Classification of the Boreal Forest for Hydrological Processes

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Abstract

Hydrological processes in the boreal forest are manifestations of the interaction of climate, vegetation and soils and in turn, strongly influence streamflow, water bodies, wild-fire, revegetation, primary productivity, nutrient status and climate. The heterogeneous structure of boreal forests, particularly in areas of intensive land use, requires that a physical, rather than empirical, understanding of hydrological processes be quantified and this is applied using a forest classification appropriate to the hydrology. A five-year study of boreal forest hydrology in the Prince Albert Model Forest of west-central Canada has yielded new hydrological information that has been related to stand and soil type. For instance, a large proportion of snowfall is intercepted by evergreen canopies and then evaporates over the winter. As a result late winter snow accumulation under these canopies are 30% to 45% less than in deciduous forests, burns or clear-cuts. However, despite deep snow in clearings, snowmelt proceeds up to three times faster when the evergreen canopy is removed, because of better exposure to radiation and wind in open areas. Mature forest canopies intercept from 9% to 55% of rainfall. Up to 70% of this intercepted rainfall evaporates directly from the canopy, reducing the amount reaching the soil. Summer evaporation from mature forest stands is one-third greater than that from clear-cuts because of interception and effective withdrawals from soil by the root system. Streamflow runoff generation is therefore substantially greater from clear-cuts than from mature forests.

A quantitative hydrological process simulation was developed from these findings. The simulation is physically-based and spatially-distributed, and its application to catchments is performed using hydrologically - significant forest classifications, *hydrological response units*, contained in a Geographic Information System. An initial test of the simulation for the hydrological effects of "virtual clear-cutting" of 20% of a basin suggested a 29% decrease in summer water deficit for the "virtually-harvested" basin. Such a methodology can therefore be used to assess the impacts of changes to boreal forest land cover and climate, whether these changes are specific or concurrent.

Introduction

Hydrological processes in the boreal forest are the result of interactions amongst climate, vegetation and soil components of the ecosystem and in turn strongly influence streamflow, water bodies, aquatic habitat, forest vegetation and climate. The changing landscape of boreal forests, particularly in areas of intensive land use, requires that a physical rather than empirical understanding of hydrological processes be quantified. The results of this physically-based understanding can be applied to the evaluation of ecological stress in river basins by using a forest classification that is sensitive to the hydrology. Development of such a classification depends upon the understanding of process interactions between hydrology, forest canopy and soils.

Hydrological processes in the boreal forest are intimately connected with the forest canopy as it influences water storage and energy exchange with the surface and the atmosphere. A conceptualisation of hydrological processes in the boreal forest is shown in Fig. 1 where on the left-side, winter processes of snowfall, snow interception in the canopy, sublimation (evaporation), throughfall of snow to the ground, snow accumulation, snow melt and infiltration of snowmelt water into frozen soils are shown. On the right side of Fig. 1 are the summer processes of rainfall, rain interception in the canopy, evaporation, drip, surface runoff, sub-surface runoff, infiltration, and redistribution of soil water. The schematic shows these processes in their vertical configuration, however, once water reaches the soil it may also move horizontally through the basin as surface or sub-surface runoff, downhill to streams or lakes and then downstream out of the basin.

The boreal forest canopy and soils sustain their ecological status, or health, by acting as water, climate and nutrient regulation systems, interacting with the atmosphere and each other to produce specific conditions of water budget and surface climate. The forest ecosystem has adapted to perform this regulation role and to thrive under certain stable hydroclimatic conditions that are commonly sustained in the forest. Recently-cut areas and regenerating stands, however, regulate water and climate in a vastly different manner from undisturbed boreal forest stands due to differences in vegetation and soils, that affect the partitioning of incoming atmospheric energy and water flow. For

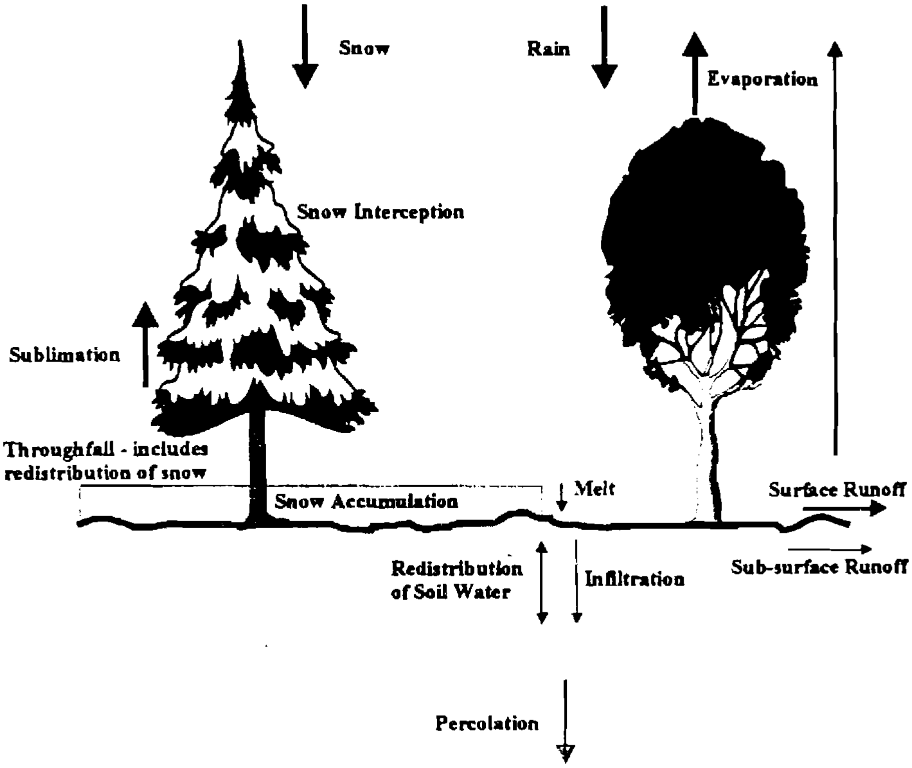

Figure 1. Major hydrological processes in the boreal forest: left hand side – winter processes, right hand side – summer processes.

instance, the aerodynamic roughness of disturbed areas is generally much smaller than that of mature forests and the ground surface is much more exposed to wind and solar radiation.

