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Wolf Creek Research Basin water balance studies

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Abstract Several classical water balance studies have been conducted in Wolf Creek. Most recently such work was carried out for the upper Wolf Creek basin to provide a comprehensive historical water balance assessment for all years of operation as part of the Northern Research Basins (NRB) water balance project. A closed annual water budget was obtained with a residual storage value of 19 mm. The relatively new CRHM model was applied to the upper Wolf Creek watershed for the 1995/1996 water year, with simulation for the remaining years ongoing. Of the past studies conducted for Wolf Creek forest environments, precipitation and evapotranspiration rates are similar in magnitude between studies. The recent CRHM water balance was carried out for higher elevation alpine and subalpine environments and yields evapotranspiration rates lower than those in forest environments, due to lower energy levels. Infiltration and runoff is variable within, and between, individual studies. In the upper Wolf Creek study, summer infiltration was simulated adequately; however, there are problems with snowmelt infiltration and runoff.

Key words CRHM model; HRU; infiltration; runoff; water balance; Wolf Creek, Canada

INTRODUCTION

The calculation of water balance components is critical for many water management issues. In northern regions such calculations are complicated by frozen ground, which affects infiltration and runoff. Cold soils in the summer affect evapotranspiration rates. Sparse vegetation influences snowpack accumulation, redistribution and melt. Several classical water balance studies have been conducted in Wolf Creek, Yukon, Canada. These studies are summarized here, and the complementary results of a recent water balance exercise for the upper Wolf Creek basin using the Cold Regions Hydrological Model (CRHM) are also presented.

STUDY AREA

The Wolf Creek Research Basin is located in the southern headwaters region of the Yukon River drainage basin in southwest Yukon. A tributary to the Yukon River, it is located 15 km south of Whitehorse, at approximately 61°N latitude, 155°W longitude

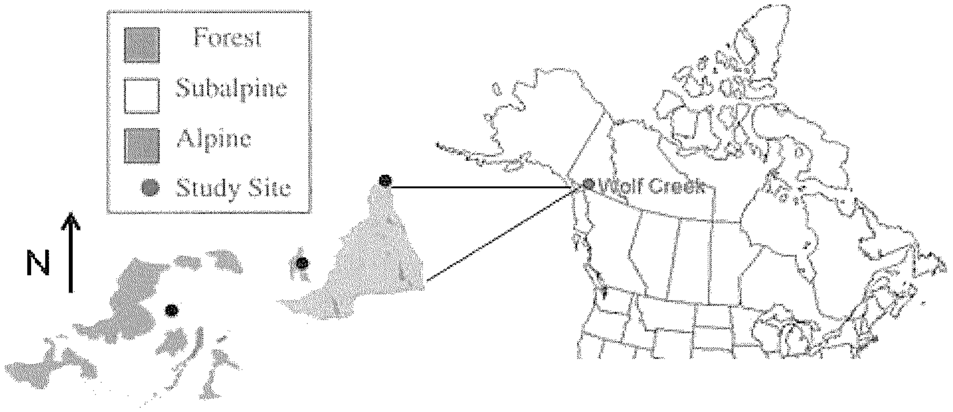

Fig. 1 Wolf Creek location plan and ecoregions.

(Fig. 1). The 195 km^2 watershed has a northeasterly drainage aspect, with elevations ranging from 800 to 2250 m, with a median elevation of 1325 m.

The bedrock is primarily sedimentary in nature, and includes limestone, sandstone, siltstone and conglomerate. Some volcanic materials consisting of andesite and basalt are present, along with some intrusions of granite. The basin is overlain with a mantle of glacial till, ranging from a thin veneer to depths of 1–2 m. Fine-textured alluvium covers most of the valley floors adjacent to the stream channel. Upper elevations have shallow deposits of colluvial material with frequent bedrock outcrops (Mougout & Smith, 1994). Terrain mapping of the watershed was conducted by Applied Ecosystem Management (2000), which produced descriptions of vegetation, soil texture, and surficial geology for Wolf Creek.

