma particle count rate, one must know the intensity of the source, the extinction coefficient of ice and the sample length. In our application, two vertical, parallel PVC access tubes placed 30 cm apart were installed in the soil. The tubes were installed to a depth of 160 cm where possible, though at some sites only 65 cm depth was obtained because of stones. At this time soil samples were taken for moisture content and property analysis. To measure a vertical profile of density, a Caesium 137 source is lowered down one tube and a gamma particle scintillation detector is lowered
simultaneously down the other tube. One-minute gamma particle counts are taken at 2-cm depth increments, using a peak detection unit built by the Division of Hydrology, University of Saskatchewan. A frozen soil-moisture profile “reading” takes from 45-60 minutes. By noting changes in density from reading to reading, the change in frozen + unfrozen soil moisture can be determined and hence the infiltration of meltwater into frozen soils. Twelve sets of twin probes were installed in PAMF and another eight sets in Wolf Creek, with readings taken during freeze-up, in mid-winter and before and during the snowmelt period. These were supplemented by time domain reflectometry measurements of liquid water content and soil temperature measurements in profiles from thermocouple arrays, logarithmically increasing in spacing from the surface downward.

**Unfrozen Soil Infiltration**

At each soil-moisture monitoring site, the soil profile was described and classified according to the Canada Soil Survey Committee, 1978. Soil cores were taken to estimate bulk density (Culley, 1993) and bulk soil samples were taken for particle size analysis by the hydrometer method (Sheldrick and Wang, 1993).

In the PAMF the rate of water infiltration was measured at the sites using a single ring infiltrometer (Bouwer, 1966). The diameter of the ring was 1 m and the head of water was maintained at 75 mm. Measurements were made for at least one hour and were continued until a constant infiltration rate was obtained (Elliott et al., 1998).

Soil-moisture changes were measured at several locations (differences in vegetation or slope position) within each site in order to characterize the natural variability. Volumetric soil water content (VWC) was measured by time domain reflectometry (TDR) to 1.6-m depth (Topp, 1993). Buriable waveguides (0.2 m long) were installed horizontally at 0.05-, 0.1-, and 0.2-m depths and vertically at 0.3- to 0.5-m, 0.7- to 0.9-m and 1.4- to 1.6-m depths at each monitoring location. Most probes were in dominantly mineral soil and the standard TDR calibration between dielectric constant (Ka) and volumetric water content was used (Topp et al., 1980), but in the organic layers Ka was measured and a custom calibration was used to obtain VWC (Herkelrath, 1991).
Radiation Balance and Radiation Penetration into Canopies

The radiation input represents the major source of energy for snowmelt. In order to carry the science forward beyond the simple degree-day method for snowmelt in forested basins, a better understanding of the interaction of radiant energy and forest canopies is required (Pomeroy and Dion, 1996; Sicart et al., 2004). Radiation sensors capable of distinguishing the major components of the radiation balance (short-wave, long-wave, net all-wave) were deployed above the canopies. Sensors were also strategically placed within and below the canopy to measure the attenuation effects and the delivery of radiant energy to the surface snow cover.

Turbulent Flux Measurements of Evaporation and Sublimation

Short-term measurements of latent and sensible heat fluxes were made using eddy correlation systems during intensive observation periods of several months each that include summer, late winter, and spring (Pomeroy and Granger, 1997; Granger and Pomeroy, 1997). The eddy correlation systems consisted of a fast 3-axis sonic anemometer for vertical wind speed and air temperature and associated fast hygrometer for humidity. By calculating the covariance of vertical wind speed and temperature or humidity, the fluxes of sensible and latent heat can be calculated. Turbulent power spectra were measured at each site to ensure that measurement heights were appropriate to the eddy length scales given the instrument spacing used. To provide surface reference conditions for flux estimates and modelling of evaporation and sublimation, surface temperatures were measured using fine-wire thermocouples, infrared thermometers and infrared imaging radiometers (e.g. Rowlands et al., 2002).

MAJOR FINDINGS

Blowing Snow Redistribution

Blowing snow was not found to be a significant transport process in either Yukon or Saskatchewan forest environments, in contrast to the suggestions of Hoover and Leaf (1967) who suggested that snow was relocated from forest to clearing. The frequency of blowing snow storms in Wolf Creek was investigated as a function of elevation and vegetation type and is shown in Table 1 (Pomeroy et al., 1999a).