The system of water and climate regulation functions at various spatial scales. The smallest scale important to hydrology is at the individual tree scale (1 to 10 m) where water and energy fluxes are important in both horizontal and vertical directions and are strongly influenced by individual tree canopy and rooting patterns. The medium scale (10 m to 5 km) corresponds to that of the forest stand, each stand having average water and energy states with characteristic variance about this mean. The horizontal fluxes of water and energy between adjacent stands can be important, particularly where streamflow occurs. However, because the region is sub-humid, the largest fluxes are vertical flows between the surface and the atmosphere or soils. The stand-scale atmospheric fluxes can vary dramatically from stand to stand, even being of opposite direction on a given day if surface characteristics are substantially different. The largest scale (5 km to 100 km) is at the landscape or river basin level. Landscape-scale hydroclimatic states and fluxes change over the season in a complex response to antecedent sub-surface and surface water and temperature conditions, atmospheric inputs/losses, energy partitioning and water storage by vegetation and soil. There is an important feedback mechanism at this scale, for over a landscape the upwind energy and water states influence the fluxes at downwind points. Hence a hot, dry landscape upwind will promote high evaporation downwind whilst a moist landscape upwind will suppress evaporation downwind. The appropriate scale for a hydrological process classification scheme depends somewhat on the application. In this example we will focus on the stand (medium) scale. Provision for the landscape scale will be made by aggregating stands in a river basin. Small-scale variation will be addressed by recognising species variability in mixed-wood stands and by using hydrological process algorithms that upscale the small-scale physics internally and can be applied at the stand scale.

Experiment

Study Site Characteristics

The study sites are in the Prince Albert Model Forest (PAMF) of central Saskatchewan, Canada 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 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.

Hydrological and climatic data were collected from five stands,

- 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/silt 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.

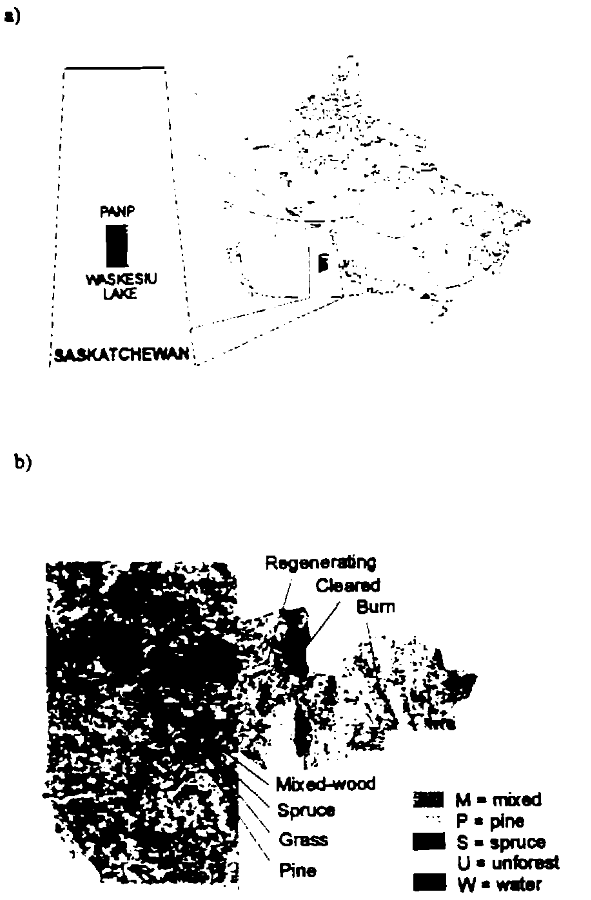

Figure 2. Location of study area in Canada and site characteristics: a) General location of the Prince Albert Model Forest in the Province of Saskatchewan, Canada, b) Forest cover, site locations and experimental basin location. Area on the left is Prince Albert National Park with a conservation/recreation-orientedforest management regime, area on the right is provincial land leased to Weyerhauser Canada Ltd. and the Montreal Lake Cree Nation where forest harvesting and fires are prevalent.

One river basin, Beartrap Creek was intensively mapped and monitored for stream discharge. The location of the sites in Canada and the forest cover and location of sites and Beartrap Creek in the PAMF are shown in Fig. 2. The area in Prince Albert National Park has been protected from timber harvesting and fires for 70 years, areas outside of the Park are in the Weyerhauser Canada timber lease and Montreal Lake Cree Nation Reserve and have been subject to intensive harvesting and are less well protected from burns. The classification "Unforest" simply means that the area has been recently logged or burnt or does not support commercial grade timber. Unforested land is composed of treed muskeg, muskeg, clearings, meadows, shrubs, burnt areas and recent clear-cuts.