Approximately 40% of the watershed is underlain with permafrost (Ednie, 2003). Permafrost is present in north-facing slopes, poorly drained areas, or areas with significant organic layers that provide insulation. The presence of permafrost generally tends to increase with elevation; however, there is significant variability related to other physical factors such as topography and vegetation cover. Seguin (1998) employed geophysical investigations and observations of altitude, ecozone classification, and forest density to estimate the occurrence of permafrost within the basin. He suggests that discontinuous permafrost occurs above 1175 m on north-facing slopes and 1300 m on south-facing slopes, and that continuous permafrost exists above 1500 m. Lewkowicz & Ednie (2004) found that an organic mat thicker than 10 cm was associated with the presence of permafrost across a wide range of elevations.

Wolf Creek is stratified by elevation into three principle ecosystems: boreal forest, sub-alpine taiga, and alpine tundra. They cover 22%, 58%, and 20%, respectively, of the basin area (Francis, 1997). The forest ecosystem consists of white spruce and lodgepole pine, which ranges in elevation from 760 m at the outlet of the basin, to approximately 1100 m. Soils in the lower forest eco-region are comprised primarily of Orthic Regosols with a highly variable texture. The parent material is mixed alluvial, lacustrine and morainal material that is poor to well-drained. The subalpine eco-region forms the broad transition between the forested lowlands and sparsely vegetated alpine regions, and is vegetated primarily by open white spruce and willow-dwarf birch shrub communities. The elevation of the subalpine ecosystem ranges from approximately 1100–1500 m. Tree density and stature generally decreases with increasing elevation to a point where few trees exist, or, if present, exhibit a Krummholz growth pattern. Where localized areas of extreme relief occur, abrupt transitions between subalpine and alpine vegetation communities often occur. Soils within the subalpine eco-region are comprised primarily of Orthic Eutric Brunisols, with textures ranging from a sandy loam to a gravelly sandy loam.

The alpine eco-region generally occurs above 1500 m with extreme physiographical conditions characterized with large changes in elevation, slope and aspect within small distances. Alpine tundra communities comprise 82% of this ecosystem, and consist of lower stature growth forms consisting of grass-forb-lichen with isolated pockets of willow-dwarf birch. The remaining 18% of the eco-region is unvegetated. Similar to the subalpine, soils in the alpine eco-region are coarse, comprised primarily of Orthic Eutric Brunisols.

The Wolf Creek watershed has a subarctic continental climate, which is characterized by a large variation in temperature, low relative humidity and relatively low precipitation (Wahl *et al.*, 1987). Mean annual temperature for Wolf Creek is on the order of –3°C, with mean monthly summer and winter values ranging from 5° to 15°, and –20° to –10°C, respectively. Summer and winter maximum and minimum temperatures of 25° and –40°C are not uncommon. Arctic inversions develop during the winter months when air temperature can increase with elevation. Mean annual precipitation is 300 to 400 mm per year, with approximately 40% falling as snow.

The streamflow regime is typical of a small, mountainous subarctic stream, with low flows occurring during March or April in response to minimum groundwater contributions. Because of significant lake storage and the moderating influence of the Gulf of Alaska, minimum winter flows of 0.4 $m^3 s^{-1}$ are relatively high (Janowicz, 1991). Peak flows of 10–20 $m^3 s^{-1}$ occur in May or early June due to snowmelt or rain on snow events, with secondary peak flow occurring later in the summer as a result of intense rainfall activity. In a relatively small catchment such as Wolf Creek, summer rainfall may occasionally produce the annual peak (Janowicz, 1986).