The effect of blowing-snow erosion on the alpine and sub-alpine snow balance is shown in Figure 5 which shows the development of snow water equivalent at the alpine site and shrub tundra site and corrected cumulative snowfall (similar amounts were recorded at both elevations). Accumulation at the shrub tundra site follows the cumulative snowfall line, suggesting that snowfall is retained in the
shrubs quite efficiently and that little ablation occurs over the mid-winter period. At the alpine tundra site, the highest SWE is recorded in late October, and subsequent accumulations decline episodically in early December and early February and do not increase when subsequent snowfalls occur. The difference between SWE and snowfall at the alpine site is due to erosion of snow by wind; the blowing snow being transported off the alpine plateau or sublimated during transport. Given the short fetch (roughly 300 m to drift), it is most likely that most (roughly 4/5) snow was transported off the ridge to nearby drifts rather than sublimated in transit. Higher sublimation amounts would be found in environments with longer fetches such as the Arctic (Pomeroy et al., 1997)

<table>
<thead>
<tr>
<th>Season</th>
<th>Alpine Tundra</th>
<th>Shrub Tundra</th>
<th>Spruce Forest</th>
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<td>8</td>
<td>0</td>
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</table>

Table 1. Frequency of occurrence of blowing snow days in Wolf Creek Research Basin. Numbers shown are days per winter with significant blowing snow as measured by a blowing snow particle detector. Winter is 180 days long at the shrub tundra and 210 days long at the alpine site.

Figure 5. Daily snow water equivalent (estimated from daily depth measurements and interpolated monthly density measurements) and cumulative monthly snowfall (corrected for undercatch) at the alpine and shrub tundra sites in Wolf Creek Research Basin, Yukon.
Snow Interception

Snow interception was found to be a major process in the boreal coniferous forests of both basins, with mid-winter interception storage from 10% to 65% of cumulative snowfall. A large portion of intercepted snow sublimates, ranging from 12% to 45% of seasonal snowfall (Pomeroy et al., 1998; 1999a). The programme of above- and below- snowfall measurements, comparative SWE surveys and use of the suspended tree permitted the development of a comprehensive snow interception, unloading and sublimation model (Pomeroy and Schmidt, 1993; Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998; Parviainen and Pomeroy, 2000; Essery et al., 2003). An example of interception being estimated as the snowfall that did not accumulate at the surface (above-canopy snowfall - below-canopy snowfall) is shown in Figure 6 for the Prince Albert Model Forest in the winter of 1994-95. Above-canopy snowfall was estimated using a Nipher-shielded snowfall gauge in a nearby large clearing and correcting for wind undercatch. Below-canopy snowfall was measured using a Nipher-shielded snowfall gauge under the canopy and then upscaled to the forest stand by adjusting the measurements by the ratio of areal sub-canopy SWE increase associated with a measured snowfall for a snowfall event. The ratio is developed for each site in each season using snow accumulation events free of melt or likelihood of significant evaporation.

Sublimation from intercepted snow was estimated over a season by mass balance as the cumulative interception loss remaining at the end of the snow season (when no snow would be physically present in the canopy). For instance, in the case of Figure 6, seasonal intercepted snow sublimation is 52 mm for black spruce, 39 mm for jack pine and 13 mm for mixed aspen-white spruce out of a snowfall of 122 mm. Sublimation fluxes on an hourly and daily basis were determined by the reduction in weight of a snow-laden suspended tree (when no unloading was occurring) and from the latent heat flux measured by an eddy correlation system over the canopy.

Snowmelt

Snowmelt rate along with SWE controls the duration and intensity of snowmelt discharge and the delivery of water from snow to the soil and stream in spring. Melt rates were found to be highly sensitive to canopy cover, slope and aspect as they influenced incoming radiation to the snow surface (Pomeroy and Granger, 1997; Faria et al., 2000; Pomeroy et al., 2003). The progressive exposure of shrubs and bare ground magnified the effects of slope on incoming shortwave radiation in Wolf Creek to dramatically change the net radiation available for snowmelt (Figure 7). This resulted in melt proceeding rapidly on the south-facing
slopes whilst the north-facing slope snowpack continued to cool. Because state variables (albedo, snow covered area) on each slope diverged, simple averaging of slopes with such differing energetics may not provide accurate areal representations of snowmelt and snow-covered area change.