Instrumentation

At each site, half-hourly measurements were made of net and solar radiation, air temperature, wind speed, relative humidity, latent heat flux, sensible heat flux, ground heat flux, precipitation, interception, and soil temperature. The measurements were made above, below and within the canopies and were digitally recorded on portable dataloggers, powered by solar panels. Instruments were located on towers which extended above the forest canopy. Sites were visited weekly throughout the study to confirm instrument operation, service instruments, conduct snow water equivalent surveys, and measure soil moisture. Leaf area index was measured seasonally using an optical attenuation device. The period of observation extended from 1993 to 1997 and a complete listing of site instrumentation, data retrieval methods and estimated measurement errors is given by Pomeroy et al. (1997).

Modelling Database Construction

Digital GIS data of forest cover, soils and drainage was received from the Saskatchewan Department of Environment and Resource Management forestry database in Prince Albert and from the Prince Albert National Park forest inventory. Both databases were created from aerial photograph interpretation and updated by foresters from the provincial government and the Prince Albert Model Forest. A digital elevation model was created using digitised elevations from topographic maps. A LANDSAT satellite image was also classified as to major vegetation and water body cover in order to evaluate the forestry database. Since the various landcover databases were not compatible, with respect to format or classification procedure, and effort was made to compare classifications and modify them so that a consistent classification could be produced for the PAMF area. Information was abstracted from the databases to produce maps of land characteristics important to hydrological processes. The key parameters identified were:

- Leaf area index (winter, fall, summer, spring)

- Canopy coverage
- Species composition
- Stand age
- Stand height
- Soil type
- Slope
- Aspect
- Elevation

Examples of some of these variables for the Beartrap Creek basin are shown in Fig. 3. As Beartrap Creek has not undergone forest harvesting since the 1920's it is representative of the protected zone of the PAMF, but not of the southern boreal forest as a whole.

Hydrological Process Characterisation

Snowfall Interception and Snow Cover Accumulation

An intensive study was made of snow interception by evergreen canopies and the subsequent sublimation or unloading of this snow to the ground (Pomeroy and Schmidt, 1993; Pomeroy and Dion, 1996; Hedstrom, 1998; Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998a). To aid in this study a full-size pine or spruce tree was suspended and weighed throughout the winter in various stands. The region is cold and dry so melt of intercepted snow is infrequent. Measured decreases in snow mass on this tree that did not contribute to ground