DATA COLLECTION PROGRAM

Baseline meteorological stations were established in 1993 within each of the three Wolf Creek eco-regions and have operated continuously since that time (Hedstrom *et al.*, 2002). The forest, subalpine, and alpine stations are located at elevations of 750, 1250, and 1615 m respectively. Each of the stations samples a comprehensive set of variables, including air temperature, relative humidity, rainfall, snowfall, snow depth, blowing snow intensity, snow temperature, wind speed and direction, solar radiation, net radiation, soil temperature, and soil heat flux. Barometric pressure is monitored at the alpine site only. At each of the stations, conventional snow surveys using the Mount Rose sampler to measure snow depth and snow water equivalent, across 25 point courses, are carried out at the beginning of each month through the snow cover season. In 1996 soil moisture probes and additional soil temperature sensors at several levels were installed. In addition, twin probe gamma sites were established at each station to measure soil moisture profiles and infiltration dynamics.

A series of three nested hydrometric stations were established during 1993 and 1994 at locations on Wolf Creek with drainage areas of 14.5, 71, and 195 km^2. An additional station on the 4.3 km^2 Granger Creek, a small upland tributary of Wolf Creek, was established in 1998, and has operated continuously since that time.

A groundwater-monitoring well was established in the lower Wolf Creek basin in March, 2001. The 49 m well provides an indication of groundwater storage conditions in the lower part of the basin. Groundwater recharge occurs during the autumn and winter months, with a decline through the spring and summer. The 3-year record indicates that there is an annual fluctuation of approximately 0.6 m.

WATER BALANCE STUDIES

Several water balance studies have been carried out for various locations within the Wolf Creek basin. Janowicz *et al.* (1995) carried out a monthly and annual water balance for the 195 km^2 basin for the 1993/1994 period using the following water balance relationship:

$$(P_m + P_r) - (Q + ET + E_s) = \mathrm{d}S \tag{1}$$

where P_m is snowmelt, P_r is rainfall, Q is streamflow, ET is evapotranspiration, E_s is sublimation/ablation, and dS is change in storage. Evapotranspiration was estimated using a model developed by Morton (1983). Sublimation/ablation was estimated by comparing nipher snowgauge data with surveys of snow on the ground. Water balance components are summarized in Table 1. Evapotranspiration may be high, since Morton's model does not account for ground heat flux. The balance calculations indicate that a significant net soil storage withdrawal took place.

Janowicz *et al.* (1996) carried out a snowmelt water balance comparison for the 195 km^2 watershed, for two consecutive years, using the following general water balance relationship:

Table 1 Wolf Creek Water Balance Components in mm, 1993/1994.

	Snow	Rain	Melt	Sub/Ab[1]	*ET*	*Q*	Storage
Oct	20.1	–	–	3.8	–	10	–10
Nov	13.3	–	–	4.5	–	7.7	–7.7
Dec	14	–	–	2.7	–	6.6	–6.6
Jan	31	–	–	6.0	–	4.9	–4.9
Feb	18	–	–	3.4	–	3.2	–3.2
Mar	18	–	–	3.5	–	2.8	–2.8
Apr	9.8	–	20	1.9	32	7.3	–21
May	–	2.7	79	–	55	9.8	17
Jun	–	45	–	–	67	16	–39
Jul	–	17	–	–	75	14	–72
Aug	–	17	–	–	44	9.4	–37
Sep	–	51	–	–	25	9.8	16
Total	125	131	99	26	298	102	–172

[1] Sublimation / Ablation

$$R = P - E + \mathrm{d}S \tag{2}$$

where R, P, E and dS are watershed runoff, precipitation, evaporation, and storage change respectively. For snowmelt runoff, P represents snowmelt (M), which is determined using the following relationship:

$$M = P_s - E_s \tag{3}$$

where M, P_s, and E_s are melt, snowfall, and evaporation during melt. Evaporation during melt was assumed to be negligible. Water balance components are summarized in Table 2. The 1994 and 1995 freshet events were quite distinct. Though snowpack conditions were similar, snowmelt discharge volumes were three times greater during 1995 as compared to 1994. The difference is thought to be explained by variations in snowmelt infiltration to frozen ground, which is influenced by pre-freeze up soil moisture amounts.