In the Prince Albert Model Forest basins, the presence or lack of forest cover was the most important parameter; variation in melt rate amongst forest covers of widely differing densities or LAI was small, but the difference between forest and cleared snowmelt rates was large (Figure 8). This insensitivity of snowmelt to forest density has been further examined in the framework of a general model suitable for the Wolf Creek environment and shown to be due to a counterbalance between reductions in shortwave radiation and increases in longwave under the canopy as leaf area index increases (Sicart et al., 2004).

**Evaporation**

Evaporation rates were found to be strongly influenced by interception of rainfall and vegetation transpiration. In general, high actual evaporation rates were found for greater vegetation density, but vegetation type and properties such as albedo also had strong effects (Granger and Pomeroy, 1997). Figure 9 shows the net radiation to four surface types in the PAMF in June, 1995 showing that the jack pine sustains the highest net radiation and the mixed aspen-spruce the lowest. This difference is largely due to low albedo over pine and high over aspen. The differences in net radiation are moderated in evapotranspiration due to additional influences such as interception of rainfall enhancing evapotranspiration from
forests over that from clearings and the rapid transpiration rate of aspen compared to conifers. The strong influence of net radiation on evaporation was also found for Wolf Creek where moisture limitations seldom exceeded the importance of energy limitations to evaporation (Granger, 1999). The partitioning of the incoming radiant energy into the turbulent components of latent (evaporation) and sensible heat is not a passive response; the vegetation exerts a strong control on the fate of the energy, and its physical state, density, health, stage of growth and seasonal progression can be important factors.

**Figure 7.** Incoming shortwave radiation and net radiation during snowmelt on two 20° tundra slopes and a brush-covered valley bottom in Wolf Creek, Yukon. Melt occurred rapidly at the south face but was negligible at the north face.
**Figure 8.** Variation in measured snowmelt rates at a point in the Prince Albert Model Forest, Saskatchewan. Melt rates are expressed in units of equivalent energy to melt the measured change in snow mass (water equivalent) during melt.

**Figure 9.** Energy balance in June, 1994 for the Prince Albert Model Forest sites showing the influence of net radiation on evaporation.
Infiltration to Frozen and Unfrozen Soils and Runoff of Extreme Events

Infiltration rates to frozen soils in the boreal forest and Wolf Creek were found to be lower than rates found in the prairie environment for equivalent soil moisture and SWE conditions. The ratio of forest to prairie infiltration is roughly 63% (for identical moisture, temperature, melt rate and SWE) and is primarily due to the vertical profile of frozen soil moisture (Gray et al., 2001). In the southern boreal forest, the melt of snowpacks with less than 65 mm SWE was associated with little to no infiltration, regardless of soil moisture conditions, suggesting the formation of basal ice layers with low permeability. Infiltration from the melt of snowpacks with more than 80 mm SWE was essentially unlimited, suggesting the lack of impermeable layers at the soil surface, slow melt rates, and/or incomplete freezing of soils (Pomeroy et al., 1997). Infiltration model development has produced full physically descriptive and parametric models of infiltration (Zhao et al., 1997; Zhao and Gray, 1999; Gray et al., 2001) that have reproduced measurements with some success. The parametric model of Zhao and Gray suggests that for fully frozen soils, the premelt soil moisture content, near surface moisture content, snow water equivalent and melt rate are the most important factors governing infiltration to frozen soils. Attempts to upscale this equation from point to landscape type have emphasized the spatial variability of primary governing factors such as soil moisture and premelt snow water equivalent (Janowicz et al., 2002; 2003); these are associated with vegetation cover and topography.

An example of variations in the plot-scale snowmelt runoff, measured over frozen soils in a boreal forest is shown in Figure 10 for three years and four stand types including a clear-cut (Pomeroy et al., 1997). Runoff is shown as the ratio of runoff to snowmelt water. It is seen that substantial increases in this runoff ratio occurred as winter forest cover decreased (highest ratio for clear-cut and regenerating cut stands). The differences are greatest in the driest year (1995) when runoff from the clear-cut was an order of magnitude greater than from the mature forest sites.