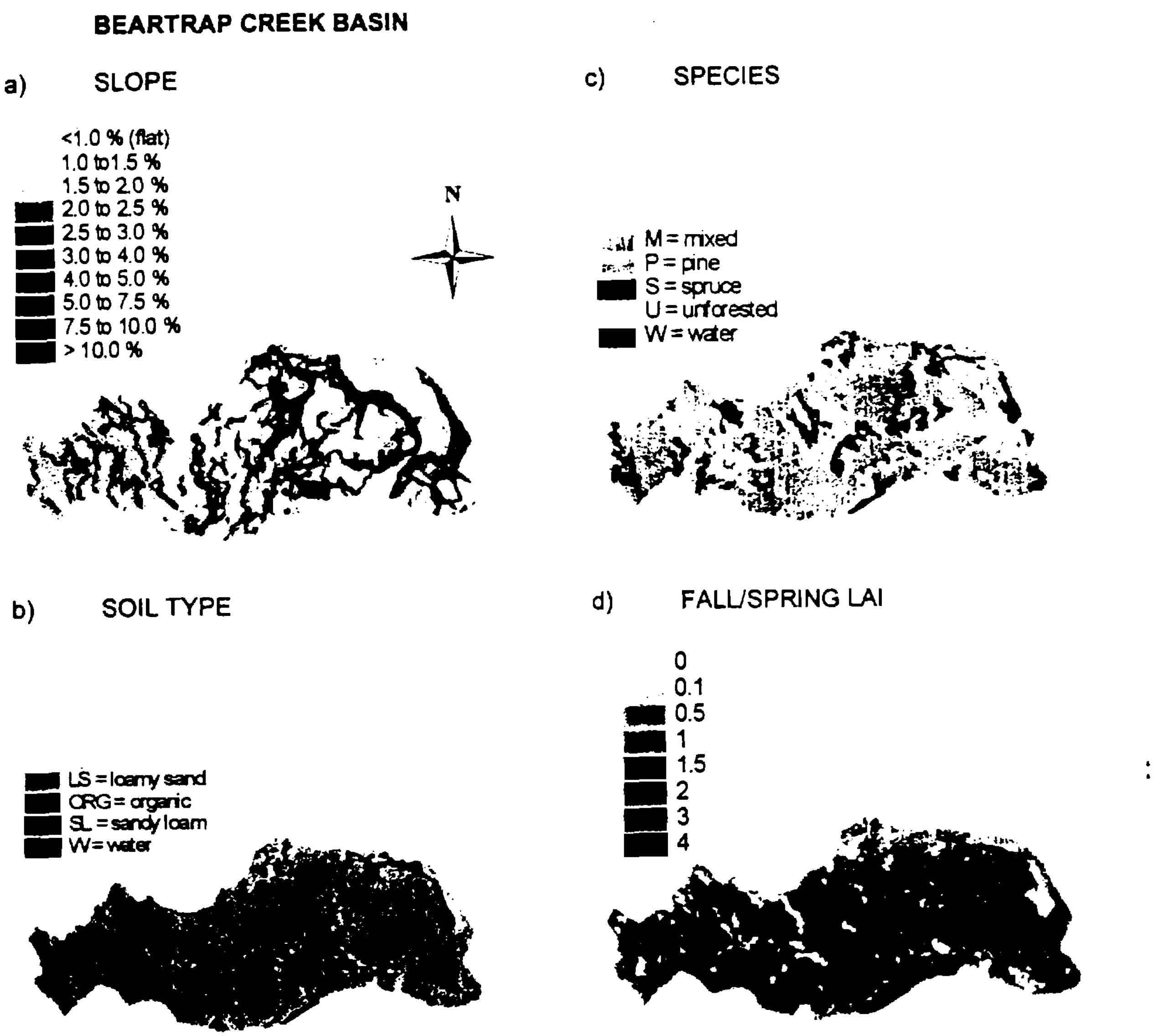

Figure 3. Beartrap Creek Hydrological Characteristic Examples: a) slope, b) soils, c) forest cover type, d) fall/spring leaf area index.

snow accumulation represent sublimation to water vapour and a hydrological loss. An example of snow mass measurements from the suspended tree, converted to areal snow water equivalent, and canopy air temperature for several sequences of snow accumulation and sublimation is shown in Fig. 4. Above and below-canopy snowfall measurements provided weekly estimates of snow interception and seasonal estimates of sublimation loss. Seasonal sublimation losses, calculated from mass balance measurements over several years for various forest stands, are shown in Fig. 5 and range from 10% to 45% of seasonal snowfall. Sublimation losses from clear-cut and burned areas were negligible.

The effect of variable interception and subsequent sublimation losses from different canopy types on snow accumulation is shown in Fig. 6 as a seasonal time series of accumulation. It is seen that accumulation under a dense spruce canopy can be less than half that found in predominately deciduous forests or in clear-cut areas. This difference in snow accumulation has important implications for organisms that live in snow (Jones et al., 1998), nutrient inputs to the ecosystem (Pomeroy et al., 1998b), insulation of soil from cold temperatures and for spring snowmelt, infiltration to soils and runoff generation.

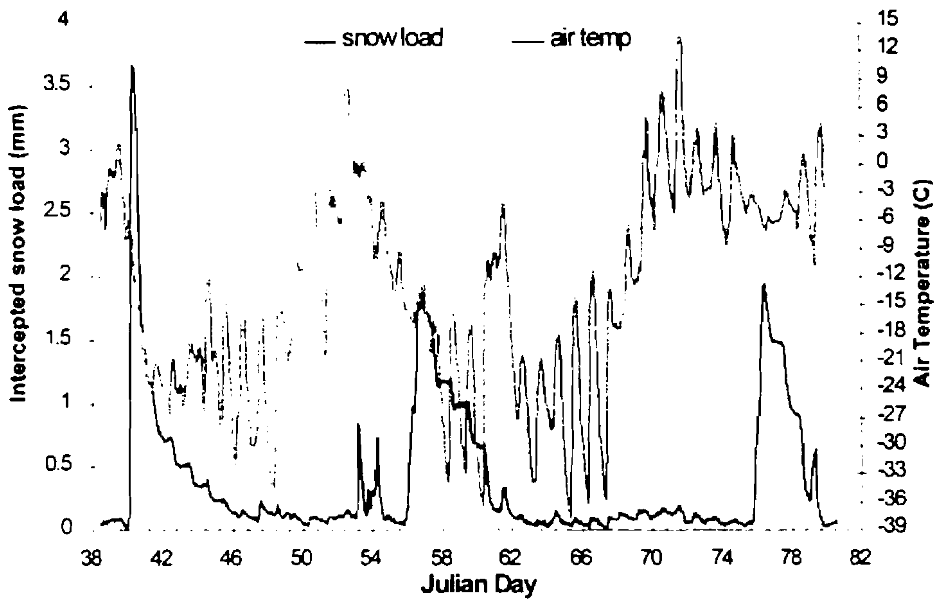

Figure 4. Sequence of snow interception and sublimation measured from a suspended jack pine tree. Snow mass on the tree has been converted to areal snow water equivalent by comparing changes to tree mass during snowfall to a mass balance of above and below canopy snowfall. Air temperature is also shown to indicate that it is sublimation rather than melt which reduces most intercepted snow in this environment.

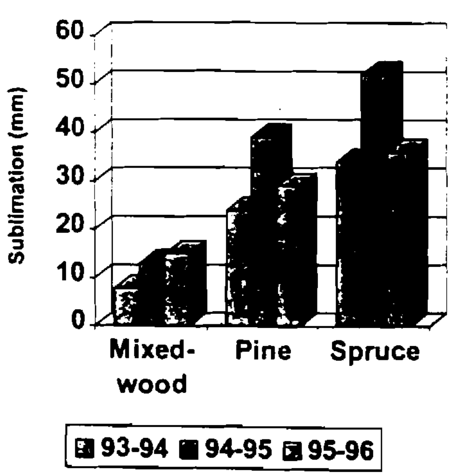

Figure 5. Seasonal sublimation losses determined from comparative above and below canopy snowfall measurements. The losses range from 10% to 45% of seasonal snowfall, increasing with winter leaf area.