Carey & Woo (1999) carried out a water balance for both snowmelt and summer seasons in an open woodland environment, for north and south facing slopes in the middle reaches of the Wolf Creek basin for the period from 1997 to 1999. This work was summarized by Carey & Woo (2001), with subsequent studies of east and west facing slopes. The snowmelt period varied by up to 2 months depending on aspect and other slope characteristics. Snowmelt runoff was limited to slopes with ice-rich substrates, primarily permafrost, which limited infiltration. Summer runoff (interflow) was limited to slopes with porous organic layers overlying mineral soil, with differences in flow determined by the location of the water table.

Evaporation was calculated using the Bowen ratio method and a modified Priestley & Taylor approach. Runoff was measured using V-notch flumes with plastic sheeting directing flow into the flumes. The following water balance equations were used:

$$\text{Snowmelt Period: } M + I + R - V \pm Q = \mathrm{dS} \tag{4}$$

$$\text{Summer Period: } R - ET \pm Q = \mathrm{d}S \tag{5}$$

where M is snowmelt, I is ice melt, R is rainfall, V is sublimation, Q is net runoff, ET is evapotranspiration, and dS is soil moisture change. Table 3 summarizes the water balance components for the study.

Snowmelt accumulation varied between the slopes due to interception and redistribution. Sublimation was determined to be a small component on all slopes. Snowmelt on the north-facing slopes proceeded slowly for the span of 5 weeks, yet produced significant runoff due to the relatively impervious permafrost, and limited storage in the active layer substrate. Snowmelt on the south-facing slope was rapid and complete 1 month prior to the north-facing slope. No runoff was observed, with a subsequent large increase on storage change. The runoff infiltration dynamics on the east and west slopes were within the range of the north- and south-facing slopes (though these slopes

Table 2 Wolf Creek Water Balance Components (mm), 1994 and 1995.

	Melt	Runoff	Storage change
1994	107	13.5	93.5
1995	101	37.5	63.8

Table 3 Water balance components for study slopes in mm.

	E–slope	W–slope	N–slope	S–slope
Snowmelt Period	24 Apr–6 May, 1998	24 Apr–6 May, 1998	21 Apr–25 May, 1997	6–26 Apr, 1997
SWE	92	90	187	160
Icing	0	0	19	0
Sublimation	8	13	18	10
Runoff	50	19	155	0
Storage Change	+45	+79	+58	+137
Cumulative Error	–11	–21	–25	+13
Summer Period	15 May–12 Sept, 1999	15 May–12 Sept, 1999	18 May–22 Sept, 1997	26 Apr–22 Sept, 1997
Rainfall	141	141	150	150
Evapotranspiration	260	220	315	372
Runoff (outflow)	30	11	97	0
Runoff (inflow)	na	na	245	0
Storage Change	–12	–96	–37	–138
Cumulative Error	–137	+17	+20	–84

were not studied in the same year). The cumulative error of 10–20% represents measurement and calculation error of soil moisture change, some of which may be compensating.

During the summer season, evapotranspiration was found to be the biggest loss from the hillslopes, exceeding rainfall by 79 mm on the west slope to 203 mm on the south slope. Over the summer, evapotranspiration and drainage depleted soil moisture on the west and south slopes, while on the east and north slopes, soil moisture was replenished by flow moving downslope. The large cumulative negative error on the east slope encompasses the error associated with inflow to the study plot from upslope. In contrast, the small error on the west slope provides support for the magnitude of the water balance components. On the south slope, the soil moisture reservoir supplied water for evapotranspiration for the summer.

A preliminary monthly and annual water balance was developed for the 14.5 km^2, upper Wolf Creek basin using the Cold Regions Hydrological Model (CRHM). The CRHM model is a spatially distributed, modular, numerical modelling system. Modules represent algorithms, which transform input data, interpret basin characteristics, and represent physically-based hydrological processes. These modules include blowing snow, interception, sublimation, snowmelt, soil freezing, frozen soil infiltration, evapotranspiration, infiltration, soil moisture balance, routing, and runoff algorithms, which are linked and compiled by CRHM into a customized simulation package. The model can select from a number of library modules those that are the most applicable to the given situation.