Runoff from snowmelt is a dramatic event in northern environments and can supply most of the annual runoff in many small streams. In dry years, in sites where vegetation permits high evaporation rates and undisturbed soil structure promotes high infiltration, the response to summer rainfall events can be minuscule by comparison to snowmelt. Figure 11 shows the spring and summer runoff from Beartrap Creek in the Prince Albert Model Forest during a very dry year, 1995. Runoff is completely dominated by snowmelt and even when heavy rainfalls occurred in early August, there was no runoff response. A severe rainfall of between 100 and 120 mm occurred 8-9 August, 1995 at all study sites. Maximum rainfall intensity was 22 mm h⁻¹ early in the event which was near the
final infiltration rates measured using a ring infiltrometer for some of the soils. Soils before this rainfall were dry, but antecedent conditions varied. Of interest is that measurements of soil-moisture profiles before and after the storm showed that all of the rainwater delivered to the soil surface infiltrated to the natural forest soils (pine, mixed aspen-spruce) whereas between 18% and 30% of rainfall did not infiltrate the disturbed soils that had been cleared and replanted (Elliott et al., 1998). Presuming any rainfall that did not infiltrate could be considered ‘point runoff’ this suggests a strong cumulative effect of infiltrability, evaporation from intercepted rain, and transpiration on runoff generation.

Figure 10. Snowmelt runoff from forest stands as a function of forest cover. The clear-cut consistently produced more runoff than did the mature forest types.

Figure 11. Stream discharge (basin runoff) as mm of water per day and daily rainfall to Beartrap Creek, a natural heavily forested basin in the Prince Albert Model Forest during 1995, a very dry year.
Figure 12 shows the effect of land-cover type on runoff generation at a point by rainfall. The lines shown are not to reflect a modelling relationship but to highlight the association between vegetation cover and runoff response; in this case there is approximately four times more runoff from the cleared sites than a mature mixed-wood stand. The differences are largely due to differences in evaporation and antecedent soil moisture. From this, one would expect a much greater response to Beartrap Creek discharge if the basin had been cleared rather than forested.

**SOLVING UNGAUAGED BASIN PROBLEMS FROM RESEARCH BASIN FINDINGS**

**Model Development**

The findings from PAMF and Wolf Creek have been compiled into several process-based hydrological models. One, the Boreal Ecosystem Evapotranspiration Runoff Simulation (BEERS) showed the effect of virtual clear-cutting on basin water balance (Pomeroy et al., 1999b). As an example, the model was applied to Beartrap Creek from 1 May to 30 Sept. 1995 for existing land-cover conditions and a modified land cover in which all pure softwood stands (20% of basin area) were converted to clear-cuts (virtual clearcutting). Figure 13 shows cumulative infiltration and evaporation on Week 20 of the simulation, mapped for Beartrap Creek basin under actual and virtual clear-cut land cover. Substantial variation in the pattern of key hydrological variables is indicated. Figure 14 shows the summer seasonal water balance for Beartrap Creek with current and virtual clear-cut land cover. Runoff was small in both scenarios, indicative of using a dry season and neglecting the variable effect of snowmelt infiltration on initial summer soil moisture. The water deficit for the summer declined by 29% when the basin land cover was subject to the virtual clear-cut in the model; a non-linear response to a land cover change of 20% of basin area.

A more recent development is the distributed Cold Regions Hydrological Model (CRHM) developed jointly by the University of Saskatchewan and the National Water Research Institute. CRHM models hydrological processes in landscape units termed hydrological response units (HRU, presumed to have uniform internal hydrological characteristics) and incorporates many features of BEERS with additional open environment and winter process modules developed from instrumented basin research (Hedstrom et al., 2001). CRHM is a modular model so that appropriate processes for the basin, selected from a library of process modules, can be linked to simulate the hydrological cycle on HRUs and then
route water between HRUs. Hydrological modelling systems assembled using CRHM have been able to successfully simulate many of the processes described above and provide important information on the structure of models that would most appropriately predict streamflow in boreal forest and northern mountain

![Figure 12. Point-scale runoff (rainfall - interception evaporation - infiltration) as a function of rainfall for various summer rainfall-runoff events in the Prince Albert Model Forest.](image)

![Figure 13. Cumulative infiltration and evapotranspiration (1 May, 1995 onward) for week 20 of the BEERS model simulation for Beartrap Creek: a) observed forest cover characteristics, b) “virtual (hypothetical) clear-cut” of all pure softwood stands (20% of basin area). Note the increase in infiltration and decrease in evapotranspiration associated with the virtual clear-cuts.](image)
environments. Because there is a high level of confidence in the process representation in models such as CRHM, there is diminished need for calibration. In addition, parameter selection from streamflow behaviour can be restricted to streamflow routing and baseflow aspects of the model. Accurate representation and parameterisation of processes leads to reduced model parameter fitting for discharge simulations. It is felt that models that represent the processes faithfully, satisfy mass and energy continuity, and yet retain fairly simple data and parameter requirements will have robust application and diminished routing parameter estimation uncertainty; however, this assertion
remains to be fully tested. CHRM will soon be freely available on the web from the Centre for Hydrology, University of Saskatchewan.