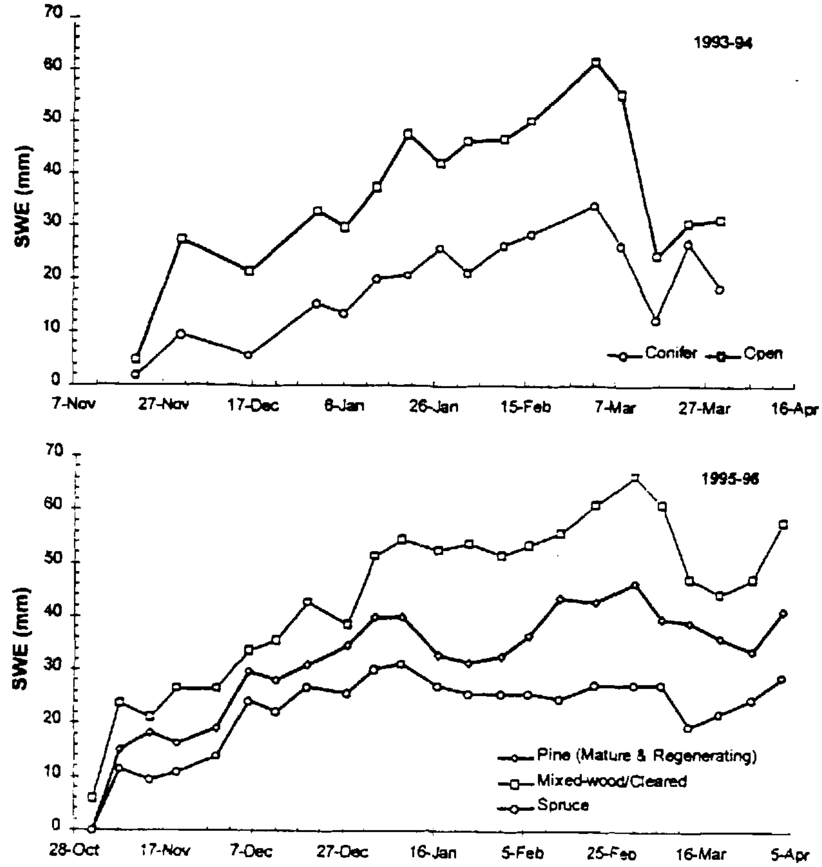

Figure 6. Seasonal time series of snow water equivalent accumulation under various canopy types. Snow accumulation decreases with increasing leaf area because of interception and subsequent sublimation losses.

Snowmelt

Snowmelt has been studied extensively in this experiment (Pomeroy and Granger, 1997; Faria, 1998) and in related studies in the region (Metcalfe and Buttle, 1998; Hardy et al., 1997; Davis et al., 1997). The key results which derive from these studies are the influence of canopy in attenuating radiation and convective heat inputs to melting snowcovers and hence in delaying snowmelt under dense forest canopies. Pomeroy and Granger found that snowmelt was three times faster in clear-cuts than under mature forest canopies, despite substantially greater snow accumulation in clear-cut areas. In all environments examined, radiation was the primary energy input to melting snow and radiation inputs to clear-cuts were 2.5 times greater during snowmelt, despite the fact that clear-cuts melted in 5 days, compared to 15 days for coniferous and deciduous forests. The sequence of snowmelt in 1996 is shown in Fig. 7 and illustrates the dramatically faster meltrate in recent clear-cuts. Interestingly, the regenerating pine plantation snowmelt rate was similar to that of the mature pine, suggesting that it was behaving in a similar manner to a mature forest stand, with respect to snow accumulation and melt energetics.

Rainfall Interception and Evapotranspiration

In spring, summer and fall, precipitation occurs mainly as rain, which like snow is partially intercepted by forest canopies where it is subject to energetic conditions that enhance evaporation compared to that directly from ground. The water that reaches the soil directly as rain or drips from the canopy tends to infiltrate and contributes to soil moisture reserves. Some of this soil water is subject to uptake by roots and is used by the plants for transpiration. The sum of evaporative losses from direct evaporation and from transpiration is termed evapotranspiration. In this study, interception of rainfall ranged from 9% to 55% of rainfall, increasing with leaf area. Up to 70% of intercepted rainfall evaporated directly from the canopy. As a result, direct canopy evaporation increased with summer leaf area, and amounted to approximately 25% of total evapotranspiration for mature conifer canopies, declining to negligible amounts for clear-cut areas (Elliott et al., 1998).

Granger and Gray (1989) developed a physically-based model which estimates evapotranspiration as a function of net radiation, ground heat flux, air temperature, wind speed and a drying power function which is controlled by the regional humidity. Whilst bounded by an energy balance, the model assumes that a humid atmosphere is partly due to strong evaporation, and therefore indicates adequate regional surface moisture for evaporation. Denser vegetation produces a greater aerodynamic roughness and facilitates evapotranspiration. The seasonal progression of evapotranspiration for various canopy types as estimated by the model (and confirmed with "direct" eddy correlation measurements) is shown in Fig. 8, and indicates that evapotranspiration is reduced by approximately one-third when forest canopy cover is removed (Granger and Pomeroy, 1997). The reduction in evapotranspiration signifies that a greater proportion of the incoming energy is being partitioned to sensible heat. This has important implications for surface temperatures, soil water supply, the infiltration capability of soils and runoff generation. Granger (1996) describes a technique where satellite observations of the surface temperature of forests can be used as an index of the relative differences in evapotranspiration, and shows that when this index is compared to a satellite-estimated vegetation index, the ratio provides an indicator of forest health with respect to transpiration.