The model uses standard land use and basin characteristics, and climate data, for the processing algorithms to calculate and graphically display hydrological variables of interest. Simulations are carried out for distinct Hydrological Response Units (HRUs) that represent sub-basins of hydrologically homogeneous characteristics, such as land cover, slope, aspect, and soil type. Required time series of meteorological data for the model include air temperature, relative humidity, wind speed, precipitation, and radiation. Hourly or half hourly time steps can be specified. Detailed information on the CRHM process modules is provided in Hedstrom *et al.* (2001).

The preliminary analysis was carried out for the 1995/1996 September to August hydrological year. Data from the subalpine meteorological station used to represent upper Wolf Creek basin conditions, which consists of a tundra and shrub-tundra environment. The upper Wolf Creek basin was subdivided into five HRUs for the water balance calculations. Table 4 lists the specified physical parameters.

Sublimation and wind transport is simulated using the Prairie Blowing Snow Module (pbsm), based on wind speed, air temperature, relative humidity, and roughness height. Simulated sublimation and wind transport from all HRUs was minimal, which is assumed to be reasonable for shrub-tundra environments. Greater wind ablation would be expected from tundra sites, indicating the model under performed in these environments. Snow ablation data, calculated by Pomeroy *et al.* (1999) for alpine tundra and shrub environments for the same period, were used for the water balance.

The energy budget (ebsm) routine was used to generate snowmelt for the five HRUs. Snow accumulation is assumed similar for all HRUs, with only slight variations due to wind losses (sublimation + transport). The snowmelt process was simulated to commence around 16 April within all HRUs; however, most of the melt occurred in May, with HRUs 3 and 5 becoming depleted last.

The module EVAP was used to calculate evaporative flux, using a combination aerodynamic and energy budget approach, based on the procedure used by Penman. The procedure uses a relationship between relative evaporation and relative drying power, a function of wind speed, saturation vapour pressure and actual vapour pressure, net radiation and ground heat flux (Granger & Gray, 1989). Evaporation commences after snowmelt, peaks with the available energy in June, and continues into the early fall. Significantly differing cumulative amounts of evapotranspiration are simulated for the five HRUs, with 110 mm in HRU 5, which has the least available energy for the process because of its northern exposure, to 189 mm for HRU 1, which has both significant amounts of energy due to its southern exposure, and available soil moisture.

The snowmelt infiltration to frozen soil was calculated using the CRACK module, which uses pre-melt soil moisture (liquid + frozen) and available meltwater (SWE) to simulate infiltration (Granger *et al.*, 1984). Summer infiltration is determined using the

Table 4 HRU physical parameters.

	HRU 1	HRU2	HRU3	HRU4	HRU5
Latitude (deg)	60.45	60.45	60.45	60.45	60.45
Elevation (m)	1677	1662	1509	1418	1387
Area (km^2)	1.6	2.4	5.6	2.5	2.4
Aspect (deg)	240 wsw	120 ese	45 ne	225 sw	40 nne
Slope Angle (deg)	33	11	4	23	9
Roughness Ht (m)	0.1	0.15	0.2	1.0	1.2
Fall Soil Saturation(%)	20	30	35	70	70
Albedo	0.17	0.17	0.17	0.17	0.17

Green-Ampt module. The module describes the infiltration of ponded water based on total porosity, effective porosity, wetted capillary pressure, and hydraulic conductivity (Rawls *et al.*, 1983). Input parameters include initial soil moisture, maximum soil moisture, and soil type. Infiltration during the snowmelt period was simulated to be about 30 mm for all HRUs. Summer infiltration was likewise similar for all HRUs.