Examples of CRHM simulations and measurements of the winter and spring water balance from open sites in the two research areas are shown in Figure 15, with snow accumulation, infiltration to frozen soils, melt and spring runoff for an alpine and forest clear cut. Bittern Creek is a basin in the Prince Albert Model Forest near Beartrap Creek, but it has been subject to substantial clear-cutting; the alpine site is characteristic of 20% of Wolf Creek basin. The simulations are uncalibrated and use measured local parameters for vegetation height, soil properties and fall moisture content. There is a reasonable agreement between modelled and measured snow water equivalent accumulation and melt. The large differences in the winter water regimes between these sites are due to several factors:

1) the alpine ridge in Wolf Creek has high snowfall, is extremely windy in the winter and with little vegetation, much of its snowfall is removed by blowing snow.

2) the clear cut in Bittern Creek has lower snowfall, small trees and low winter wind speeds so there is little to no blowing snow loss.

As a result, spring snowpacks are similar in water equivalent between the two sites. The runoff regimes differ substantially because the Bittern Creek melt is relatively fast and soils are moist from the previous autumn; hence, despite roughly similar premelt snow accumulation at both sites, there is approximately six times greater runoff from the Bittern Creek clear cut than from the alpine ridge in Wolf Creek.

Application of Process Hydrology Findings

Cold regions hydrology is poorly described in science and engineering texts and handbooks. For instance, many of the processes that have been found to be fundamental to the hydrological behaviour of our research basins in northern Canada are simply not addressed in standard texts. The importance, prevalence, rates and limitations of the processes noted in this chapter may therefore be useful to practitioners who are trying to estimate small-scale water balances, the hydrological impacts of changing land use, chemical transport pathways or bound the uncertainty in estimations of flow rates, available water abstractions and larger scale water resources from existing techniques. It is possible to include many of these processes in applied water resource assessments using relatively simple techniques. Parametric equations for estimating blowing snow losses (Pomeroy and Gray, 1995), snow interception loss (Pomeroy et al., 2002), infiltration to frozen soils (Granger et al., 1984; Gray et al., 2001) and physically
based methods with minimal data requirements for snowmelt (Gray and Landine, 1987) and actual evaporation estimation (Granger and Gray, 1989) have been developed and extensively verified in Canadian conditions. These parametric or physically based methods were designed such that they could be used in Canadian cold regions hydrology applications, and the practitioner is advised to consider them before applying temperate-zone technologies to cold regions.

CONCLUSIONS

Research basins are expensive to develop and maintain over long periods of time, and history has shown that few have been sustained over several decades in Canada. However, by focusing on hydrological processes, process interactions, variability of basin properties and then how the basin discharge responds to various process rates and combinations of processes, a rapid increase in understanding basin hydrological dynamics can be gained. This requires the study of individual processes rather than comprehensive basin behaviour by itself. From two sets of research basins, one in the southern boreal forest and one in the sub-arctic, improvements in the description of snow redistribution, snow interception, snow sublimation, snowmelt, infiltration to frozen soils, evaporation and runoff generation from extreme events were made. Several physically based models were developed from these studies which have good performance in uncalibrated simulation of the observed hydrology. There is high confidence in transferring these models to other, ungauged basins. Fundamentally, research basins that improve our hydrological understanding over the range from individual hydrological processes to runoff generation are seen as more productive for both hydrological science and practice than long-term observations of basin response and resultant calibrated modelling that is conducted and compiled without the benefits of this understanding.

ACKNOWLEDGEMENTS

The Prince Albert Model Forest and Wolf Creek Research Basin were implemented and observed with the assistance of Dell Bayne, Glenn Ford, Kerry Paslowski, Glen Carpenter, Cuyler Onclin, Brenda Toth and many other students and hydrological technologists. Much of the funding for these studies was derived from the Mackenzie GEWEX Study. The Cold Regions Hydrological Model has been written by Tom Brown, P.Eng. of the University of Saskatchewan.
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