Infiltration and Runoff Generation

Infiltration and runoff generation occur when water is applied to the soil surface either through snowmelt or rainfall. The major annual runoff events in boreal forests are usually linked to snowmelt because of saturated or frozen soils. In the PAMF area, soils are normally frozen at the time of snowmelt, which restricts the infiltration capacity. Relatively high-ice content soils in clear-cut areas (because of low evapotranspiration the previous summer) produce the greatest runoff during spring snowmelt. The effect is magnified because of high snow accumulation and rapid snowmelt in clear-cut areas. The amount of runoff produced from snowmelt is therefore remarkably high from clear-cuts as compared to mature forests and regenerating forests as shown in Fig. 9. The clear-cut area produced snowmelt runoff consistently even in 1995, a dry snow year.

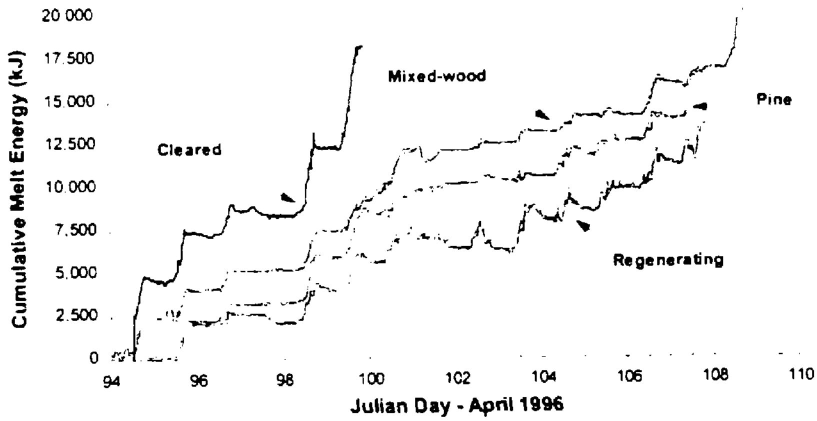

Figure 7. Snowmelt sequence for various forest cover types, spring 1996, expressed as energy used in melting snow. Snowmelt rate decreases with increasing leaf area because of the reduction of net radiation beneath the canopy.

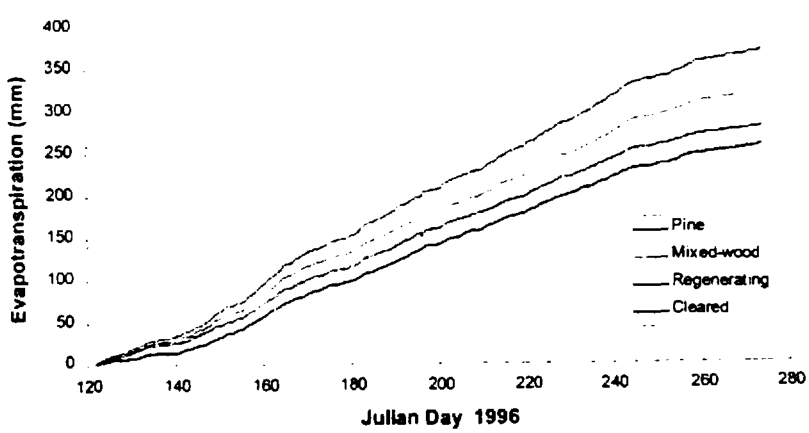

Figure 8. Seasonal cumulative evapotranspiration from 1 May to September, as calculated using the Granger evapotranspiration model for various forest cover types.

Table 1. Land cover attributes used to define and map Hydrological Response Units.

Field	Attributes									
Green-Ampt	Loamy sand	sandy loam	sand	silt	clay	organic	Water	unknown		
Elevation (m ASL)	< 500	500 - 520	520 - 540	540 - 560	560 - 580	580 - 600	600 - 650	650 - 700	> 700	
Slope (percent)	< 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 7.5	7.5 - 10	> 10.0
Species	Pine	Spruce	Mixed	Unforest	Water					
Unforest	Clearing	Grass	Shrub	Burn	Treed Muskeg	Muskeg	Clear-cut	Unknown		
Stand Origin	No Vegetation	< 1888	1888-1908	1908-1938	1938-1958	1958-1968	1968 to present			
Height (m)	No Vegetation	2.5-7.5	7.5-12.5	12.5-17.5	17.5- 2.5	> 22.5				
Density	No Vegetation	sparse	dense	lush						
Summer LAI	Ranges of values from 0.1 - 4.0 m^2/m^2									
Fall-Spring LAI	Ranges of values from 0.1 - 4.0 m^2/m^2									
Winter LAI	Ranges of values from 0.1 - 4.0 m^2/m^2									

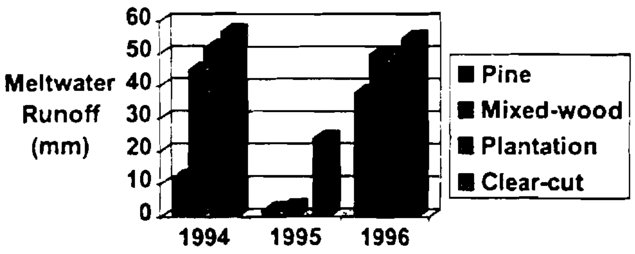

Figure 9. Snowmelt runoff from forest stands as a function of forest cover. The clear-cut consistently produces more runoff than do the undisturbed forest sites.