The monthly and annual water balance for the upper Wolf Creek basin is summarized in Table 5, based on the following relationship:

$$dS = P - E - S_b - R \tag{6}$$

where P, E, S_b, R and dS are precipitation, evapotranspiration, sublimation, runoff, and storage, respectively. Basin runoff is based on measured discharge from the hydrometric station at the bottom of the 14.5-km^2 basin. The storage term represents both snow and soil storage. It is assumed that precipitation is initially evenly distributed over the basin area. Aggregate values of the evapotranspiration and sublimation were calculated based on the pro-rated HRU areas. The annual budget is quite close, with values of 331, 135, 58, 119 and 19 mm for precipitation, evapotranspiration, sublimation, runoff, and storage, respectively. The relatively tight annual balance, with a storage surplus of 19 mm, indicates the model performed reasonably well in simulating evapotranspiration, while the other measured or calculated components were reasonable.

Precipitation and simulated evaporation, SWE, snowmelt, and infiltration are summarized in Table 6. Monthly winter SWE totalled 184 mm, with simulated snowmelt and infiltration amounts of 174 and 29 mm, respectively. While the simulated snowmelt seems reasonable, infiltration appears to be low, indicating that perhaps preferential flow and storage in the organic layer need to be considered. Summer monthly 1996 rainfall ranges from 7 to 60 mm with a total of 146 mm. Summer infiltration amounts follows a similar pattern as precipitation, with values ranging from 14 to 43 mm with a total of 87 mm, which seems reasonable.

Table 5 Upper Wolf Creek monthly water balance summary in mm, 1995/1996.

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	TOT
Precip.	24	23	45	45	38	26	12	7	7	15	29	60	331
Evap.	4	–	–	–	–	–	–	–	35	40	34	22	135
Sub.			16	16	13	9	4	0.3					58
Run	8	8	5	4	2	1	0.4	0.4	6	54	19	11	119
Stor.	12	15	24	25	23	16	7.6	6.3	–34	–79	–24	27	19

Table 6 Upper Wolf Creek water balance components in mm, 1995/1996.

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Melt[1]	Rain[2]	TOT
Precip.	24	23	45	45	38	26	12	7	7	15	29	60			331
Evap.	4	–	–	–	–	–	–	–	35	40	34	22	–	131	135
Rain	24	23						7	35	15	29	60	–	146	193
SWE	–	–	7	45	40	50	38	4	–	–	–	–	184	–	184
Melt	–	–	–	–	–	–	–	10	164				174	–	174
Inf	24	16	–	–	–	–	–	–	29	14	30	43	29	87	156

[1] 1995/96 melt period; [2] 1996 rainfall period.

DISCUSSION AND CONCLUSIONS

A number of water balance studies have been conducted in Wolf Creek. Most recently, such work was carried out for the upper Wolf Creek basin in an attempt to provide a comprehensive historical water balance assessment for all years of operation for the NRB water balance project. A closed annual water budget was obtained with a residual storage value of 19 mm. The relatively new CRHM model was applied to the upper Wolf Creek watershed, but results for 1995/1996 indicated that not all components were adequately simulated. Further simulations for other years are ongoing.

Of the past studies carried out for forest environments in Wolf Creek, precipitation and evapotranspiration rates are similar in magnitude between studies. The recent CRHM water balance was carried out for higher elevation alpine and subalpine environments and yields evapotranspiration rates lower than those in the forest. This trend is reasonable, due to lower energy levels, with values similar to those calculated by Granger (1999). Sublimation seems to not be very significant in all reviewed studies, which is contrary to the findings of Pomeroy *et al.* (1999), indicating that additional consideration of this component is required. Infiltration and runoff is variable within, and between, studies, and is a function of aspect, elevation, soil texture, and antecedent soil moisture. In the upper Wolf Creek study, summer infiltration was simulated adequately; however, there are problems with snowmelt infiltration and runoff, and additional work is required in this area. Some additional consideration of soil moisture distribution between upper and lower soil layers is also required.

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