Though runoff from frozen soils is large, some infiltration does occur and soils normally enter the summer period with high moisture status. Later in the summer, as evapotranspiration often exceeds infiltration, soil moisture status is an indicator of the seasonal water balance amongst sub-canopy rainfall, infiltration and transpiration (there is little deep soil percolation of water from these sites, except for the pine). Soil moisture status is consistently higher in clear-cut areas than in mature forests. By late summer, soil moisture reserves in the upper half-metre of soil can be twice as high in the clear-cut as in the mixed-wood, pine or spruce soils (Elliott et al., 1998). The effect of high soil moisture reserves and reduced interception and canopy evaporation in clear-cuts is to promote runoff generation from rainfall. The observed relationship between rainfall events and water excess indicating runoff is shown in Fig. 10. The pine site produced no runoff because of its sandy soils and the other mature forest sites produced little runoff, however up to one-third of rainfall contributed to runoff from the clear-cut site, with an apparently linear relationship between rainfall and runoff. The slope of the relationship is strongly related to canopy leaf area and to soil moisture retention characteristics.

Model Generation

Hydrological models attempt to represent the hydrological cycle from precipitation to streamflow in mathematical form. Simple regression or stochastic models can provide reliable streamflow predictions for current conditions in the specific region of development, but have several limitations which become apparent with changing climate or land use in the basin of application. Their internal operation is also often characterised by compensating errors in individual hydrological terms and violation of conservation of mass and energy which usually makes them unsuitable for calculating hydrological variables other than runoff. The modelling approach here is that of a physically-based, spatially-distributed model (Kite and Pietroniro, 1996). The model uses a Geographical Information System (GIS) to map and track *hydrological response units* (HRU) in the basin. These HRU have characteristic vegetation cover, soils and topography which make them hydrologically-distinctive with respect to the operation of the hydrological processes. Physically-based hydrological process algorithms are used to calculate terms of the water cycle in order to produce a water budget within each HRU. In an ultimate modelling stage these HRU transfer water amongst each other and through the basin. However, this is a computationally-intensive simulation. For this initial demonstration of physically-based HRU modelling of a boreal forest, a summertime vertical water budget is specified and water excess or deficit is calculated as an indicator of the hydrological status of the forest and basin. Driving atmospheric parameters (precipitation, wind speed, air temperature, humidity, net radiation) are obtained from direct measurement at the instrument towers. Basin characteristics used to define HRU are described below.

Land attributes derived from digital elevation models, soil surveys and forest inventories are used in defining HRU are listed in Table 1. The attributes are: stand height, canopy density, year of origin, forest species, winter LAI, summer LAI, spring/fall LAI, soil properties, type of disturbance or condition, aspect, elevation, slope. The basin is then divided into areas having similar combinations of attributes. There areas are lumped and termed HRUs. The water balance simulation is run for each distinctive HRU on an hourly basis.

Key algorithms in the summer-time operation of the model include interception of rainfall, evapotranspiration and infiltration of water to soils. Each algorithm was consituted as a *class* in the model: a Rutter Class, Granger Class and Green-Ampt Class respectively. The algorithm classes are physically-based descriptions of processes examined in the study, details of which are described by Pomeroy et al. (1997). The water balance for each HRU is summed each week to calculate various terms important to forest hydrology: infiltration, runoff (infiltration excess), evapotranspiration, canopy water storage, canopy drip and effective rainfall (that which reaches the soil).

As an example the model was applied to Beartrap Creek from 1 May to 30 Sept. 1995 for existing landcover conditions and modified landcover, in which all pure softwood stands were converted to clear-cuts (virtual clear-cutting). Fig. 11 shows cumulative infiltration and cumulative evapotranspiration on week 20 of the simulation, mapped for Beartrap Creek under actual and virtual clear-cut land classes. Substantial variation in the pattern of the key hydrological parameters is indicated. Figure 12 shows the summer seasonal water balance for Beartrap Creek as it is sensitive to forest class; i.e. with current land use and with a virtual clear-cut of softwood stands (20% of basin area). Note that runoff was small in both scenarios, indicative of using a dry year and the neglect of variable snowmelt infiltration inputs in this

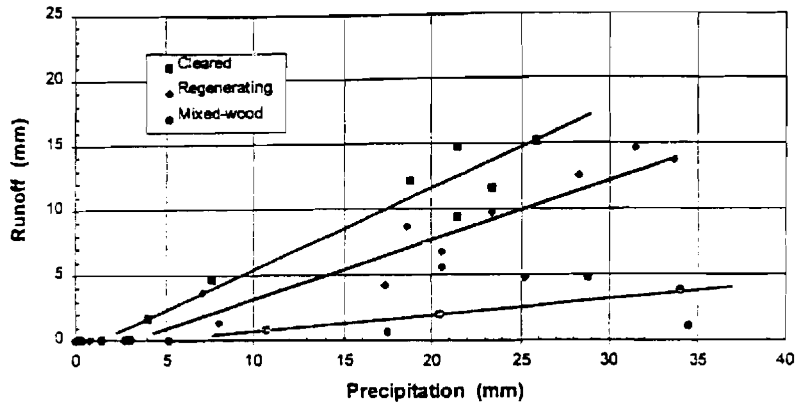

Figure 10. Observed water balance excess (indicating runoff) and rainfall for various forest cover types with an arbitrary straight line to represent the observations. The lines are to help visualise the observations and do not indicate the relationship used in modelling runoff.

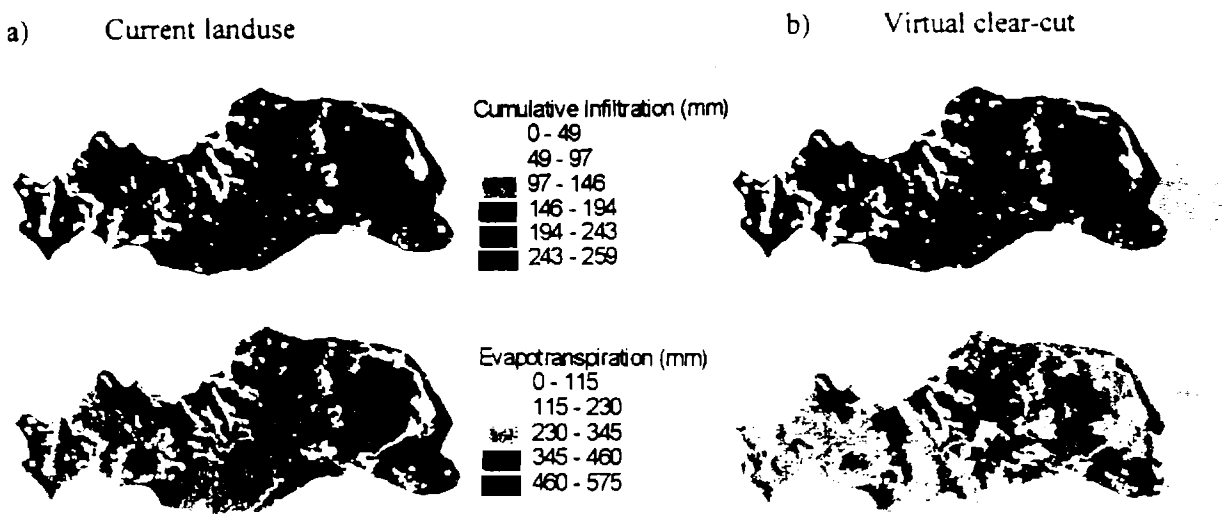

Figure 11. Cumulative infiltration and evapotranspiration (1 May, 1995 onward) for week 20 of the model simulation for Beartrap Creek: a) observed forest cover characteristics, b) "virtual (hypothetical) clear-cut" of all pure softwood stands (20% of basin area). Note the increase in infiltration and decrease in evapotranspiration associated with the virtual clear-cuts.

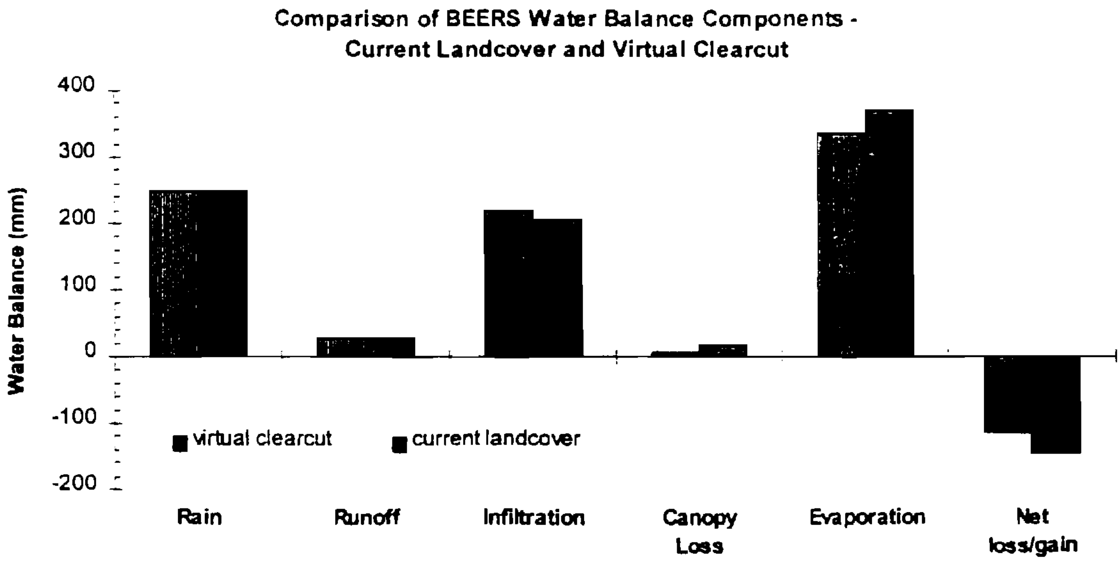

Figure 12. Comparison of modelled summer water balance for undisturbed and virtual clear-cut of conifer stands in Beartrap Creek basin, 1995.

simulation. The water deficit for the summer declined by 29% with the virtual clearcut, suggesting a very strong response in the hydrology to changes in forest class. A decline of summer water deficit of this magnitude would increase water storage in wetlands, aquifers, lakes and increase average streamflow and peak streamflow response to subsequent heavy rainfall and snowmelt events.

Conclusions

An investigation of hydrological processes in the southern boreal forest of western Canada has shown that these processes are key indicators of ecosystem health and water resource status and that they are quite sensitive to forest classification and changes to classification resulting from land use activities. Significant differences were found in the management of boreal forest water resources by natural, cleared and plantation forests, specifically due to:

1. Removal of forest canopy or changes to forest species,
2. Soil type or disturbance.
3. Spatial pattern of alterations to canopy and soils within a basin.

Clear-cuts have wetter soils, hotter surfaces, greater runoff and lower evaporation than natural forests, however there is evidence for partial hydrological recovery of plantations after about 15 years. A computer simulation of these processes that uses forest classifications on a Geographical Information System can indicate the hydrological impact of forest cover change. For a virtual clear-cut of softwoods from 20% of the basin area, the summer water balance deficit decreased by 29% over 20 weeks. This suggests that forest classifications, coupled with hydrological process models, can provide a powerful tool for evaluating the sustainable management of water resources in the boreal forest.

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